Univerzitet „Džemal Bijedić“ u Mostaru

Mašinski fakultet

Stručni program

Hibridni energetski sistemi

- Skripta -

Doc.dr. Emir Nezirić

Doc.dr. Edin Šunje

KALCEA

Co-funded by the European Union

Chapter 1
Hybrid Renewable Energy Systems Overview

1.1 Introduction

Wind and photovoltaic sources are one of the cleaner forms of energy conversion available. One of the advantages offered by the hybridization of different sources is to provide sustainable electricity in areas not served by the conventional power grid. They are very used in many applications, but due to their nonlinearity, hybrid energy systems are proposed to overcome this problem with important improvements [1–204]. In general, hybridization consists of combining several energy sources and storage units within the same system in order to optimize the production and energy management. In review papers, they can be found under the following names: hybrid renewable energy systems (HRESs) or multi-source multi-storage systems (MSMSSs).

1.2 Advantages and Disadvantages of an Hybrid System

Hybrid renewable energy systems (HRESs) are attractive configurations used for different applications and especially in standalone power generation systems as electrification, water pumping and telecommunications. The most advantages of these systems are their simplicity to use and their independent from one energy source, so they can be productive during the day the night. On the other side, the disadvantage is that there are different sources and storage units, so the system is more complex than a single-source system. In this case, an energy management control is necessary to control the power flow, so the global system will be more complex and of course higher cost [42, 62].

D. Rekioua, *Hybrid Renewable Energy Systems*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-34021-6_1

1.3 Configuration of Hybrid System

The first and most basic decision that a power system designer is faced is what architecture to be used. This decision will influence every other aspects of the system design including the types and quantities of power converters that will be needed. So two choices must be considered [42, 54]:

- Choice of power converters
- Choice of common bus type.

1.3.1 Choice of Common Bus Type

The different energy sources can been interconnected through a DC bus or through an AC bus or through DC/AC bus [43, 55–62].

1.3.1.1 Architecture of DC Bus

In the hybrid system presented in Fig. 1.1, the power supplied by each source is centralized on a DC bus. Thus, the energy conversion system to provide AC power

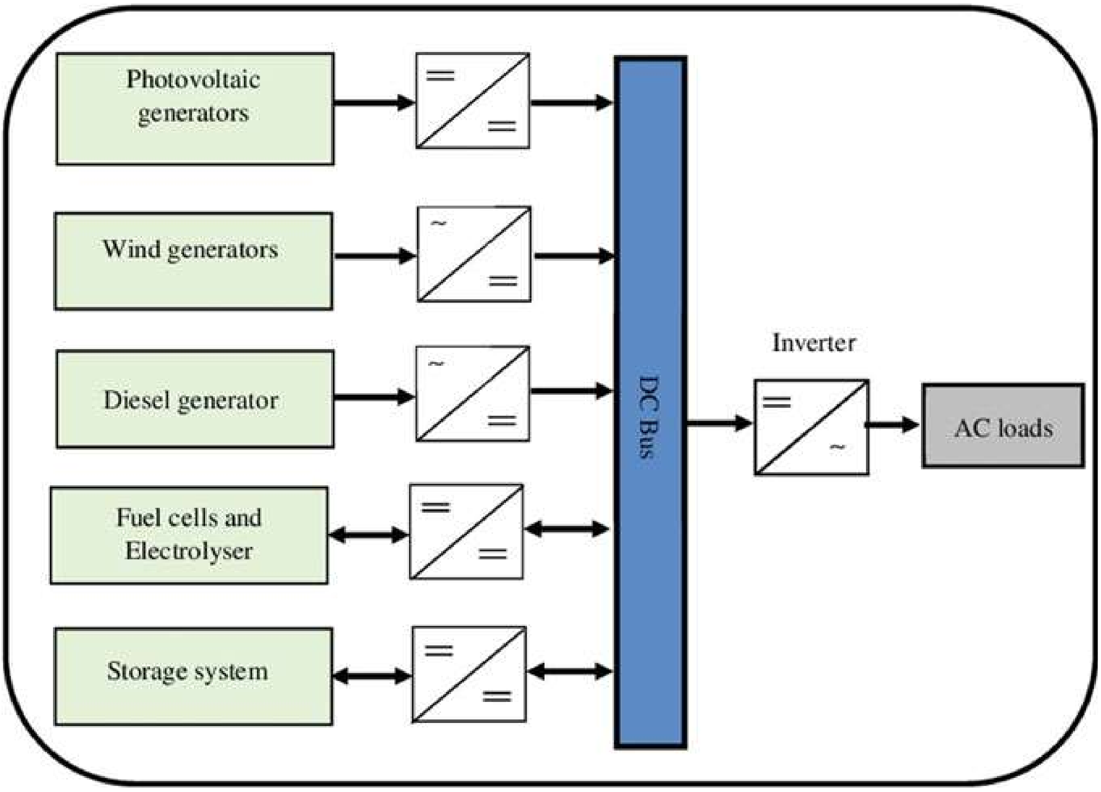

Fig. 1.1 Configuration of the hybrid system with DC bus

at their first rectifier has to be converted then continuously. The generators are connected in series with the inverter to power the load alternatives. The inverter should supply the alternating loads from the DC bus and must follow the set point for the amplitude and frequency. The batteries are sized to supply peak loads. The advantage of this topology is the simplicity of operation, and the load demand is satisfied without interruption even when the generators charge the short-term storage units.

1.3.1.2 Architecture of AC Bus

In this topology, all components of the HPS are related to alternating loads, as shown in Fig. 1.2. This configuration provides superior performance compared to the previous configuration, since each converter can be synchronized with the generator so that it can supply the load independently and simultaneously with other converters. This provides flexibility for the energy sources which supply the load demand. In the case of low load demand, all generators and storage systems are stationary except, for example, the photovoltaic generator to cover the load demand. However, during heavy load demands or during peak hours, generators and storage units operate in parallel to cover the load demand. The realization of this system is relatively complicated because of parallel operation, by

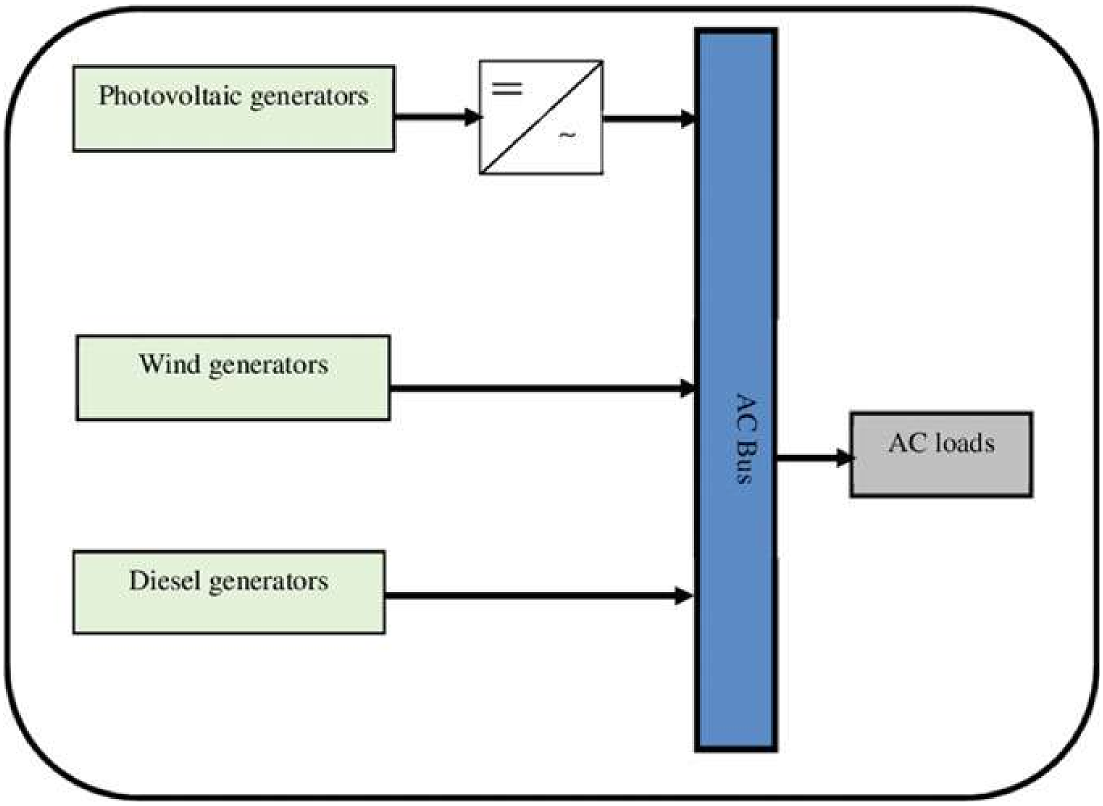

Fig. 1.2 Configuration of the hybrid system with AC bus

synchronizing the output voltages with the charge voltages. This topology has several advantages compared to the DC-coupled topology such as higher overall efficiency, smaller sizes of the power conditioning unit while keeping a high level of energy availability, and optimal operation of the diesel generator due to reducing its operating time and consequently its maintenance cost.

1.3.1.3 Architecture of DC/AC Bus

The configuration of DC and AC buses is shown in Fig. 1.3. It has superior performance compared to the previous configurations. In this case, renewable energy and diesel generators can power a portion of the load directly to AC, which can increase system performance and reduce power rating of the diesel generator and the inverter. The diesel generator and the inverter can operate independently or in parallel by synchronizing their output voltages. Converters located between two buses (the rectifier and inverter) can be replaced by a bidirectional converter which, in normal operation, performs the conversion DC/AC (inverter operation). When there is a surplus of energy from the diesel generator, it can also charge batteries (operating as a rectifier). The bidirectional inverter can supply the peak load when the diesel generator is overloaded.

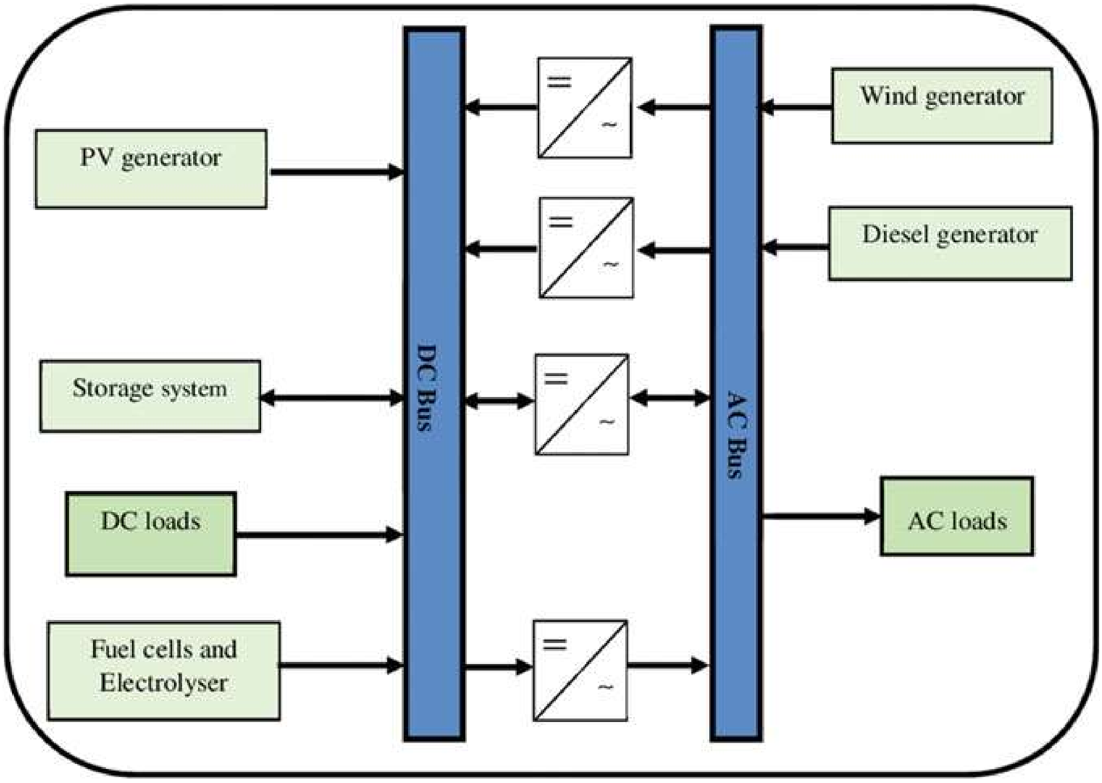

Fig. 1.3 Configuration of the hybrid system with AC bus and DC bus

The advantages of this configuration are:

- The diesel generator and the inverter can operate independently or in parallel. When the load level is low, one or the other can generate the necessary energy. However, both sources can operate in parallel during peak load.
- The possibility of reducing the nominal power of the diesel generator and the inverter without affecting the system's ability to supply peak loads.

The disadvantages of this configuration are:

- The implementation of this system is relatively complicated because of the parallel operation (the inverter should be able to operate autonomously and operate with synchronization of the output voltages with output voltages of diesel generator).

1.3.2 *Choice of Converters*

A power converter is a system for adapting the source of electrical energy to a given receiver by converting it (Fig. 1.4).

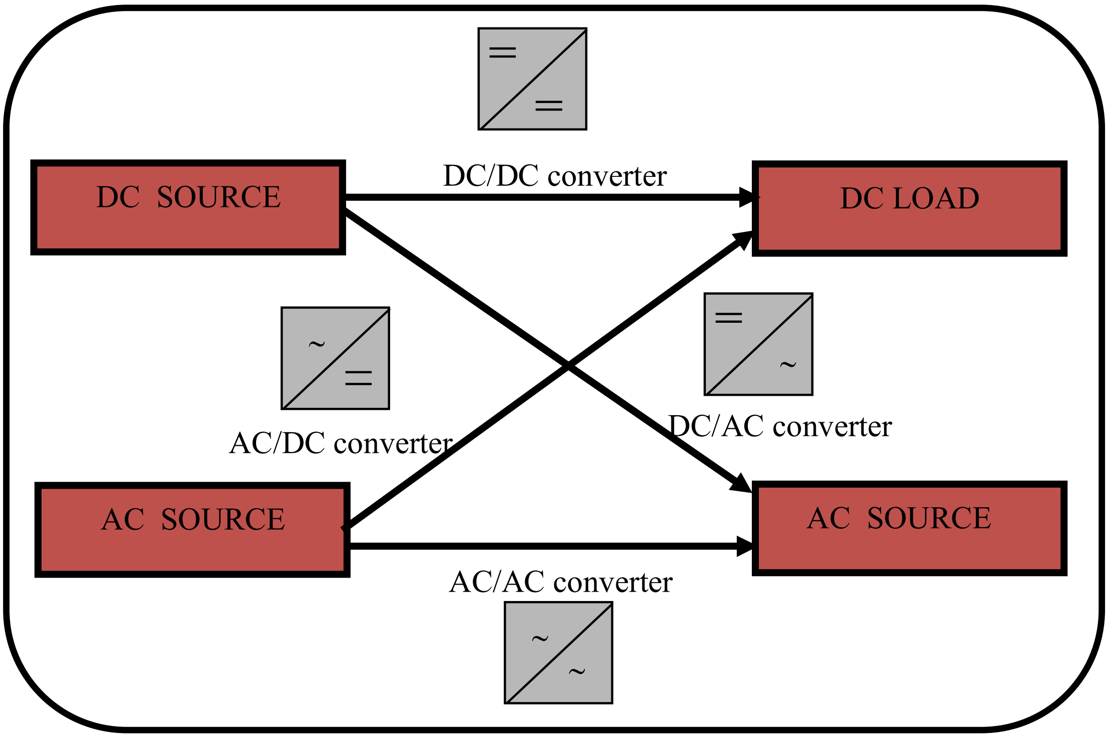

Fig. 1.4 Sources and loads supplied by various static converters

1.4 Classifications of Hybrid Energy Systems

The power delivered by the hybrid system can vary from a few watts for domestic applications up to a few megawatts for systems used in the electrification of small islands. Thus, for hybrid systems with a power below 100 kW, the configuration with AC and DC bus, with battery storage, is the most used. The storage system uses a high number of batteries to be able to cover the average load for several days. This type of hybrid system uses small renewable energy sources connected to the DC bus. Another possibility is to convert the continuous power to an alternative one by using inverters. Hybrid systems used for applications with very low power (below 5 kW) supply generally DC loads (Table 1.1).

1.5 Different Combinations of Hybrid Systems

Mathematically, it can have 2 power n (2^n) combinations of hybrid systems. In the following, the most used combinations of hybrid system are presented as follows (Fig. 1.5).

Mathematically, it can have the following combinations with one storage (Tables 1.2 and 1.3).

By combining just one element with another, there are about eighteen alternatives.

And by considering multiple storages, it can obtain a multiplicity of configurations (about seventy). Some of them have been cited in the literature, others not at all, which may be impossible to do because of the complexity of some combinations (Table 1.4).

The most important systems are presented, and references of the most cited systems are given to have an overview.

The most used hybrid systems can be summarized as shown in Table 1.5.

Table 1.1 Classification of hybrid systems by power range

Hybrid system power	Applications
Low power	Autonomous systems: pumping water, telecommunication stations, …
Average power	Micro-isolated systems: supplying village, rural…
Great power	Large isolated systems, for example, islands

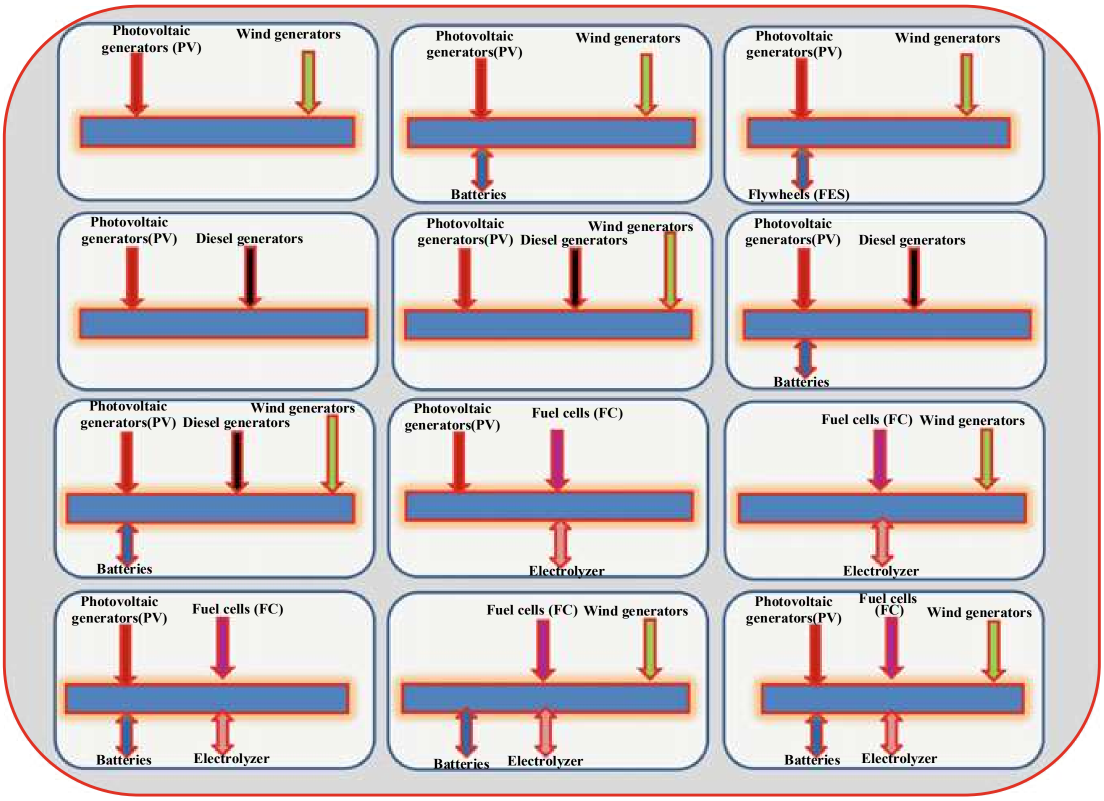

Fig. 1.5 Representation of some used hybrid systems

Table 1.2 Different hybrid systems

	PVG	Batt	FCs	SCs	WT	FES	DG	HP
PVG								
Batt	*x*							
FCs	*x*	**x**						
SCs	*x*	**x**	**x**					
WT	*x*	*x*	*x*	*x*				
FES	*x*	**x**	**x**	**x**	*x*			
DG	*x*	**x**	**x**	**x**	*x*			
HP	*x*	*x*	*x*	*x*	*x*	*x*	*x*	

Table 1.3 Different alternatives with only two components

1	PVG/Batt	10	WT/SCs
2	PVG/FCs	11	WT/FES
3	PVG/SCs	12	HP/FCs
4	PVG/WT	13	HP/SCs
5	PVG/DG	14	WT/HP
6	PVG/HP	15	HP/FES
7	WT/Batt	16	WT/DG
8	HP/Batt	17	HP/DG
9	WT/FCs	18	PV/FES

Table 1.4 Different alternatives considering multiple storages

1	PVG/ Batt	2	PVG/WT/Batt	43	HP/FCs
		3	PVG/WT/SCs	44	HP/SCs
		4	PVG/WT/Batt/SCs	45	WT/HP
5	PVG/ FCs	6	PVG/FCs/Batt	46	HP/FES
		7	PVG/FCs/SCs	47	WT/DG
		8	PVG/FCs/Batt/SCs	48	HP/DG
9	PVG/ SCs	10	PVG/SCs/Batt	49	PVG/FES
11	PVG/ WT	12	PVG/WT/FES	50	PVG/FES/Batt
		13	PVG/WT/FES/Batt	51	PVG/FES/FCs
		14	PVG/WT/FES/SCs	52	PVG/FES/SCs
		15	PVG/WT/FES/FCs	53	PVG/FES/Batt/FCs
		16	PVG/WT/FES/Batt/FCs	54	PVG/FES/Batt/SCs
		17	PVG/WT/FES/Batt/SCs	55	PVG/FES/FCs/SCs
		18	PVG/WT/FES/FCs/SCs	56	PVG/FES/Batt/FCs/SCs
		19	PVG/WT/FES/Batt/FCs/SCs	57	WT/Batt
		20	PVG/WT/DG	58	HP/Batt
		21	PVG/WT/DG/Batt	59	WT/FCs
		22	PVG/WT/DG/FCs	60	WT/SCs
		23	PVG/WT/DG/SCs	61	WT/FES
		24	PVG/WT/DG/Batt/FCs	62	WT/FES/SCs
		25	PVG/WT/DG/Batt/SCs	63	WT/FES/FCS
		26	PVG/WT/DG/FCs/SCs	64	WT/FES/Batt
		27	PVG/WT/DG/Batt/FCs/SCs	65	WT/FES/SCs/Batt
		28	PVG/WT/DG/FES	66	WT/FES/SCs/FCs
		29	PVG/WT/DG/FES/Batt	67	WT/FES/FCs/Batt
		30	PVG/WT/DG/FES/FCs	68	WT/FES/SCs/Batt/FCs
		31	PVG/WT/DG/FES/SCs	69	PVG/HP
		32	PVG/WT/DG/FES/Batt/FCs	70	PVG/HP/Batt
		33	PVG/WT/DG/FES/Batt/SCs	71	PVG/HP/Batt/FCs
		34	PVG/WT/DG/FES/FCs/SCs	72	PVG/HP/Batt/FCs/WT
		35	PVG/WT/DG/FES/Batt/FCs/ SCs	73	PVG/HP/Batt/FCs/WT/FES
5	PVG/ DG	36	PVG/DG/Batt	74	PVG/HP/Batt/FCs/WT/ FES/DG
		37	PVG/DG/FCs		
		38	PVG/DG/SCS		
		39	PVG/DG/Batt/FCs		
		40	PVG/DG/Batt/SCs		
		41	PVG/DG/FCs/SCs		
		42	PVG/DG/Batt/FCs/SCs		

Table 1.5 Summary of the most used hybrid systems

Hybrid systems	Some references
PVG/Batt	[14, 15, 42, 76–88]
PVG/FCs	[22, 54, 62, 10, 116, 117, 145]
PVG/FCs/Batt	[30, 55, 52, 184, 185]
PVG/Wind	[47, 65, 112, 113, 142]
PVG/Wind/Batt	[123–127]
PVG/Wind/FES	[193–195]
WT/FCs	[1, 5, 23, 171, 178]
WT/FCs/Batt/SCs	[196–198]
WT/FCs/Batt	[182, 183]
PVG/FCs/DG	[24, 26, 31, 33, 39, 51, 26, 52, 63, 51]
PVG/DG	[19, 28, 32, 34, 37, 38, 40, 94, 95]
PVG/Batt/DG	[4, 12, 25, 29, 41, 98–100]
PVG/WT/DG	[96, 97, 128, 129]
PVG/WT/FCs/Batt	[120, 188]
PVG/WT/FCs/DG	[186, 190]
PVG/DG/FES	[189, 199]
PVG/Batt/DG/FCs	[2, 11, 2]
PVG/WT/Batt/DG	[13, 13, 102, 111, 151]
PVG/WT/FCs	[118, 119, 121, 122, 146]
PVG/HP/Batt	[104, 130–132, 130]
PVG/Batt/SCs	[103, 133–137]
PVG/WT/FCs	[3, 6, 10, 16–18, 44, 48, 53, 59, 64]
PVG/HP	[105, 106, 114, 179, 180]
PVG/DG/HP	[27, 98, 147, 148]
PVG/DG/HP/FCs	[187, 191]
WT/DG/Batt	[140, 142, 170]
WT/HP	[100, 101, 109, 181]
WT/Batt	[68, 154, 162, 168, 174]
WT/HP/DG	[192, 200, 201]
WT/PVG/HP	[104, 107, 108, 110, 115, 149]
WT/DG	[141, 153–158, 164, 176]
WT/PVG/HP/DG	[147, 150]
WT/SCs	[159, 169, 172, 173]
WT/FES	[160, 161, 166, 167, 177]
WT/DG/FES	[163, 165, 175]
PVG/WT/FCs/DG/UC	[202]
PVG/WT/SCs/Batt	[203, 204]
PVG/FCs/Batt/SCs	[90, 93, 103]

1.5.1 PV System with Battery Storage

In standalone PV applications, electrical power is required from the system during night or hours of darkness [14, 15]. Thus, the storage must be added to the system. Generally, batteries are used for energy storage (Fig. 1.6).

This system can supply DC and AC loads (Fig. 1.7) [42, 49–88].

It can be implemented under MATLAB/Simulink as shown in Fig. 1.8.

And the different subsystems are in Fig. 1.9.

1.5.2 PV System/Fuel Cells

The role of PV/FCs system is the production of electricity without interruption in remote areas. It consists generally of a photovoltaic generator (PV), an alkaline water electrolyzer, a storage gas tank and a proton exchange membrane fuel cell (PEMFC) (Fig. 1.10) [22, 54].

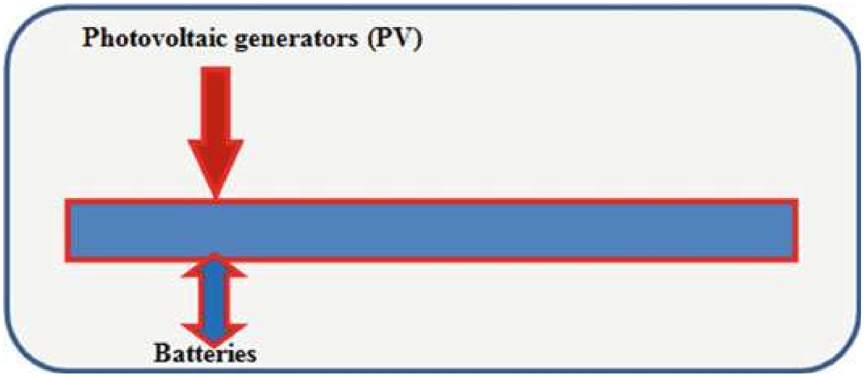

Fig. 1.6 Photovoltaic system with battery storage

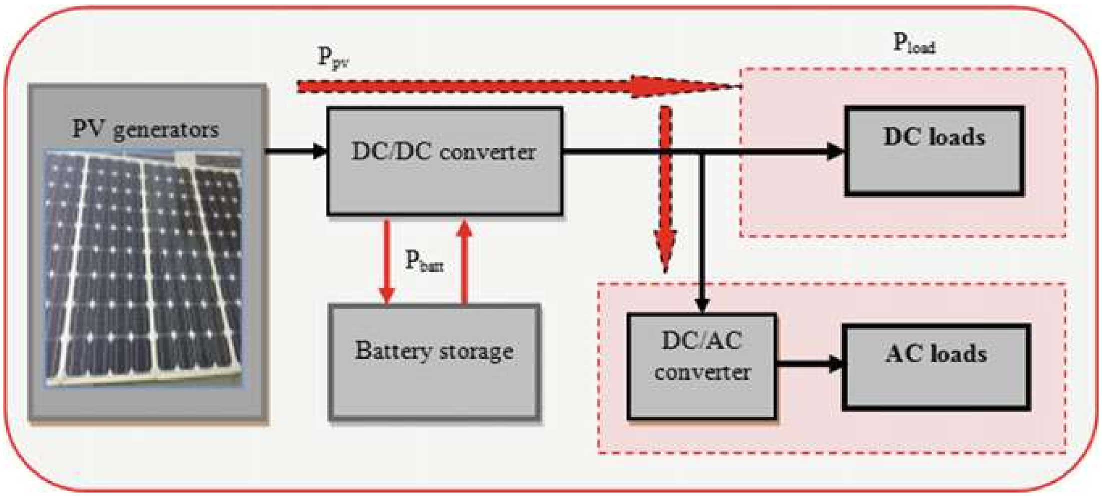

Fig. 1.7 Standalone PV system with battery storage powering DC and AC loads

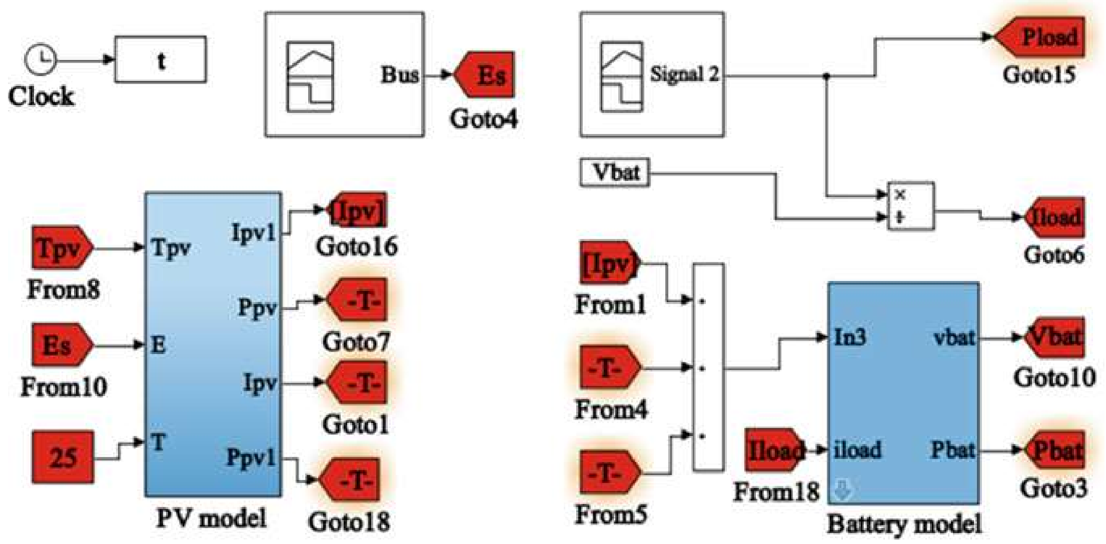

Fig. 1.8 PV/batteries under MATLAB/Simulink

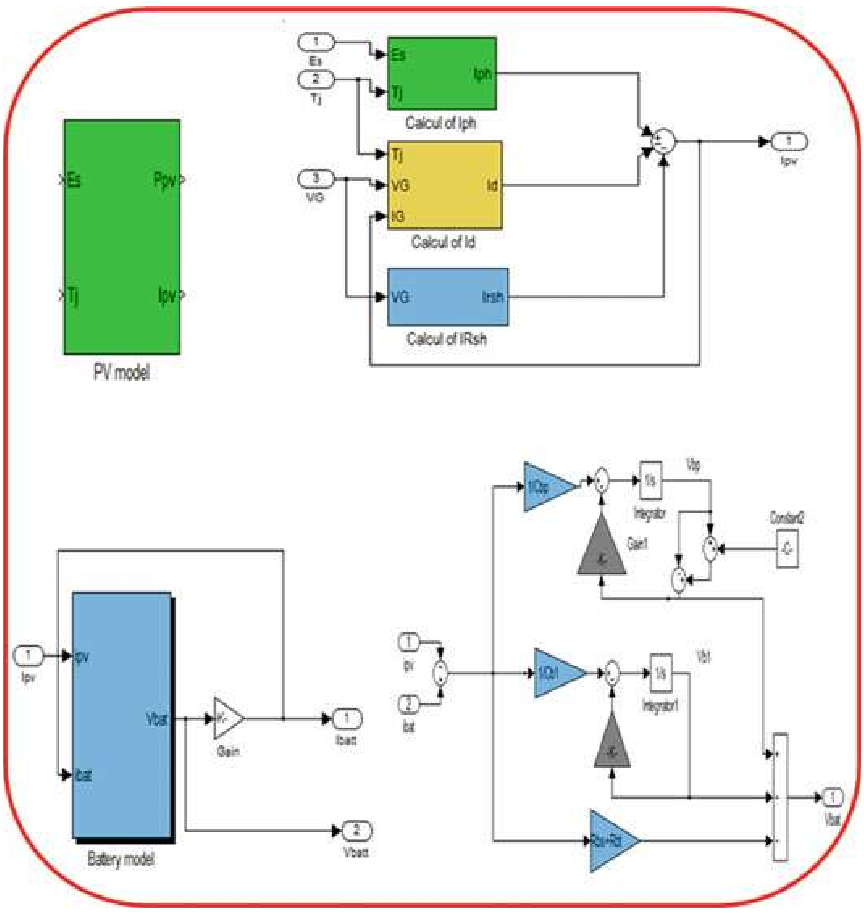

Fig. 1.9 Different blocks of PV/battery system

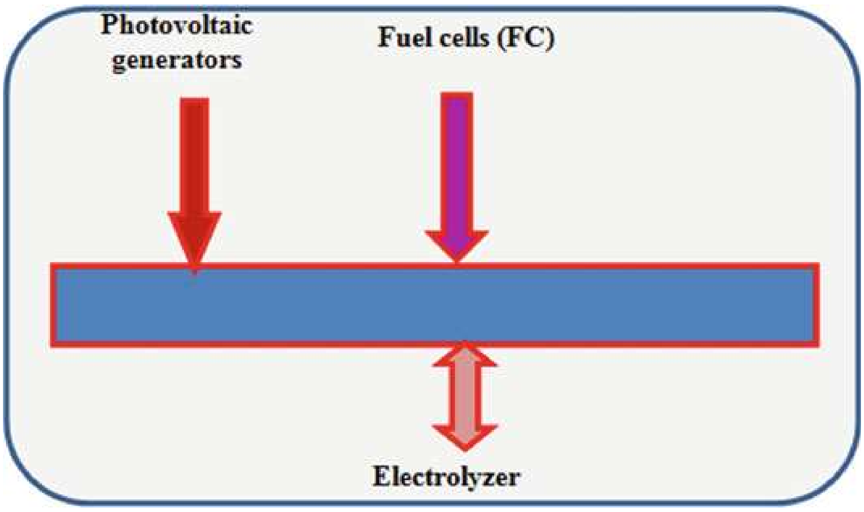

Fig. 1.10 PV system with fuel cells

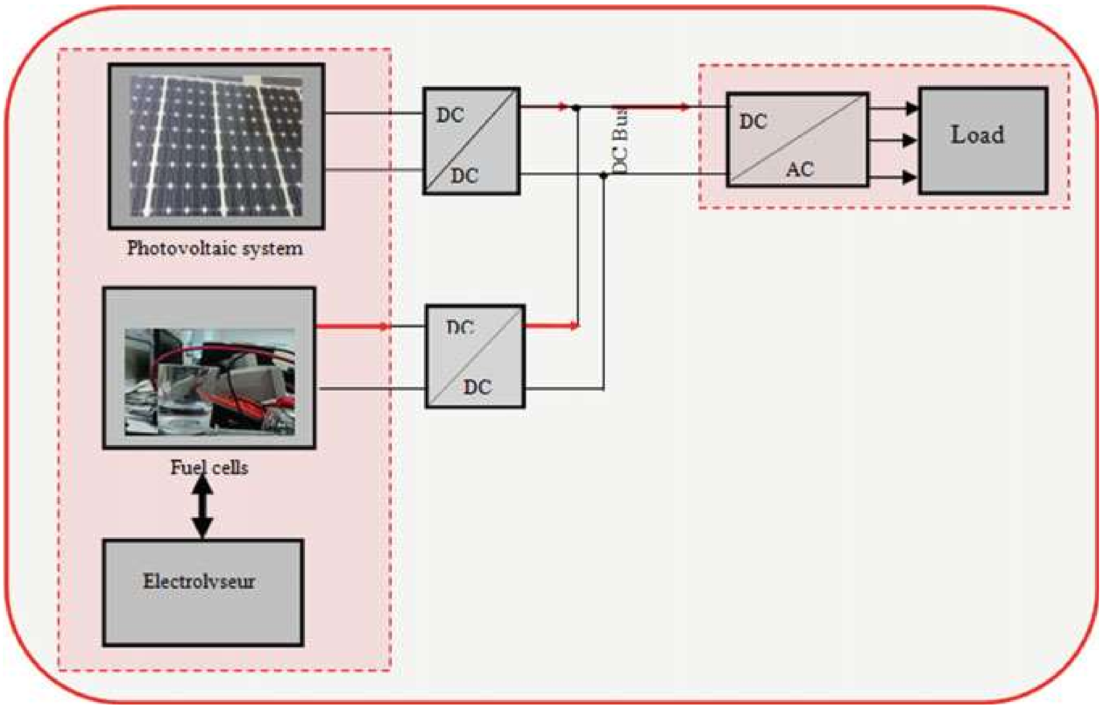

Fig. 1.11 Hybrid photovoltaic/fuel cell block diagram

PV subsystem works as a primary source, converting solar irradiation into electricity that is given to a DC bus (Fig. 1.11). The second working subsystem is the electrolyzer which produces hydrogen and oxygen from water as a result of an electrochemical process. When there is an excess of solar generation available, the electrolyzer is turned on to begin producing hydrogen which is sent to a storage tank. The produced hydrogen is used by the third working subsystem (the fuel cell stack) which produces electrical energy to supply the DC bus [62, 10, 116, 117, 145].

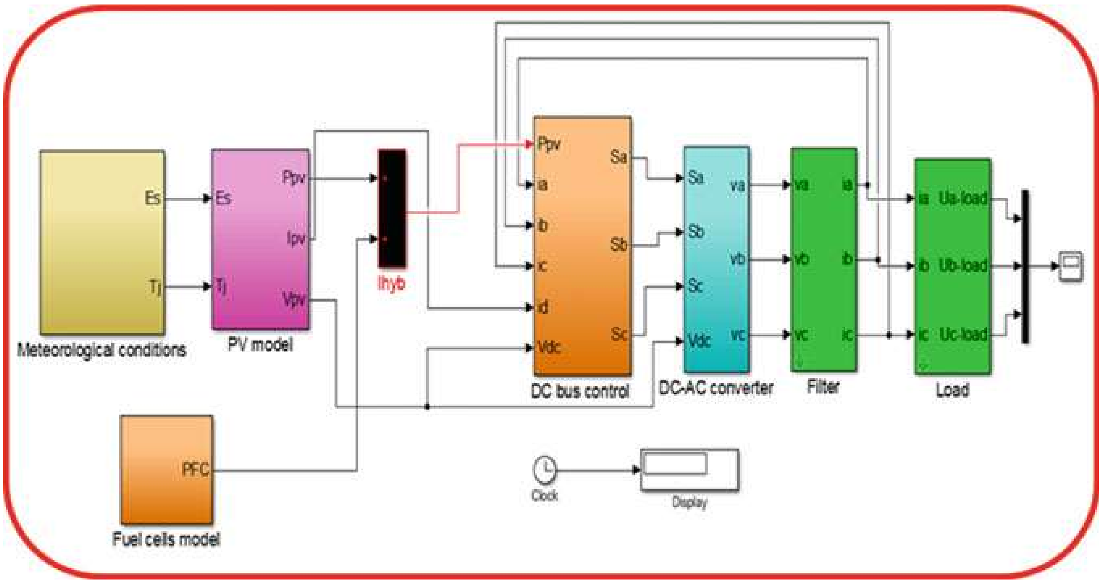

Fig. 1.12 PV/FC system

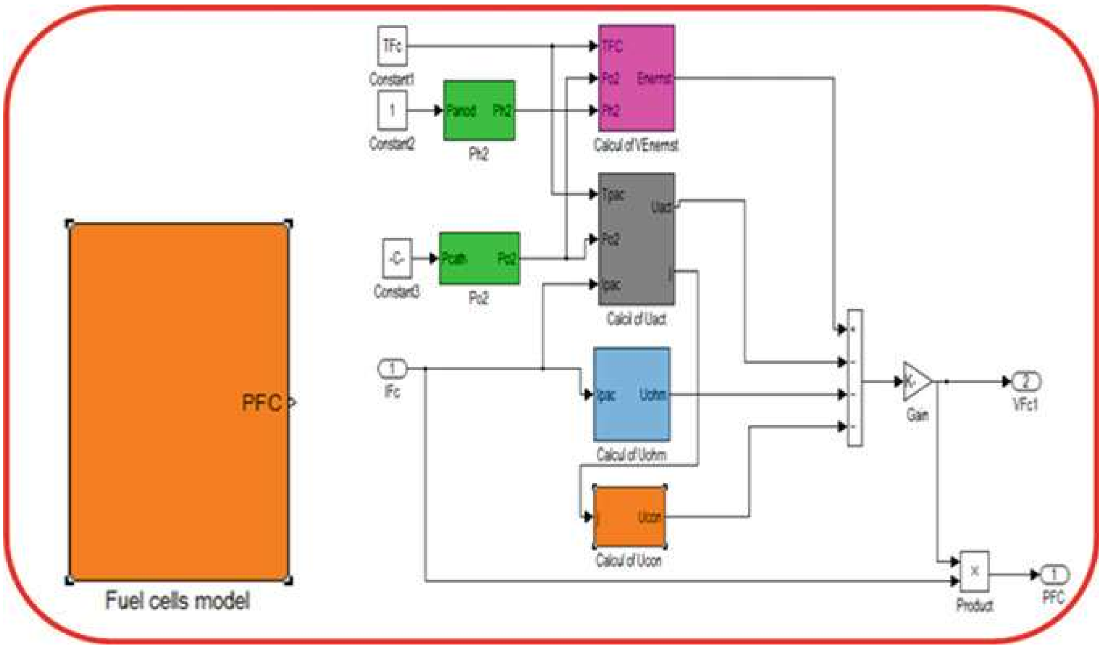

Fig. 1.13 Fuel cell model

It can be implemented under MATLAB/Simulink as shown in Fig. 1.12. The fuel cell model is shown in Fig. 1.13.

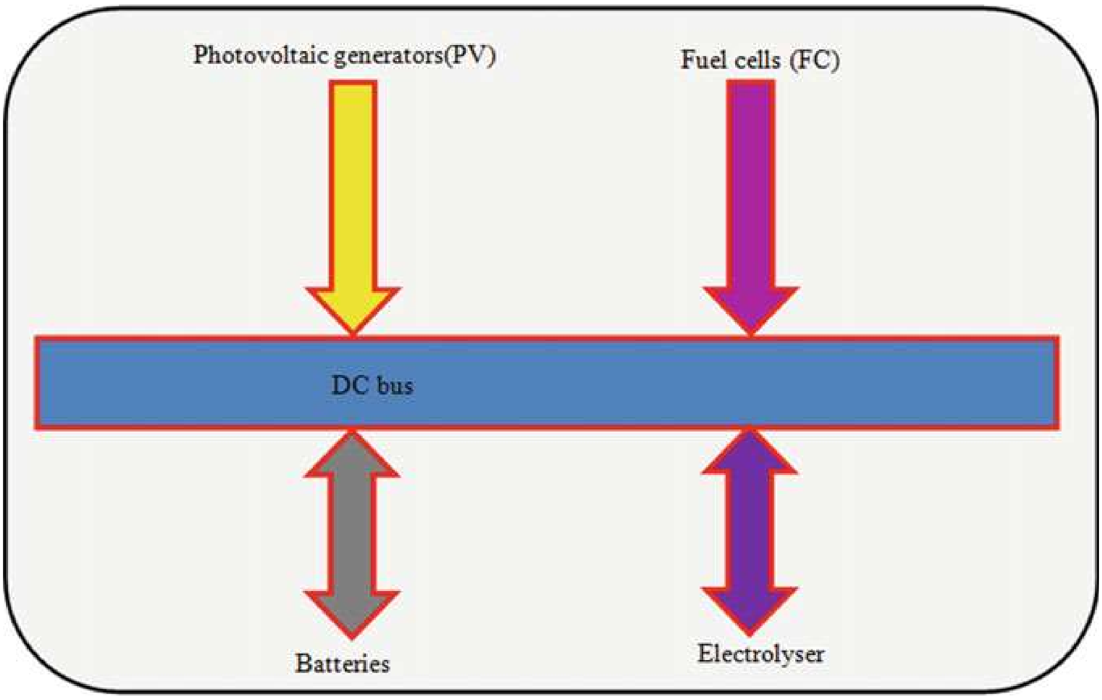

Fig. 1.14 PV/FC system with batteries storage

1.5.3 PV System/Fuel Cells with Battery Storage

In this system, PV subsystem always works as a primary source; then, the second working subsystems are the battery storage and the electrolyzer which supplies the fuel cells (Fig. 1.14) [30, 153–184].

The block diagram representing PV/FC system is given in Fig. 1.15 [43, 55–62]. It can be implemented under MATLAB/Simulink as shown in Fig. 1.16.

1.5.4 PV System/FC Multi-storage Batteries/ Super-Capacitors

In this system, it is added a multi-storage to the previous system (Fig. 1.15). It consists of batteries and super-capacitors (Fig. 1.17).

The block diagram representing PV/FC system with multi-storage is given in Fig. 1.18.

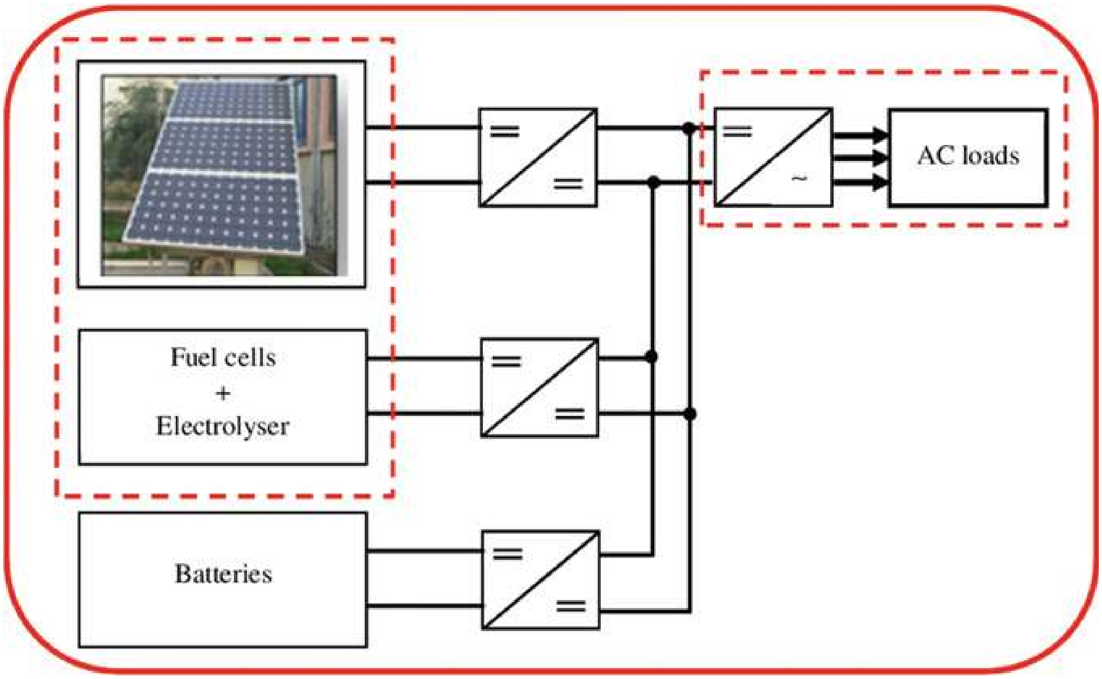

Fig. 1.15 PV/FC system with battery storage block diagram

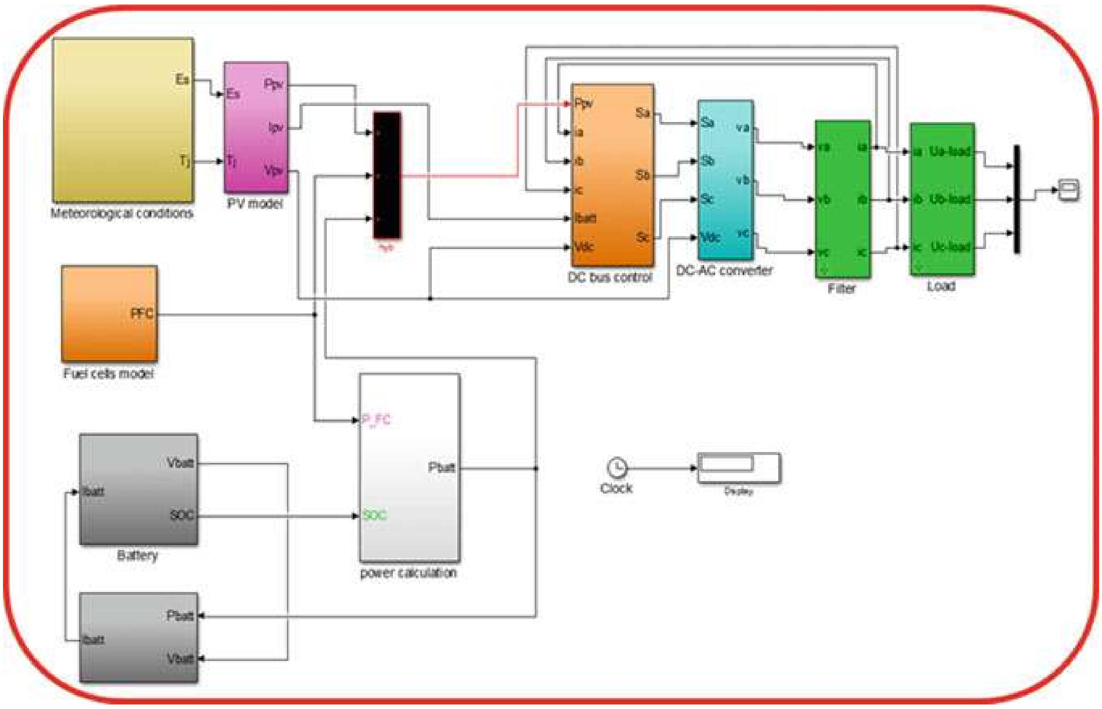

Fig. 1.16 PV/battery/FC system

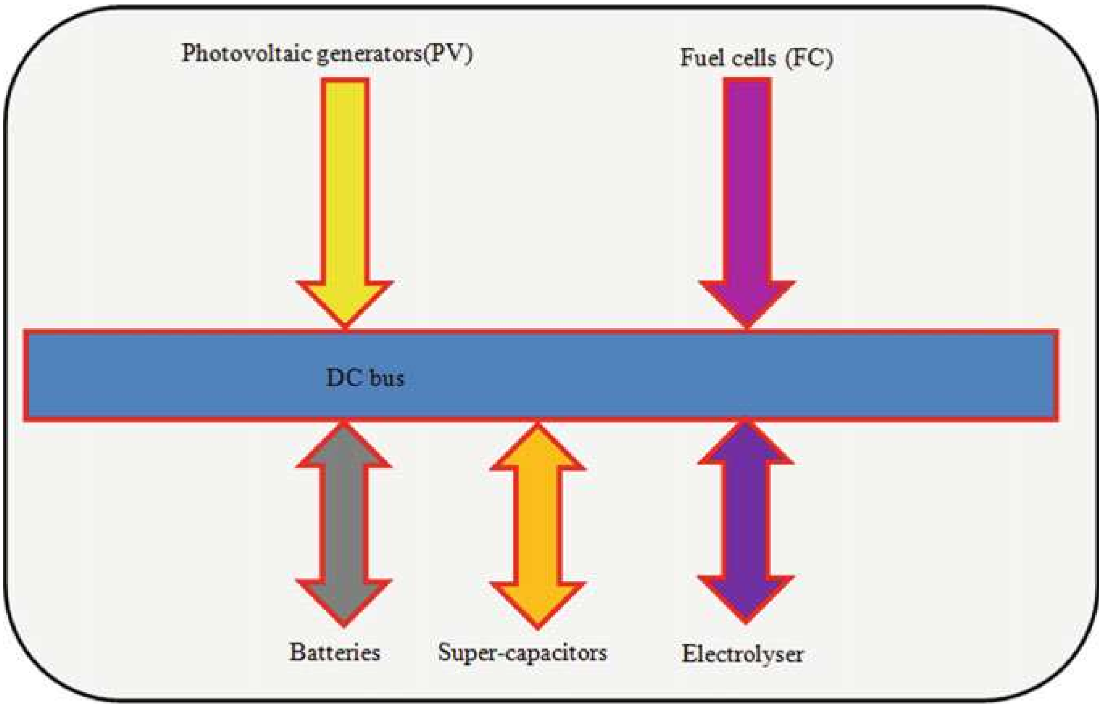

Fig. 1.17 PV/FC system multi-storage batteries/super-capacitors

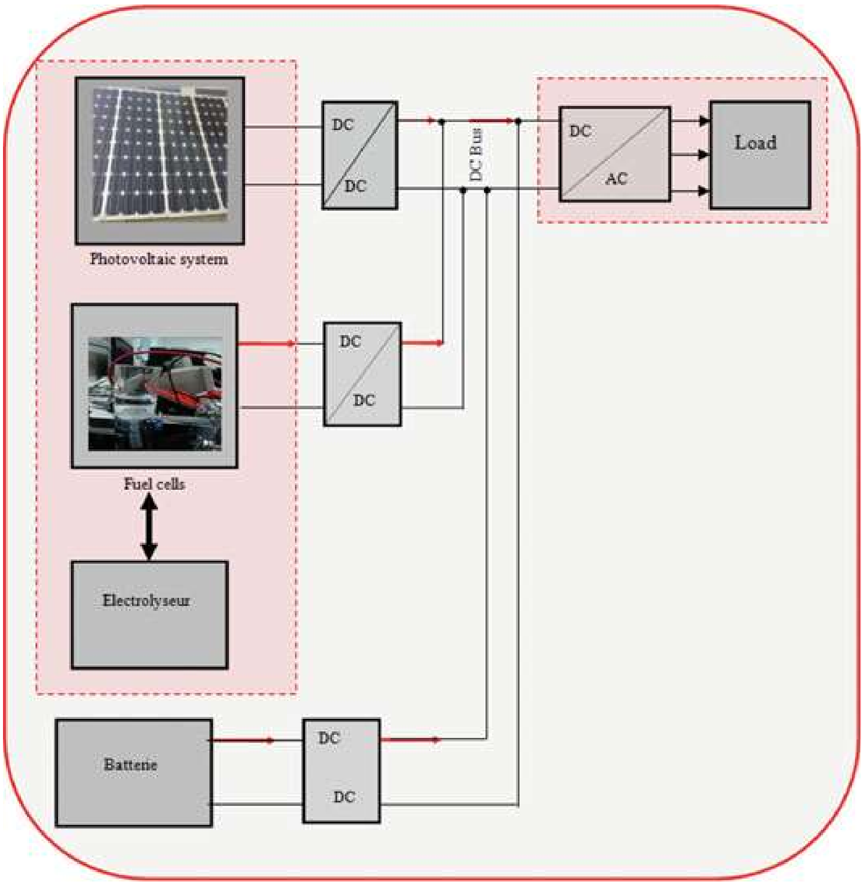

Fig. 1.18 PV/FC system with multi-storage batteries/super-capacitor block diagram

1.5.5 Hybrid Wind/Photovoltaic System

The advantage of this type of hybrid system depends on the wind, solar radiation and the type of load. It consists of a photovoltaic subsystem, a DC/DC converter and a wind turbine. The two energy sources are connected to a DC bus [47, 48, 112, 113, 143] (Fig. 1.19).

It can be implemented under MATLAB/Simulink as shown in Fig. 1.20.

The aerogenerator subsystem is modeled as shown in Fig. 1.21.

And the wind turbine model is shown in Fig. 1.22.

1.5.6 Hybrid Wind/Photovoltaic System with Battery Storage

Both energy sources are connected to a DC bus, and batteries are added as a storage system [123–127] (Fig. 1.23).

It can be implemented under MATLAB/Simulink as shown in Fig. 1.24.

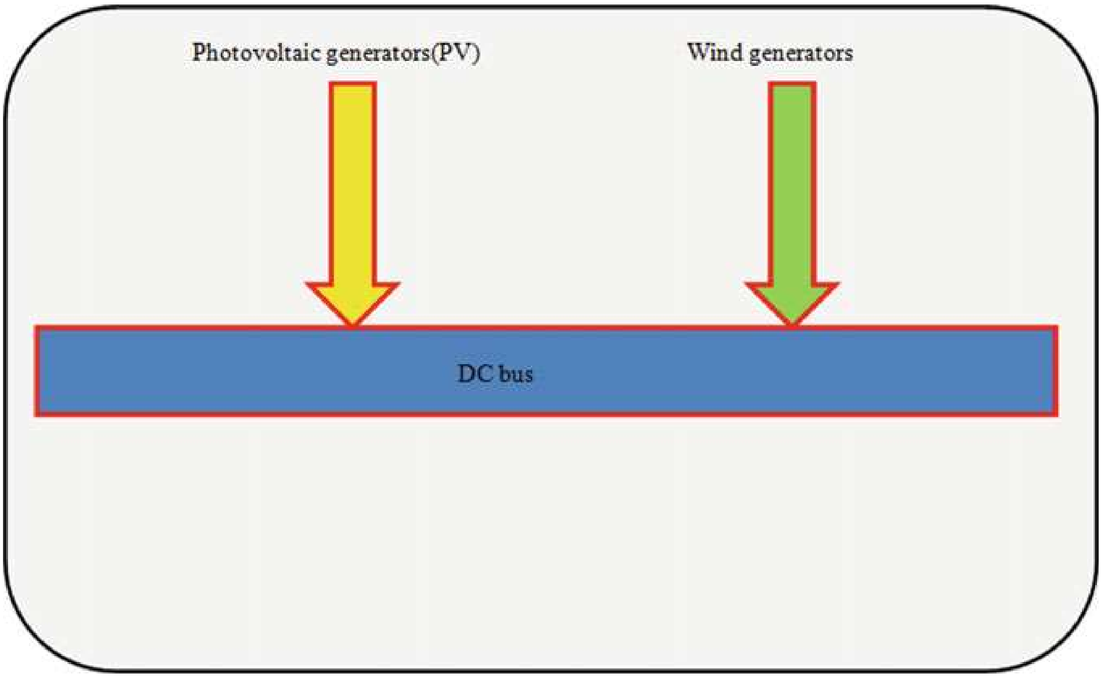

Fig. 1.19 Hybrid wind/photovoltaic system

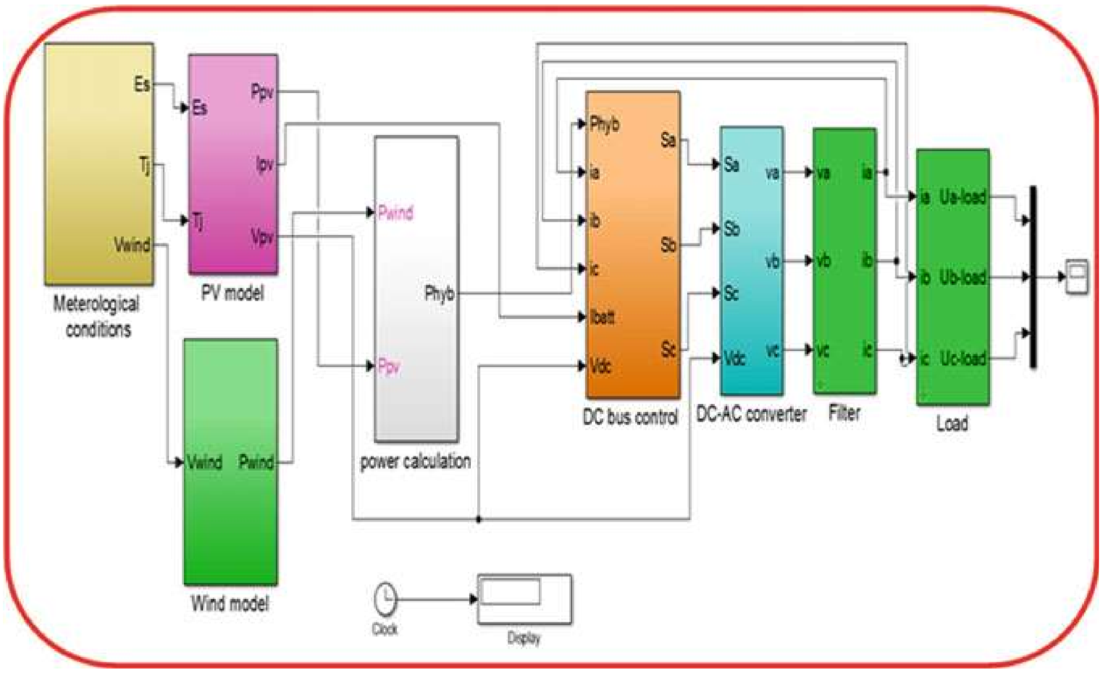

Fig. 1.20 PV/wind system

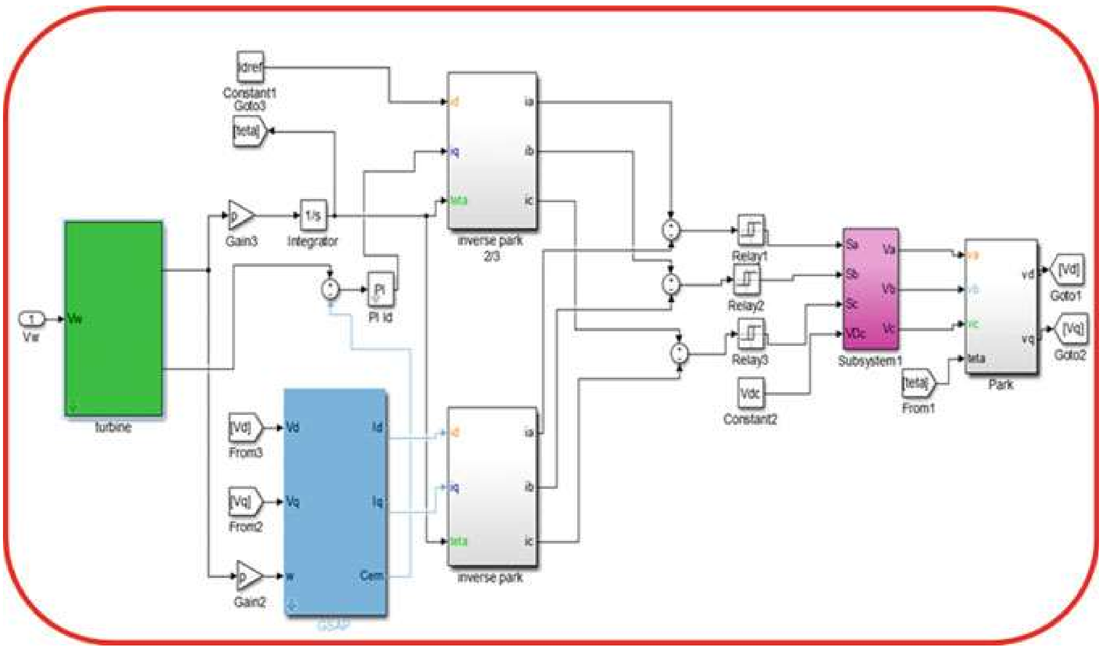

Fig. 1.21 Aerogenerator model

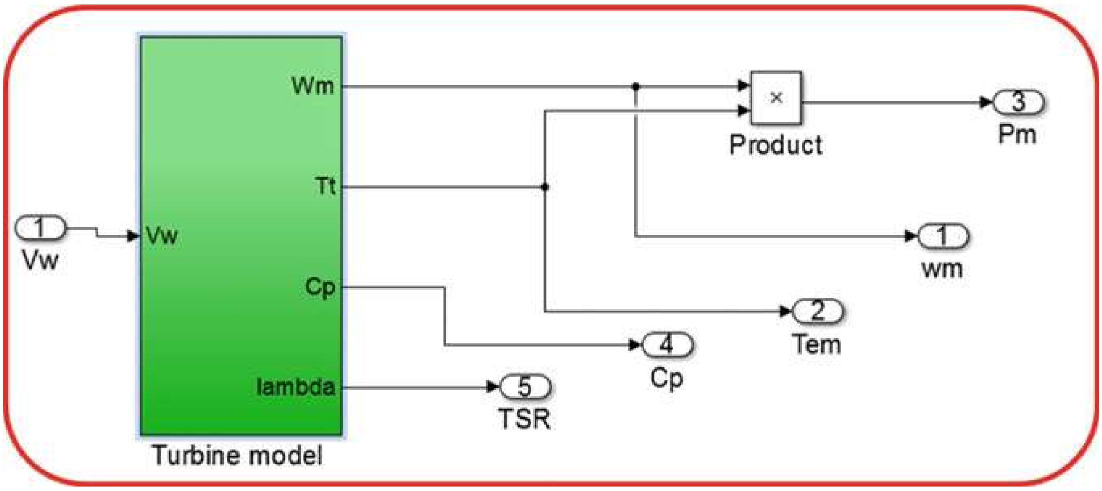

Fig. 1.22 Wind turbine model

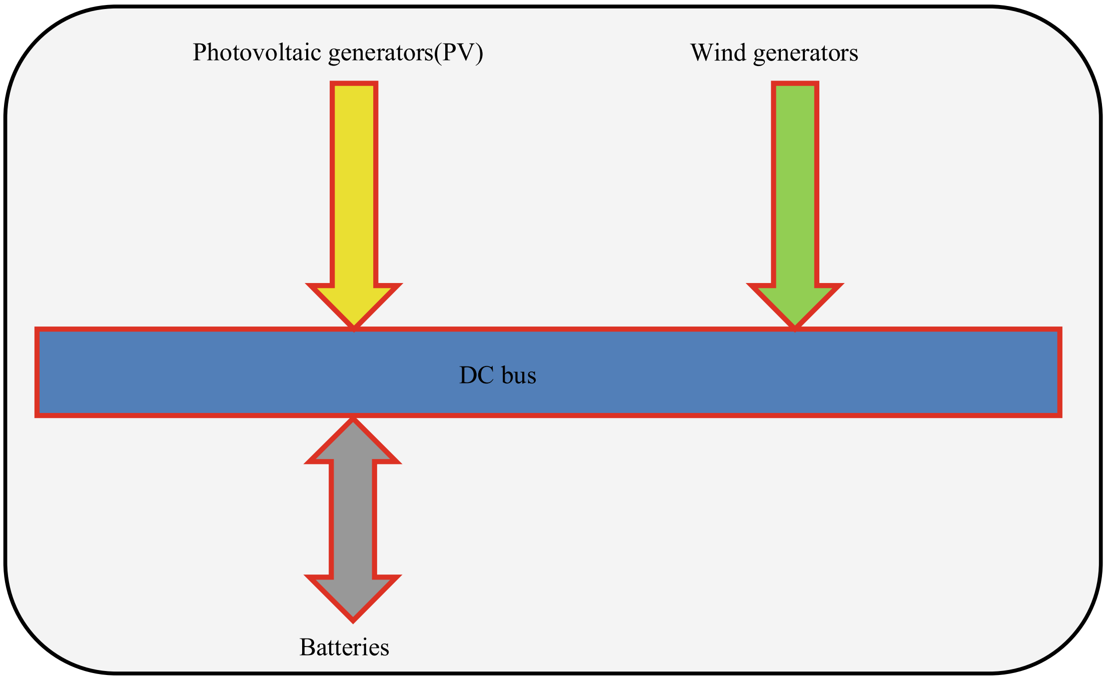

Fig. 1.23 Hybrid wind/photovoltaic system with battery storage

1.5.7 Hybrid Wind/Photovoltaic System with Flywheels Storage

Flywheels energy storage can also be used. FES works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy (Fig. 1.25) [193–195].

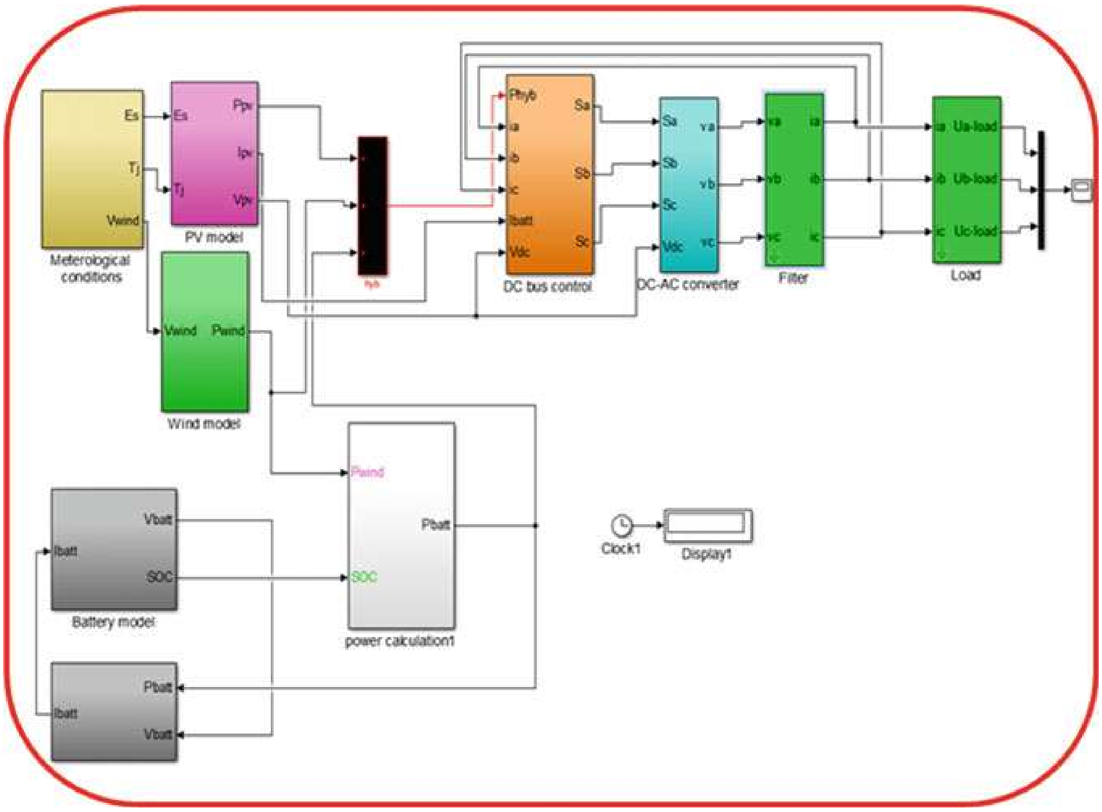

Fig. 1.24 Wind/photovoltaic system with battery storage

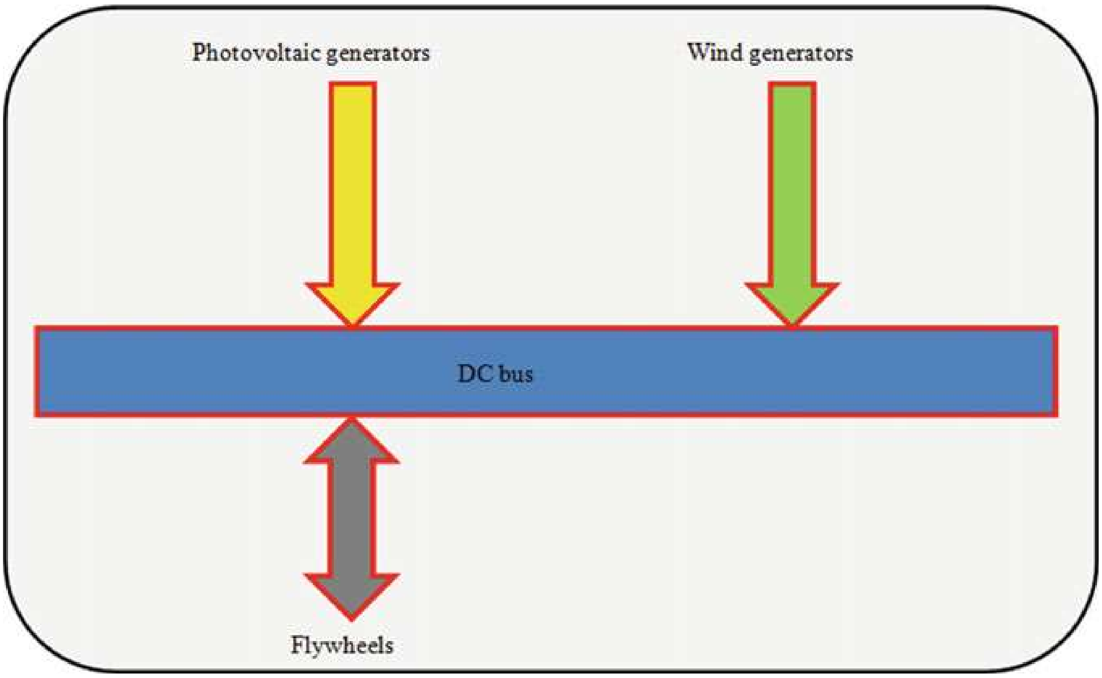

Fig. 1.25 Hybrid wind/photovoltaic system with flywheel storage

1.5.8 Wind Turbine System with Fuel Cells

The system consists of a wind generation system with an electrolyzer to generate hydrogen from surplus wind and a fuel cell for storage. Wind generator turbine provides electricity for electrolyzer, and the excess of energy can be send to generate hydrogen for storage and converted into electricity during peak times [1, 5, 23, 171–178] (Fig. 1.26).

1.5.9 Wind System/Fuel Cells with Battery Storage

Battery storage can be added to the previous system (Fig. 1.27) [182, 183].

1.5.10 Wind System/Fuel Cells with Hybrid Storage Batteries/Super-Capacitors

In this system, it is added a multi-storage. It consists of batteries and super-capacitors (Fig. 1.28) [196–198].

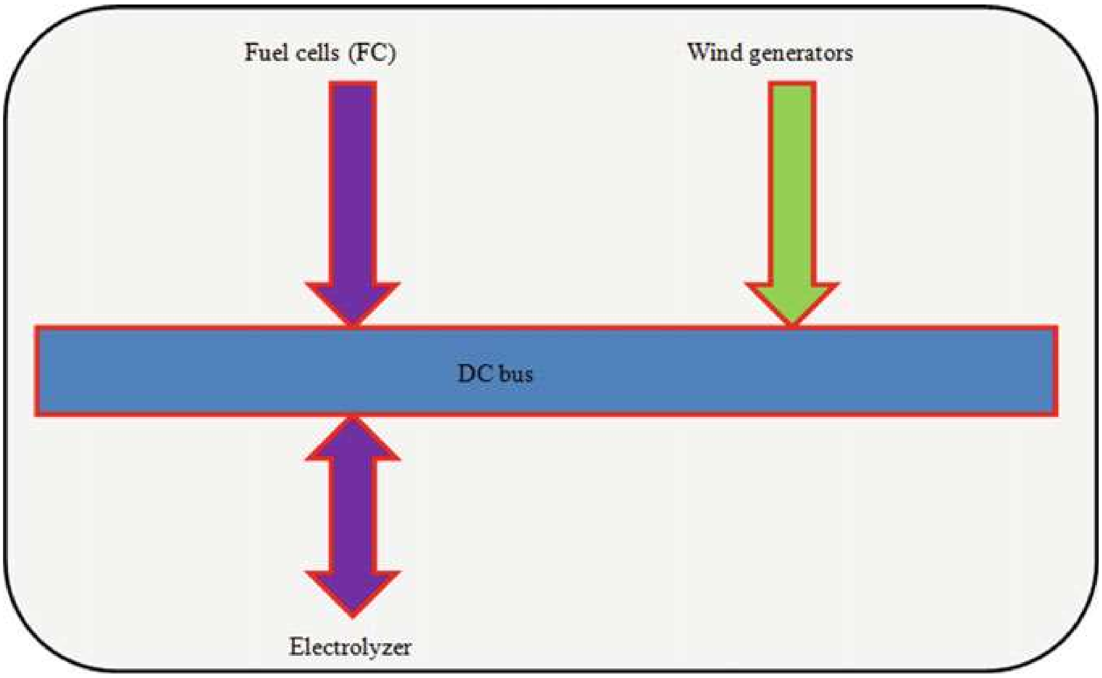

Fig. 1.26 Hybrid wind/photovoltaic system

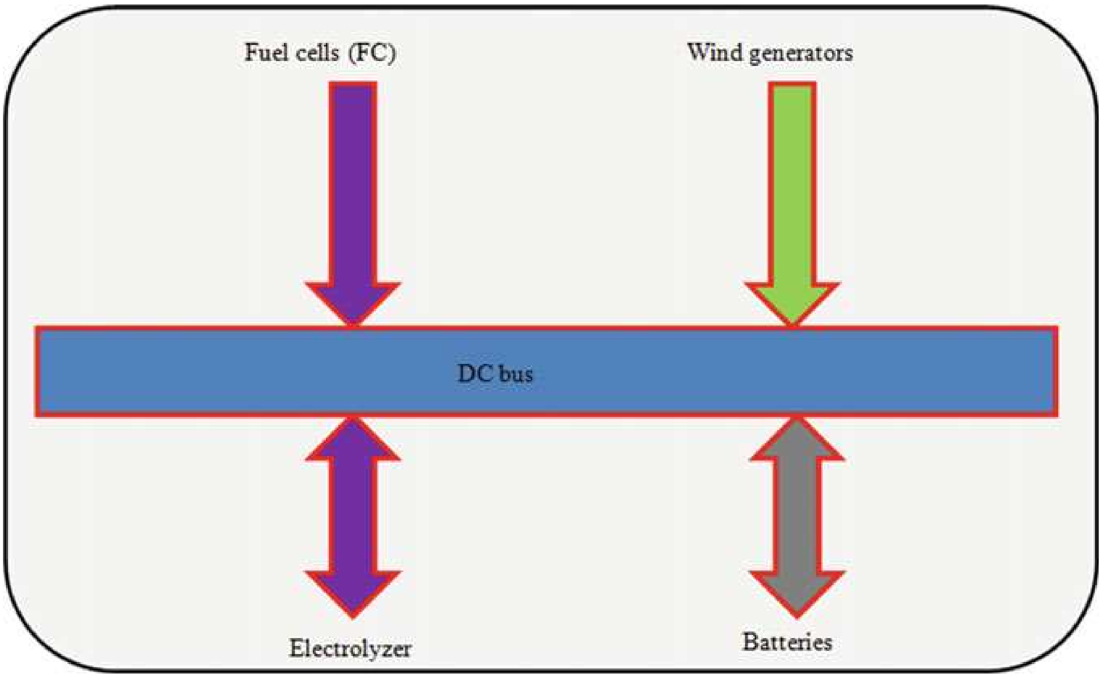

Fig. 1.27 Hybrid wind/fuel cell system with battery storage

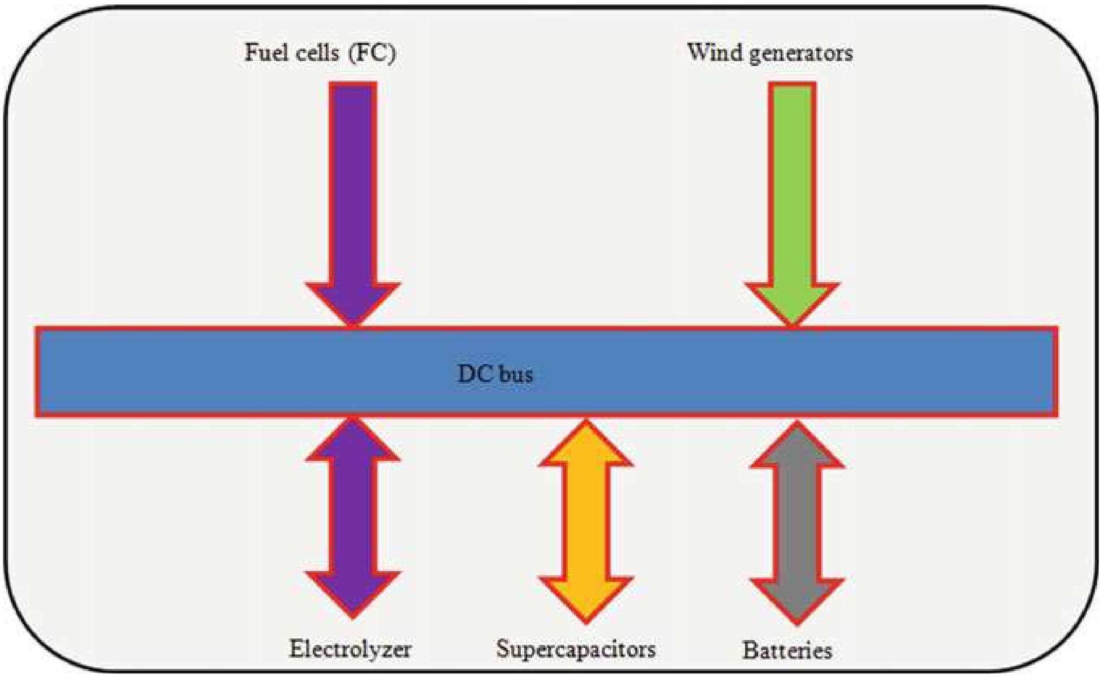

Fig. 1.28 Hybrid wind/fuel cell system with hybrid storage

1.5.11 PV System with Diesel Generators

It is the most used hybrid system. It comprises a photovoltaic generator with a diesel generator (Fig. 1.29) [19, 28, 32, 34, 37–40, 94, 95].

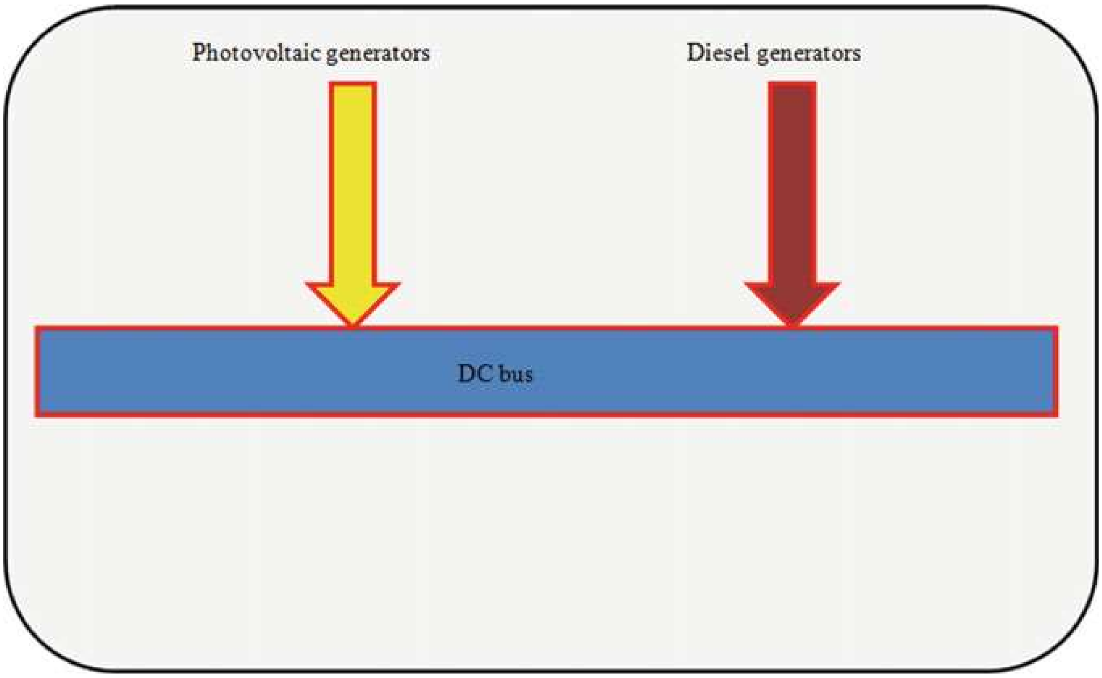

Fig. 1.29 Hybrid photovoltaic system/diesel generators

1.5.12 PV System with Diesel Generators with Battery Storage

Battery storage can be added to the previous system (Fig. 1.30) [4, 12, 25, 29, 41, 19, 98–100].

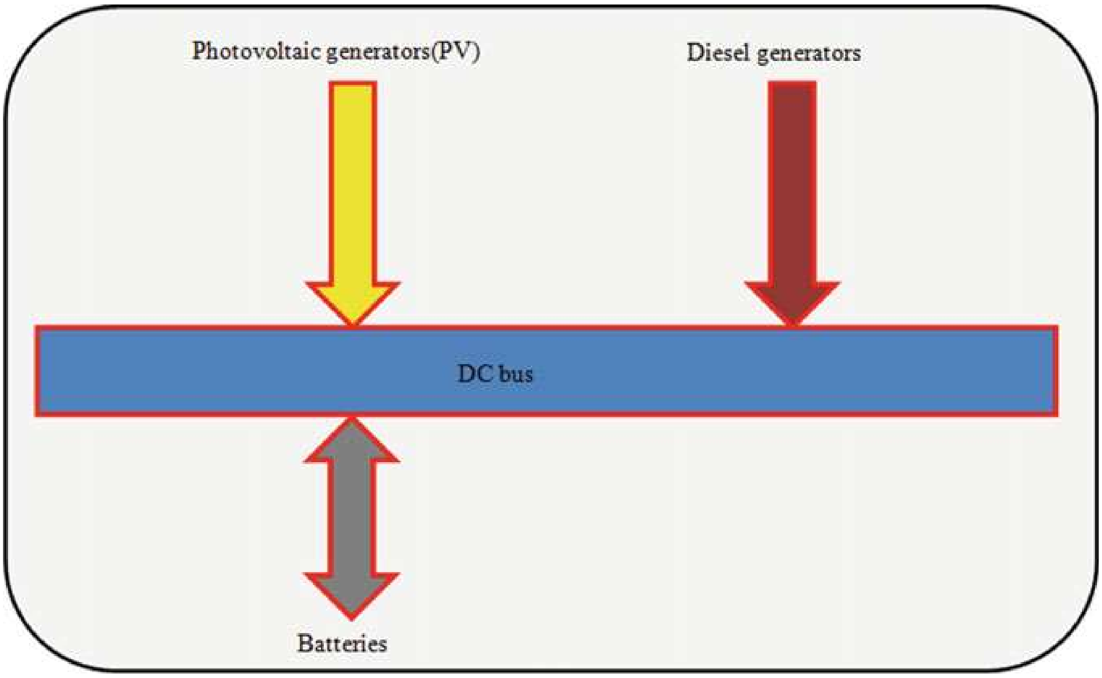

Fig. 1.30 Hybrid wind/photovoltaic system with battery storage

1.5.13 PV System with Wind Turbine System and Diesel Generators

Diesel generators are added as a backup system to PV/wind turbine system (Fig. 1.31).

1.5.14 PV System with Wind Turbine and Diesel Generators with Battery Storage

In this case, battery storage is added to the previous system (Fig. 1.32) [96, 97, 128, 129].

It can be implemented under MATLAB/Simulink as shown in Fig. 1.33.

1.6 Conclusion

This chapter has been devoted to hybrid wind systems. The different configurations and the different combinations of hybrid wind systems have been presented and described. Different synoptic schemes and models are also presented to show their implementation under MATLAB/Simulink.

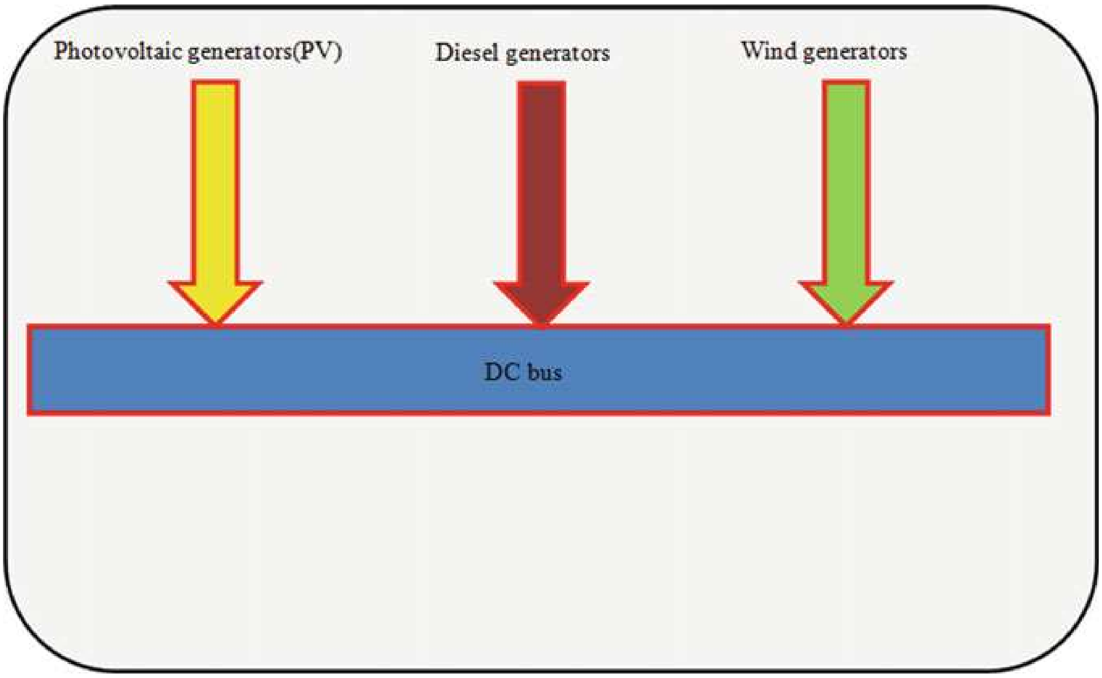

Fig. 1.31 Hybrid wind/photovoltaic system

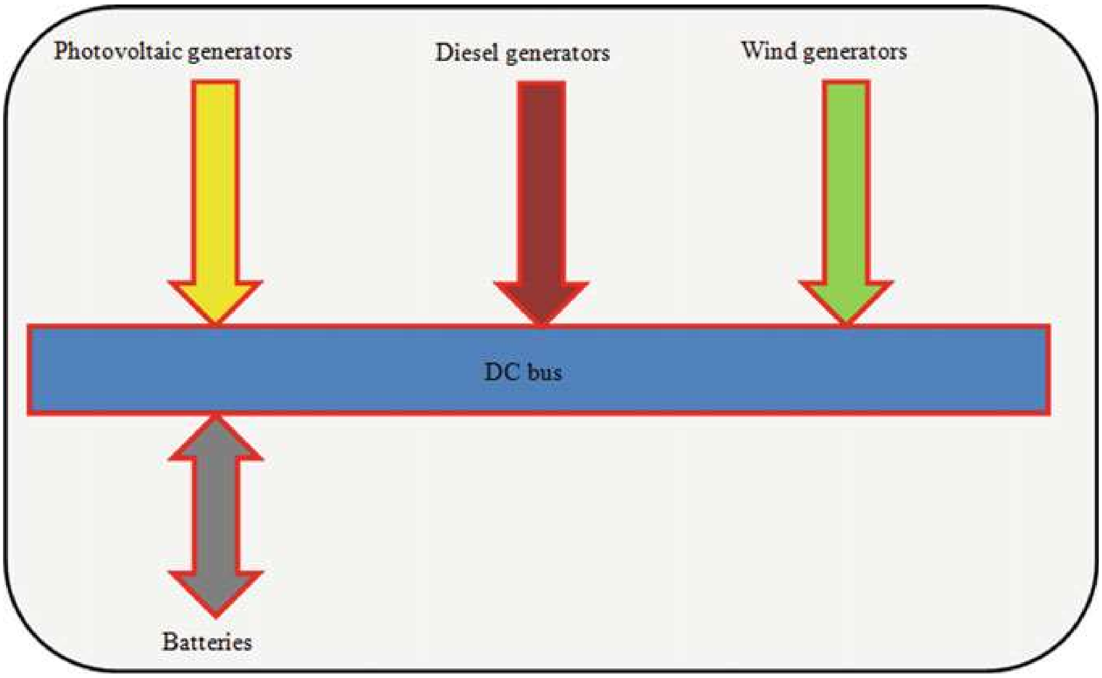

Fig. 1.32 Hybrid wind/photovoltaic system/diesel generators with battery storage

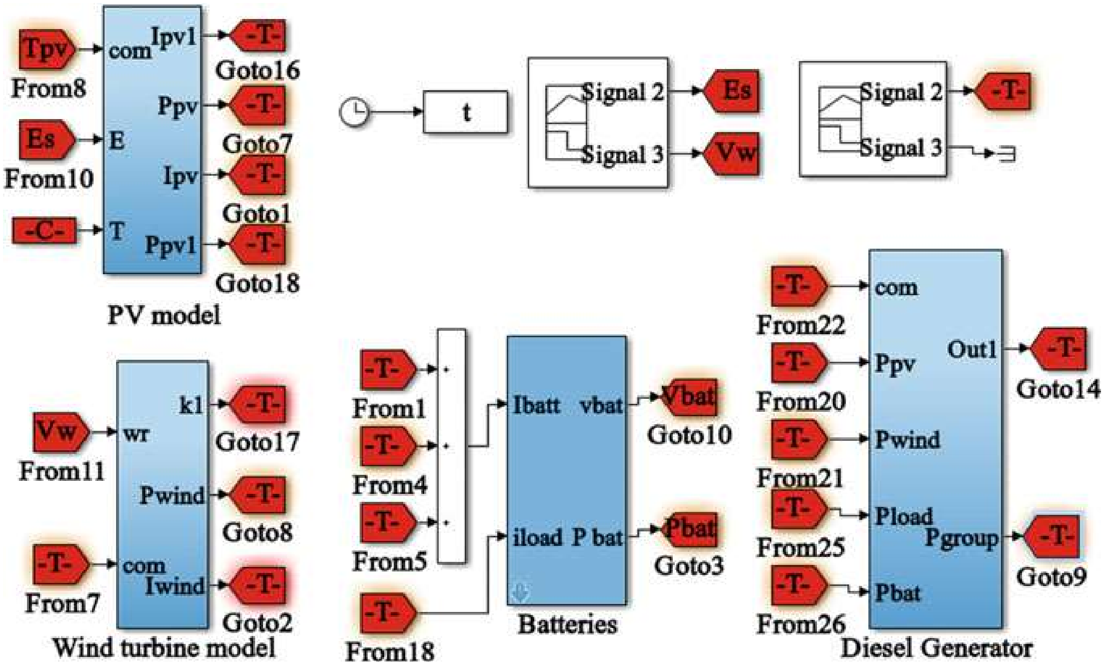

Fig. 1.33 Wind/photovoltaic system/diesel generators with battery storage under MATLAB/ Simulink

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Chapter 5
Design of Hybrid Renewable Energy Systems

5.1 Introduction

The design of a PV, wind or hybrid system can be made based on the exact knowledge of the load, the absorbed solar radiation, the estimates surface to be installed (especially for PV panels) and the choice of other equipment (controllers, inverters).

5.2 Design of Photovoltaic Systems

The effectiveness of any electric system depends on its design and its use. The sizing should be based on meteorological data, solar radiation and the exact load profile of consumers over long periods.

5.2.1 Determination of the Load Demand of Consumers

The exact knowledge of the customers load demand determines the size of generators [1].

$$D_{\text{energy-total}} = \sum P_{\text{Load}}.t \tag{5.1}$$

where P_{load} is the load power and t is run time (hours) per day (Fig. 5.1).

D. Rekioua, *Hybrid Renewable Energy Systems*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-34021-6_5

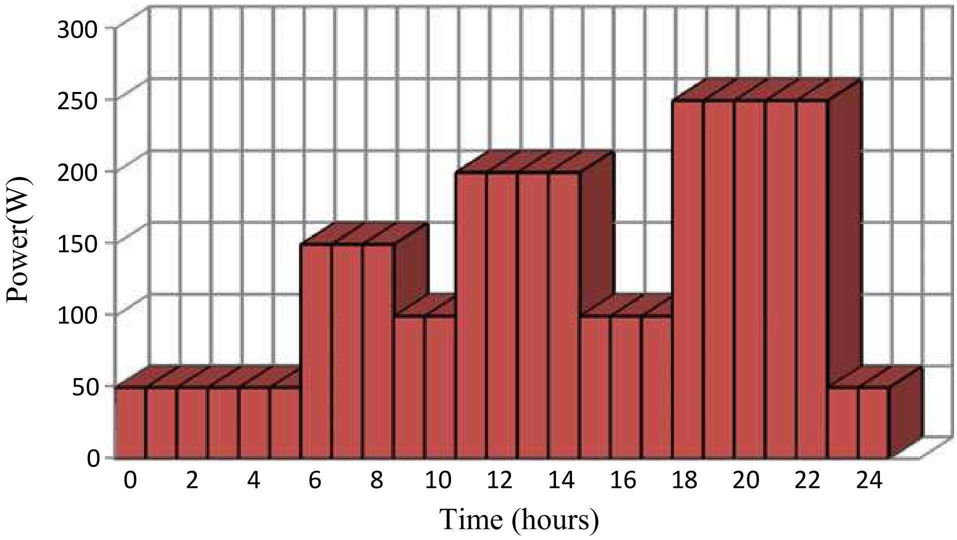

Fig. 5.1 Example of a time schedule diagram

Application 1

For example, in this case, the daily energy is calculated as:

$$D_{\text{energy}} = (50\,\text{W})\times(5\,\text{h}) + (150\,\text{W})\times(3\,\text{h}) + (100\,\text{W})\times(2\,\text{h}) + (200\,\text{W})\times(4\,\text{h}) + (100\,\text{W})\times(3\,\text{h}) + (250\,\text{W})\times(5\,\text{h}) + (50\,\text{W})\times(2\,\text{h})$$

$$D_{\text{energy}} = 3350\,\text{Wh/day}$$

It can be also calculated by knowing the different appliances, their power and their run time. For example, (see Table 5.1). In this example, it is listed some appliances used in a house to supply them with renewable energy (solar, Wind,…).

Table 5.1 Results of Application 2

Appliances	Number (N)	Power (W) P	Run time (h/day)t	Daily energy (Wh/day) D_{energy}
Oven	1	500	1	500
Steam iron	1	850	1	850
Washing machine	1	300	1	300
Television	1	200	6	200
Laptop computer	1	30	6	180
Water pump	1	400	2	800
Lights	2	12	5	120
Hair dryer	1	400	1	300
			Total Daily energy (Wh/day)$D_{\text{energy-total}}$	**3050**

The total daily energy will be calculated as:

$$D_{\text{energy\_total}} = N \cdot P \cdot t \tag{5.2}$$

Application 2
For example, we want to supply a house with solar energy. The different electrical devices are listed in Table 5.1.

5.2.2 Photovoltaic System Design

Once the load and absorbed solar radiation are known, the design of the PV system can be carried out, including the estimation of the required PV panel's area and the selection of the other equipment (controllers, inverters,…).

Different methods have been used for designing PV systems. Each method depends on specifically output parameters.

5.2.2.1 First Method

This method is based on the load demand. The actual daily solar energy is given as:

$$P_{a-\text{PV/day}} = P_p \cdot \frac{E_{s-\text{Worst}}}{E_{s-\text{STC}}}\left(1 - \sum \text{losses}\right) \tag{5.3}$$

with: $P_{a-\text{PV/day}}$: actual daily power, P_p: peak power of panels, $E_{s-\text{Worst}}$: value of the monthly average irradiation of the worst month of irradiation, $E_{s-\text{STC}}$ the irradiation value under STC conditions (standard test conditions), $\sum \text{losses} = 20\%$.

Hence, the PV panel number is:

$$N_{\text{pv}} = \frac{D_{\text{energy-total}}}{P_{a-\text{PV/day}}} \tag{5.4}$$

The total peak power will be:

$$P_{p-\text{total}} = N_{\text{pv}} \cdot P_p \tag{5.5}$$

Ant the total PV panel area is:

$$A_{\text{pv-total}} = N_{\text{pv}} \cdot A_{\text{pv}-u} \tag{5.6}$$

with: $A_{\text{pv}-u}$ is the unit PV panel area (m^2), $A_{\text{pv-tot}}$ the estimated total PV area (m^2).

Application 3

$$D_{\text{energy\_total}} = 500\,\text{Wh/day}, E_{s-\text{Worst}} = 2.73\,\text{kWh/m}^2\cdot\text{day}, E_{s-\text{STC}} = 1000\,\text{W/m}^2, A_{\text{pv}-u} = 1.4\,\text{m}^2.$$

The obtained results for three different photovoltaic powers can be summarized in Table 5.2.

5.2.2.2 Second Method

This method is very simple but remains an estimated one. It is necessary to know the need energy, the PV efficiency (material) and the value of the radiation of the most unfavorable month of the site.

$$P_{\text{pv-totale-est}} = \frac{D_{\text{energy\_total}} \cdot E_{\text{STC}}}{E_{\text{worst}}} \tag{5.7}$$

where h_{sun} is the peak sun-hour can be written as:

$$h_{\text{sun}} = \frac{E_{\text{worst}}}{E_{\text{STC}}} \tag{5.8}$$

Thus:

$$P_{\text{pv-totale-est}} = \frac{D_{\text{energy\_total}}}{h_{\text{sun}}} \tag{5.9}$$

Application 4

$$E_{s-\text{Worst}} = 2.73\,\text{kWh/m}^2.\text{day}, E_{s-\text{STC}} = 1000\,\text{W/m}^2, A_{\text{pv}-u} = 1.4\,\text{m}^2.$$

See (Table 5.3).

Table 5.2 Results of the Application 3

$D_{\text{energy\_total}}$ (Wh/day)	$P_p(\text{W}_p)$	$E_{s-\text{worst}}(\text{kWh/m}^2/\text{day})$	$P_{\text{a-PV/day}}(W)$	N_{pv}	$P_{\text{pv-total}}(W)$	$A_{\text{pv-total}}$
500	80	2.73	174.72	3	240	4.2
	100		218.4	3	300	4.2
	160		349.44	2	320	2.8

Table 5.3 Results of the Application 4

$D_{\text{energy\_total}}$ Wh/day	$P_p (W_p)$	h_{sun} (hour)	$P_{\text{pv-totale-est}}$	N_{pv}	$P_{\text{pv-total}} (W)$	$A_{\text{pv-total}} (\text{m}^2)$
500	80	2.73	183.1501832	3	240	4.2
	100		183.1501832	2	200	2.8
	160		109.8901099	1	160	1.4

5.2.2.3 Third Method

This method is based on the monthly average solar irradiance. The monthly energy produced by the system per unit area is denoted $E_{\text{pv},m}$ (kWh/m^2) and $M_{\text{energy},m}$ is the monthly energy required by the load (where m = 1, 2, …, 12 represents the month of the year.). The minimum surface of the generator needed to ensure full (100%) energy (F_{energy}) is expressed by [1]:

$$A_{\text{pv-tot}} = \frac{M_{\text{energy},m}}{E_{\text{pv},m}} \tag{5.10}$$

The full energy can be given by:

$$F_{\text{energy}} = E_{\text{pv}} \cdot A_{\text{pv-tot}} \tag{5.11}$$

The number of photovoltaic generators is calculated using the surface of the system unit $A_{\text{pv}-u}$ taking the entire value:

$$N_{\text{pv}} = \frac{A_{\text{pv-tot}}}{A_{\text{pv}-u}} \tag{5.12}$$

Application 5
An application is made with the different parameters: $A_{\text{pv},\ u}$ = 1.4 m^2, η_{pv} = 0.12, P_{pv} = 80 W_p (Table 5.4).

5.2.2.4 Method Based on Load Needs

The number of the series-connection PV modules is calculated by:

$$N_{\text{pv-serial}} = \frac{F_{\text{energy}}}{E_{\text{worst}} \cdot \eta_{\text{batt}} \cdot \eta_{\text{el}} \cdot \eta_{\text{DC}}} \tag{5.13}$$

η_{batt} is the efficiency of the battery, η_{el} is the electrical efficiency of the whole installation (charge controller, inverter…), η_{DC} is the distribution circuit.

Table 5.4 Results of the application 5

Months	G (kWh/m^2/day)	$M_{energy,m}$ (Wh)	F_{energy} (Wh/m^2/day)	$A_{pv,tot,m}$ (m^2)	N_{pv}
January	2.38	12,395.04	37,200.00	3.00	3.00
February	3.31	16,126.32	34,800.00	2.16	2.00
March	4.44	23,123.52	37,200.00	1.61	2.00
April	5.46	27,518.40	36,000.00	1.31	1.00
May	6.41	33,383.28	37,200.00	1.11	1.00
June	7.12	35,884.80	36,000.00	1.00	1.00
July	7.23	37,653.84	37,200.00	0.99	1.00
August	6.38	33,227.04	37,200.00	1.12	1.00
September	5.08	25,603.20	36,000.00	1.41	2.00
October	3.66	19,061.28	37,200.00	1.95	2.00
November	2.51	12,650.40	36,000.00	2.85	3.00
December	2.06	10,728.48	37,200.00	3.47	3.00

It can be also written as:

$$N_{pv-serial} = \frac{F_{energy}}{E_{worst} \cdot K_E} \tag{5.14}$$

where $K_E = \eta_{batt}.\eta_{el}.\eta_{DC}$ is energy efficiency, it varies [0.6–0.75].

The maximum terminal voltage of the photovoltaic generator is estimated by:

$$V_{pv-max} = 1.15.N_{pv-serial}.V_{oc} \tag{5.15}$$

(1.15 is a correction factor).

The PV parallel panels can be calculated by using Eq. 5.15, where V_{DC-bus} is DC bus voltage

$$N_{pv-para} = \frac{U_{pv-max}}{V_{DC-bus}} \tag{5.16}$$

Then, the total number of panels is deduced:

$$N_{pv} = N_{pv-para} \cdot N_{pv-serial} \tag{5.17}$$

The total photovoltaic power to be installed will be:

$$P_{pv-totale} = N_{pv} \cdot P_p \tag{5.18}$$

Application 6

The obtained results for three different photovoltaic powers can be summarized in Table 5.5.

Table 5.5 Results of the Application 6

F_{energy} (Wh/day)	P_p (W_p)	V_{oc} (V)	$N_{pv-serial}$	V_{pv-max}(V)	$N_{pv-para}$	N_{pv}
500	80	22.4	1	25.76	3	3
	100	20.5	1	23.575	2	2
	160	21.8	1	25.07	3	3

5.3 Design of Wind System

5.3.1 Calculation of Wind Energy

The energy produced by the wind generator during a period time Δt is expressed by:

$$E_{wind} = P_{mec} \cdot \Delta t \tag{5.19}$$

where Δt period of time.

5.3.2 Determination of the Wind Generator Size

The total area of the wind turbine generators required to ensure full coverage (100%) of the load $\left(F_{energy}\right)$ is expressed by:

$$A_{wind-total} = \frac{D_{energy}}{E_{wind}} \tag{5.20}$$

with: $E_{wind}(\text{kWh/m}^2)$ is the monthly energy produced by the wind system per unit area and $M_{energy}(\text{kWh})$ represents the monthly energy required by the load.

The number of wind turbine generators is calculated according to the surface area of the system unit by taking the entire value of the excess ratio.

$$N_{wind} = \frac{A_{wind-total}}{A_{wind}} \tag{5.21}$$

with A_{wind} is the surface area of a wind turbine.

5.4 Sizing of Hybrid Photovoltaic/Wind System

The energy produced by a photovoltaic generator per unit area is estimated using data from the global irradiance on an inclined plane, ambient temperature and the data sheet for the used photovoltaic pannels. It is given by:

$$E_{pv} = \eta_{pv} \cdot GA_{pv} \tag{5.22}$$

where: G is the solar radiation incident.

The power contained in the form of kinetic energy per unit area in the wind is expressed by:

$$P_{mec} = \frac{1}{2} \cdot \rho_{air} \cdot v_{wind}^3 C_p \cdot A_{wind} \tag{5.23}$$

with: v_{wind} is the speed wind, C_p the power coefficient, ρ_{air} the air density and A_{wind} the wind area.

- Pre-sizing of photovoltaic and wind systems:

The monthly energy produced by the system per unit of area is denoted $E_{pv,m}$ (kWh/m^2) for photovoltaic energy and $E_{wind,m}$ (kWh/m^2) for wind energy and $E_{L,m}$ M_{energy} represents the energy required by load every month (where m=1, 2, …, 12 represents the month of the year). Owe have:

$$E_{pv,m} = \sum_{\text{month m}} \Delta E_{pv} \tag{5.24}$$

$$E_{wind,m} = \sum_{\text{month m}} \Delta E_{wind} \tag{5.25}$$

and

$$F_{energy} = \sum_{\text{month m}} M_{energy} \tag{5.26}$$

Pre-sizing is sometimes based on the worst month of the year.

$$E_{L,\text{worst } m} = E_{pv,\text{worst } m} \cdot A_{pv} + E_{wind,\text{worst } m} \cdot A_{wind} \tag{5.27}$$

The parameter f which is the fraction of load supplied by the photovoltaic energy is introduced, $(1 - f)$ being the fraction of load supplied by the wind energy. Then:

$f = 1$ indicates that the entire load is supplied by the photovoltaic source.
$f = 0$ indicates that the entire load is powered by the wind source.

The different PV and wind area can be calculated as:

$$A_{pv} = \frac{f E_{L,\text{worst}\, m}}{E_{pv,\text{worst}\, m}} \tag{5.28}$$

$$A_{wind} = \frac{(1 - f) E_{L,\text{worst m}}}{E_{\text{wind,worst m}}} \tag{5.29}$$

The pre-sizing is often also based on monthly annual average [2, 3]. The calculation of the size of wind generator and photovoltaic (A_{pv} and A_{wind}) is established from the annual average values of each monthly contribution $\left(\overline{E_{pv}} \text{ and } \overline{E_{wind}}\right)$. The load is represented by the monthly annual average $\overline{F_{energy}}$.

$$A_{pv} = f \cdot \frac{\overline{F_{energy}}}{\overline{E_{pv}}}$$
$$A_{wind} = (1 - f) \cdot \frac{\overline{F_{energy}}}{\overline{E_{wind}}} \tag{5.30}$$

The number of photovoltaic and wind generator to consider is calculated according to the area of the system unit taking the integer value of the ratio by excess.

$$N_{pv} = \text{ENT}\left[\frac{A_{pv}}{A_{pv,u}}\right]$$
$$N_{wind} = \text{ENT}\left[\frac{A_{wind}}{A_{wind,u}}\right] \tag{5.31}$$

Application 7

Table 5.6 shows the monthly energy production of the generators and the size required to satisfy a constant daily consumption load of about 3050 Wh/day.

Table 5.6 Monthly energies produced by photovoltaic and wind generators

Months	G (kWh/m^2/day)	V_{wind} (m/s)	$M_{energy\text{-}pv,m}$ (kWh/day)	$M_{energy\text{-}wind,m}$ (kWh/day)	F_{energy} (kWh/m^2/day)	A_{pv} (m^2)	A_{wind} (m^2)
January	2.38	5.22	11.56	14.97	153.45	6.70	4.87
February	3.31	5.32	11.80	13.90	143.55	6.14	4.91
March	4.44	5.3	13.51	14.32	153.45	5.73	5.09
April	5.46	5.34	13.34	12.75	148.5	5.62	5.53
May	6.41	4.52	13.68	11.35	153.45	5.66	6.42
June	7.12	4.33	13.71	12.27	148.5	5.46	5.75
July	7.23	4.46	14.48	13.28	153.45	5.35	5.49
August	6.38	4.36	14.65	13.89	153.45	5.28	5.25
September	5.08	4.17	13.91	11.25	148.5	5.39	6.27
October	3.66	4.48	13.13	12.29	153.45	5.90	5.93
November	2.51	5.15	11.31	12.95	148.5	6.63	5.45
December	2.06	5.33	10.91	17.88	153.45	7.10	4.08
Monthly average	4.67	4.83	13.00	13.42	150.975		

Table 5.7 Sizing according to the annual monthly average

f	$1-f$	A_{pv} (m^2)	N_{pv}	A_{wind} (m^2)	N_{wind}	F_{moy}
0	1.00	0.00	0	9.42	3	126.4164
0.1	0.90	1.29	2	9.42	3	143.1864
0.2	0.80	1.94	3	9.42	3	151.6364
0.3	0.70	3.23	5	9.42	3	168.4064
0.4	0.60	3.88	6	6.28	2	134.7176
0.5	0.50	5.17	8	6.28	2	151.4876
0.6	0.40	5.81	9	6.28	2	159.8076
0.7	0.30	7.11	11	3.14	1	134.5688
0.8	0.20	7.75	12	3.14	1	142.8888
0.9	0.10	8.40	13	3.14	1	151.3388
1	0.00	9.69	15	0.00	0	

After having calculated the total required surfaces of the two generators (photovoltaic, wind), we will determine the number to install according to the fraction of the load (f) taken with an interval of [0–1] (Table 5.7).

The obtained results can be represented in Fig. 5.2.

5.5 Sizing of Hybrid Photovoltaic/Wind System/Batteries

The global system includes a PG generator, a charge controller, a battery bank and a DC/AC converter supplying a load profile. These major ¡components should be selected to the location site and the application. Figure 5.3 shows a diagram of a typical standalone PV system powering AC loads [5–32].

5.5.1 Battery Design

Battery capacity is the energy per day capable of charging a battery. The calculation can be written as:

$$C_{batt}(A \cdot h) = \frac{D_{energy} \cdot N_{aut}}{V_{batt} \cdot \mathrm{DOD} \cdot \eta_{batt}} \tag{5.32}$$

where:V_{batt} is the battery voltage, DOD is the depth of discharge, η_{batt} the efficiency battery, N_{aut} is the days of autonomy and D_{energy} is the total energy required.

The number of batteries to be used is determined from the capacity of a battery unit $C_{batt,u}$ is given by:

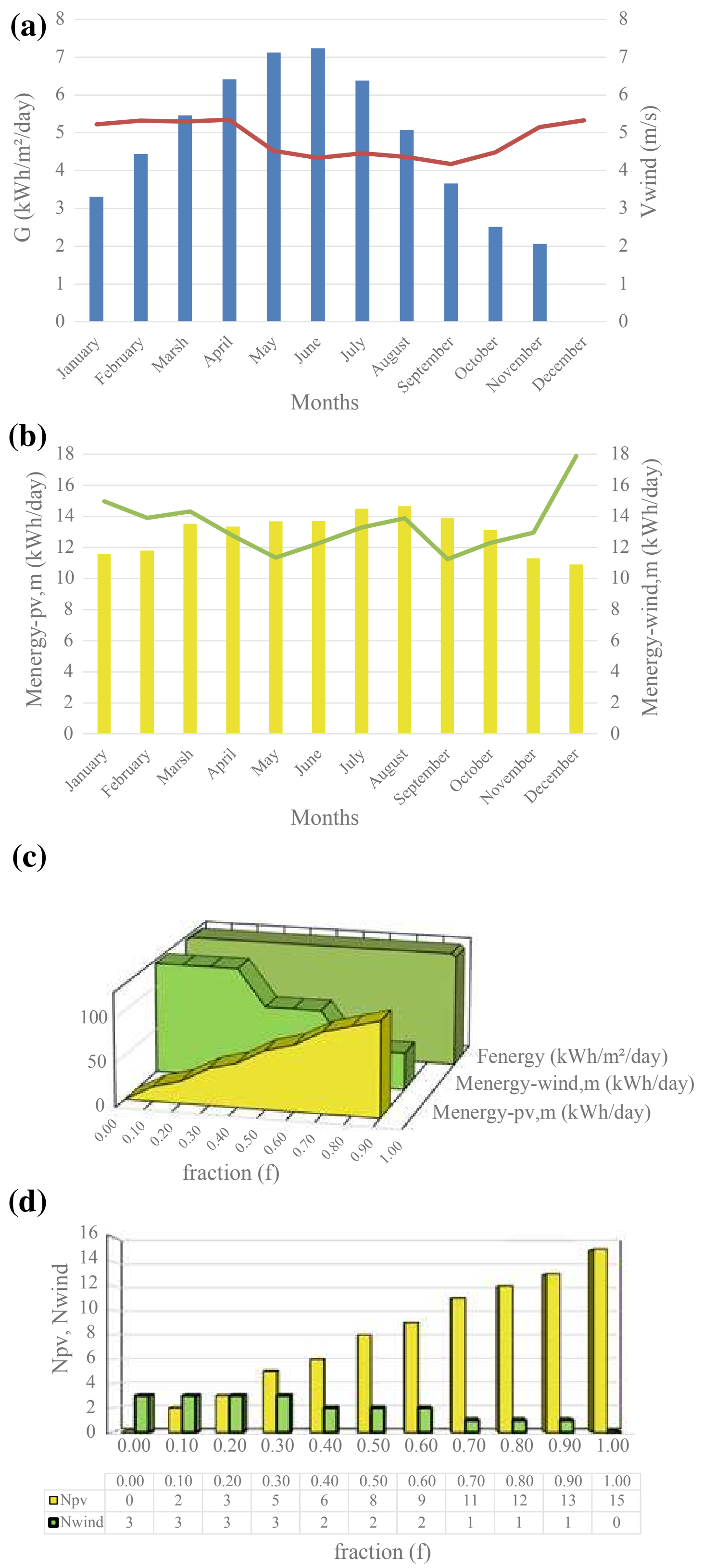

Fig. 5.2 Obtained results of PV/wind design. **a** Solar radiation and wind speeds of the location. **b** Average daily energy of PV and wind generators. **c** Full energy with PV and wind turbine energies. **d** Combinations of number of PV and wind turbines

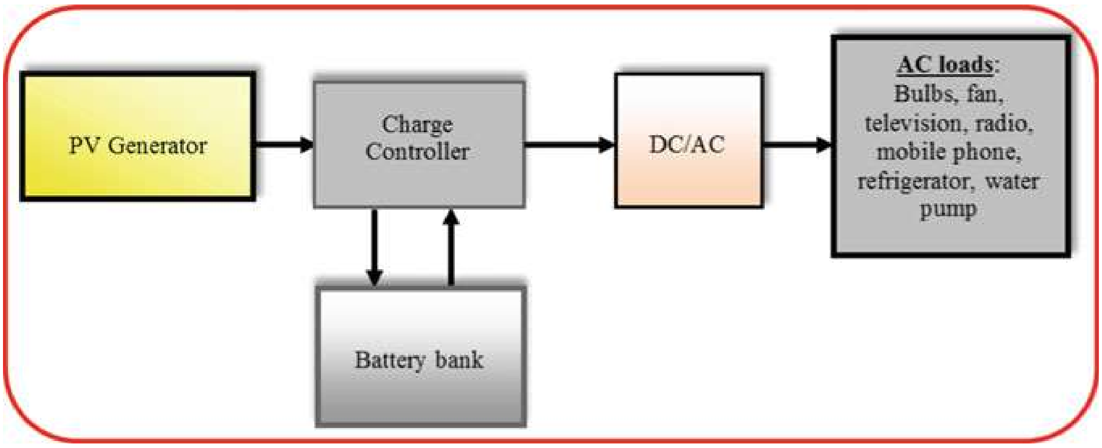

Fig. 5.3 Diagram of a typical standalone PV system powering AC loads

Table 5.8 Results of Application 9

D_{energy} (Wh/day)	V_{batt} (V)	η_{batt}	DOD	N_{aut} (h/day)	C_{batt} (Ah)	$C_{batt,u}$ (Ah)	N_{batt}
300	12	0.85	0.6	2	98.04	90	1
3030					990.1		11

$$N_{batt} = \left[\frac{C_{batt,min}}{C_{batt,u}} \right] \tag{5.33}$$

Application 8
We make an application for two different daily energies (300 Wh/day and 3030 Wh/day). (Table 5.8).

5.5.2 DC/AC Converter Design

5.6 Design of Hybrid Photovoltaic/Wind System/Fuel Cells

In this case, PV and wind turbine generators are considered as a main source and fuel cells as a secondary one.

$$P_{Ren} = P_{PV} + P_{wind} \tag{5.34}$$

$$P_{\text{Load}} = P_{\text{Ren}} + P_{\text{FC}} \tag{5.35}$$

where: P_{Ren} is the power produced by PV and wind systems and P_{FC} is the power produced by fuel cell system.

The design of PV panels and wind turbine has been explained in Sect. 5.4. For fuel cells, the sizing methodology is as follows: Stack design consists of calculating the number and area of cells that make up a fuel cell stack. This sizing must take into account the nominal power of the cell and the current density desired to obtain by adding 20% of the power that will be consumed by the cell auxiliaries.

5.6.1 Power Calculation

$$P_{\text{FC-stack}} = P_{\text{inv}}.(1 + 0.2) \tag{5.36}$$

where P_{inv} *is* the input inverter power.

5.6.2 Cell Number and Cell Surface

The maximum electrical power of the stack is calculated by the following relationship [4]:

$$P_{\text{FC-stack}} = N_{\text{FC}} \cdot E_{\text{FC}} \cdot j \cdot A_{\text{FC}} \tag{5.37}$$

with: $P_{\text{FC-stack}}$ is the maximum electrical power of the stack (W), N_{FC} is the number of cells in the stack, E_{FC} is the voltage per cell (V), j is the current density (A/m^2) and A_{FC} is the active cell area (m^2).

The voltage of the stack depends on the cells number:

$$U_{\text{stack}} = N_{\text{FC}} \cdot E_{\text{FC}} \tag{5.38}$$

To determine the area of the stack, the FC current must first be calculated:

$$I_{\text{stack}} = \frac{P_{\text{stack}}}{U_{\text{stack}}} \tag{5.39}$$

$$A_{\text{FC}} = I_{\text{stack}}/j \tag{5.40}$$

Table 5.9 Results of application 8

$V_{DC-bus}(V)$	$E_{FC}(V)$	$j(A/cm^2)$	$U_{stack}(V)$	N_{FC}	$P_{inv}(W)$	$P_{FC-stack}(W)$	$I_{stack}(A)$	$A_{FC}(cm^2)$
450	1	1	225	376	1500	1800	8	13.33

It is interesting to have the highest voltage U_{stach} and, therefore, the lowest current I_{stach} because it limits losses in the cell.

Application 9
An example is made to follow the sizing method (Table 5.9).

5.7 Application to Water Pumping System

Depending on the size of pump, three-phase induction machines or single-phase induction machines can be used. In this work, induction motor associated with a centrifugal pump has been used. The energy consumed by the pump depends on the desired water flow, which represents the energy that must be provided by the two generators (PV and wind).

Sizing of the different components of the system supplying a small village with water has been made. The specifications must satisfy the following conditions:

- the volume of water tank pumped per day about 100 m^3.
- the water tank is situated at 10 m above the surface level.
- a nominal flow rate of 34 m^3/h=0.0094 m^3/s.

The different results can be summarized in Table 5.10.

As the height increases, the powers increase, which will improve efficiency (Fig. 5.4).

Table 5.10 Moto-pump group sizing

Symbols	Equations	Results
Hydraulic power P_{Hyd}	$P_{Hyd} = \rho_{water} \cdot g \cdot h \cdot q_v$	922.14 W
Mechanical power required by the pump P_{mec}	$P_{mec} = \frac{P_{Hyd}}{\eta_{pump}}$	2049.20 W
Electrical power required for the motor to operate P_{elec}	$P_{elec} = \frac{P_{mec}}{\eta_{motor}}$	2561.50 W
Input inverter power P_{inv}	$P_{inv} = \frac{P_{elec}}{\eta_{inv}}$	2696.32 W
Pumping time required to satisfy the water needs τ_{pump}	$\tau_{pump} = \frac{V_{tank}}{q_v}$	2.94 h
Daily electrical energy required E_c	$D_{energy} = \tau_{pump} \cdot P_{inv}$	7930.34 Wh/day

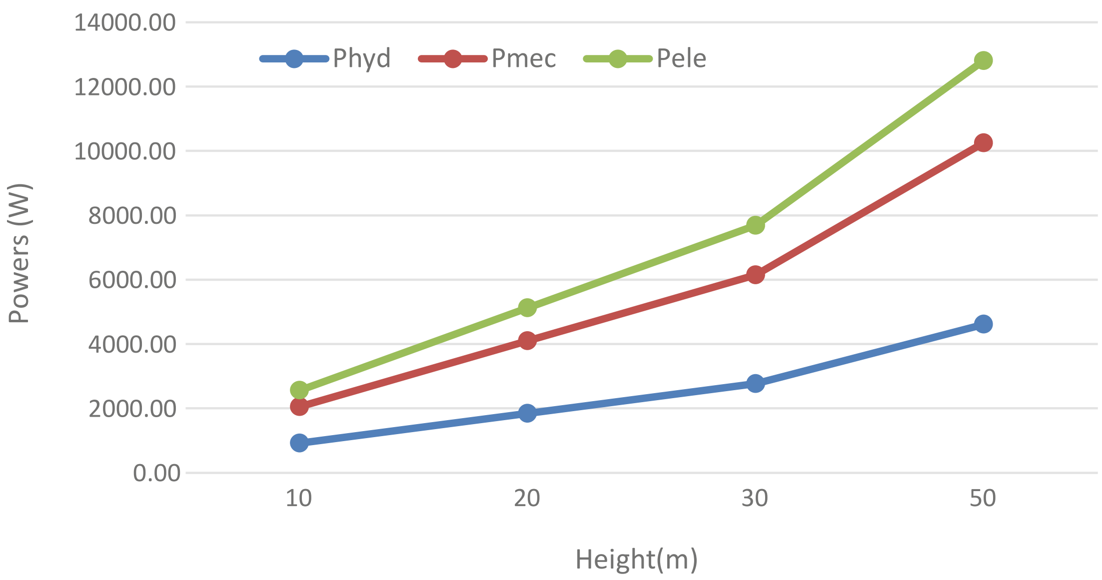

Fig. 5.4 Variation of powers

5.8 Optimization of Power System Using HOMER Pro Software

5.8.1 Introduction to HOMER Pro Software

Hybrid optimization model for electric renewable (HOMER) software performs economic analysis on hybrid power systems. Homer is a simulation and optimization software for multi-source (hybrid) power generation systems, with different components: (PV, wind, grid, storage, diesel…). It is dedicated directly to the simulation of on-grid and off-grid systems. The software allows the simulation of a system based on inputs (solar, wind, diesel, etc.) according to energy consumption. Subsequently, it is possible to analyze several different configurations for the same system in order to obtain a cost-effective system. The software simulates all the required configurations and gives the best solution, the cheapest solution, among them. Then, it is finally possible to perform sensitivity analyses to determine if the solution found is the best even if there are some changes in the various parameters entered (variation in the cost of the technology, variation in the deposit data, etc.). It is, therefore, possible to perform many analyses with many different configurations in less than a few minutes of simulation.

The software allows simulations to be performed with different energy production systems:

- photovoltaic solar panels,
- wind turbines,
- hydro power,
- biomass,
- generators (diesel, gasoline, biogas, alternative and customized fuels),

– power grid,
– fuel cells.

HOMER also offers a wide range of energy storage or recovery systems:

– battery bank,
– flywheels,
– flow batteries,
– hydrogen.

You can also input various types of energy needs:

– daily consumption profiles with seasonal variations,
– delayed charging for water pumping or refrigeration,
– thermal load,
– energy efficiency measures.

HOMER can, therefore, simulate a wide range of different systems in addition to all possible combinations of hybrid systems (Fig. 5.5).

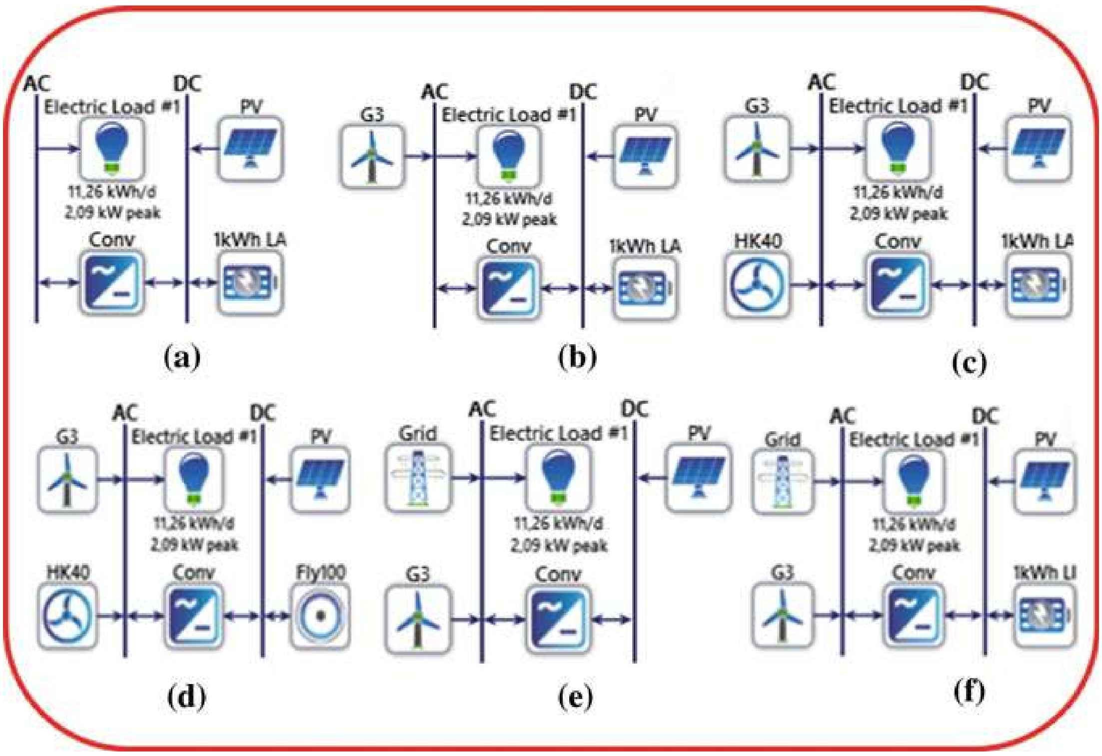

Fig. 5.5 Example hybrid combinations systems in Homer Pro. **a** PV/batteries. **b** PV/wind/batteries. **c** PV/wind/batteries/HPS. **d** PV/wind/HPS/FEES. **e** PV/wind/batteries on grid. **f** PV/wind/batteries/batteries on grid

Fig. 5.6 Bejaia location in Algeria (Latitude 36°45.3522′ N, Longitude 5°5.0598′ E) with HOMER software License Agreement

5.8.2 *Application to PV/Wind System with Battery Storage*

The main purpose of this application is to optimize the size of PV/wind/wind/ battery hybrid system components, minimize excess production and perform a cost analysis based on life-cycle cost. Solar radiation and wind speed data were collected for Bejaia area in Algeria (Latitude 36°45.3522′ N, Longitude 5°5.0598′ E) using

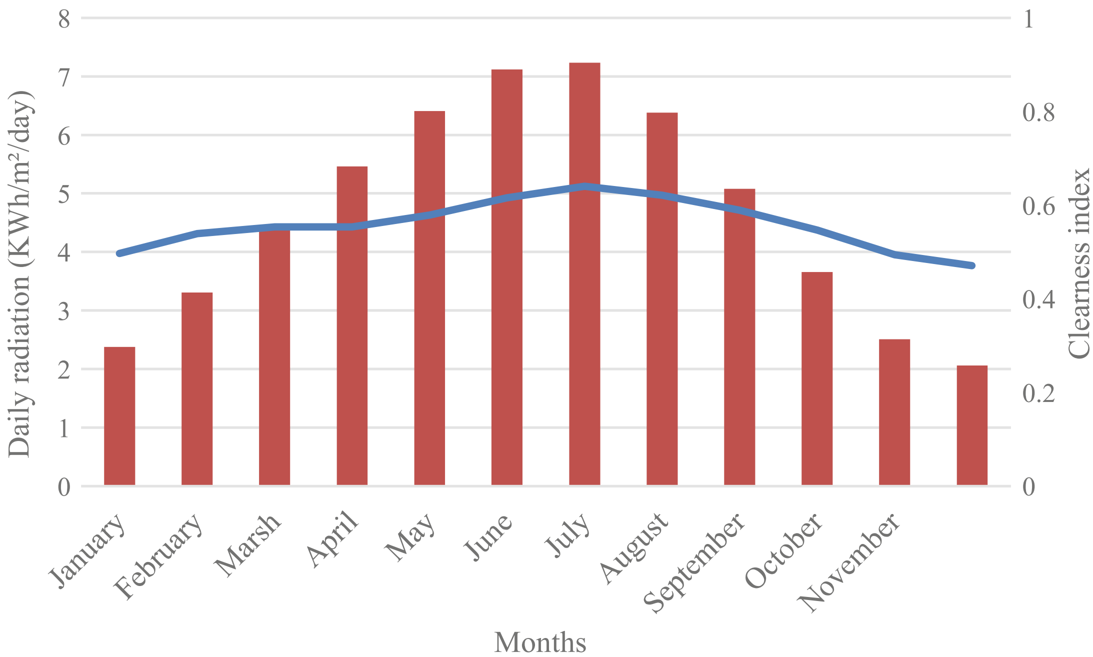

Fig. 5.7 Daily radiation and clearness index at Bejaia location (downloaded at 18/08/2019 18:58:26 from HOMER software License Agreement)

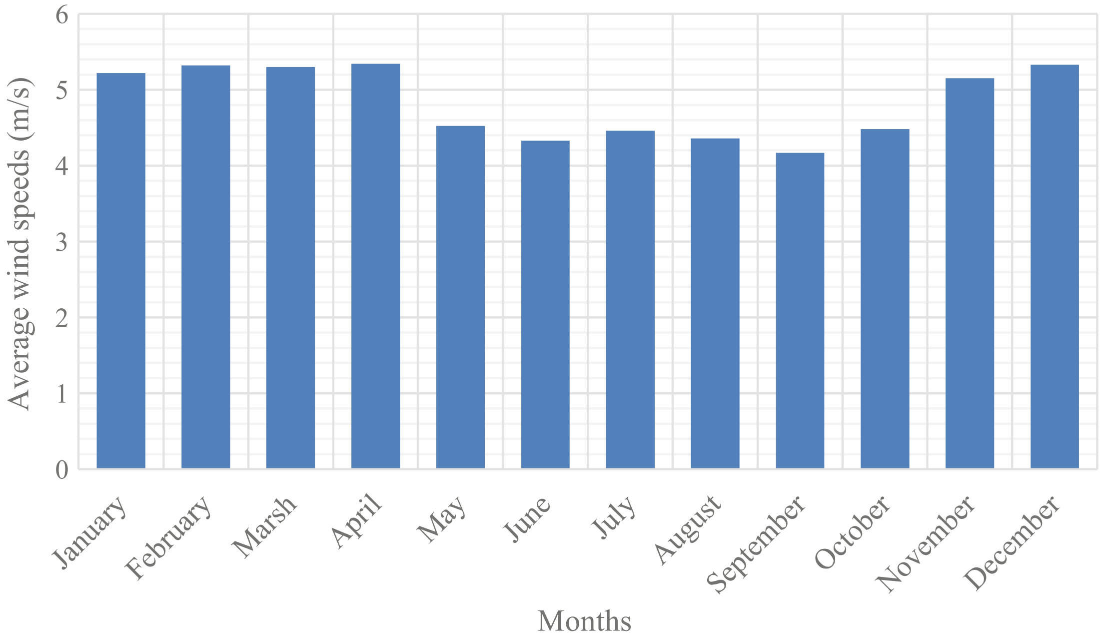

Fig. 5.8 Average wind speeds (downloaded at 18/08/2019 18:58:26 from HOMER software License Agreement)

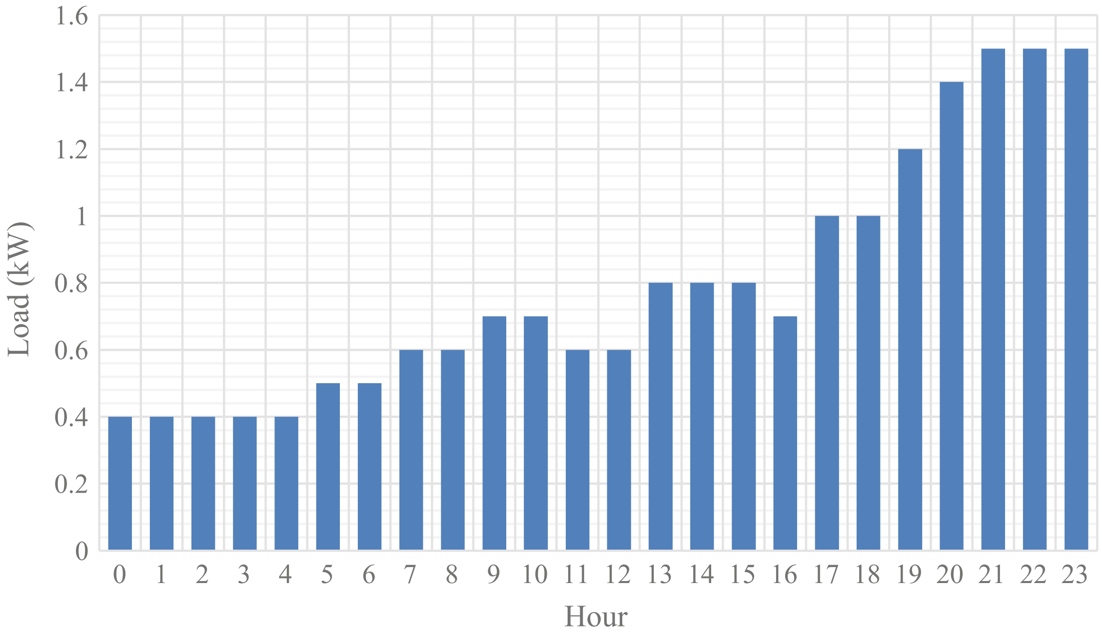

Fig. 5.9 Daily average load profile for a residential house

the function of "Get Data via Internet" in the HOMER software (the NASA Atmospheric Data Center), (see Fig. 5.6).

Figure 5.7 shows monthly average daily solar radiation with the clearness radiation at Bejaia site.

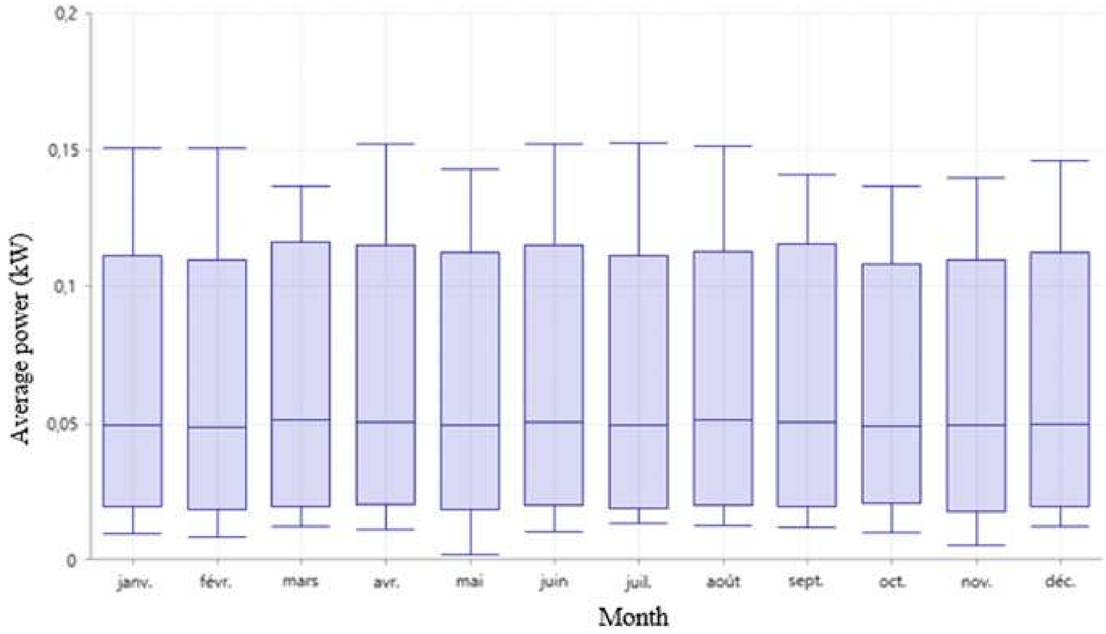

Fig. 5.10 Scaled data monthly average

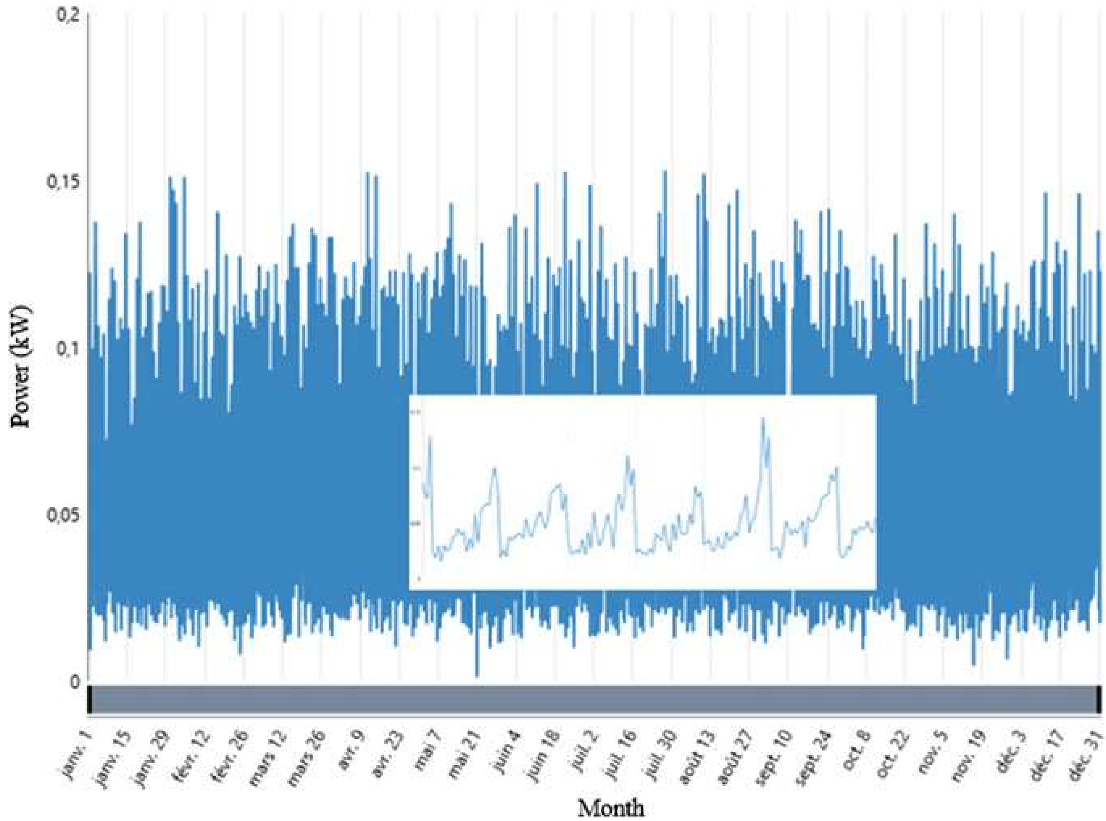

Fig. 5.11 Daily average load for a complete year

The average wind speeds are as follows in Fig. 5.8. It varies from 4.170 to 5.33 (m/s). The annual average is about 4.83 m/s.

In this application, load data were collected for a residential house located in Bejaia region. The measured annual consumption is estimated as 1.2 kWh/day (Fig. 5.9). The peak load decides the size of system components.

The scaled data monthly average is as Fig. 5.10.

The daily average load for a complete year is (Fig. 5.11).

The hourly average load variations in a year for all months can be represented as (Fig. 5.12).

The main components of the developed hybrid system under Homer are shown in Fig. 5.13.

Once the technical parameters of each component are chosen, the cost of each component is entered by entering the initial price, the maintenance price and their estimated lifetime, in order to allow the software to determine the overall price of the installation and to optimize for the lowest net present cost (NPC). HOMER calculates the net present cost of each component and of the hybrid system as a whole. The results were computed in different simulations to show the technico-economic feasibility of the studied hybrid system.

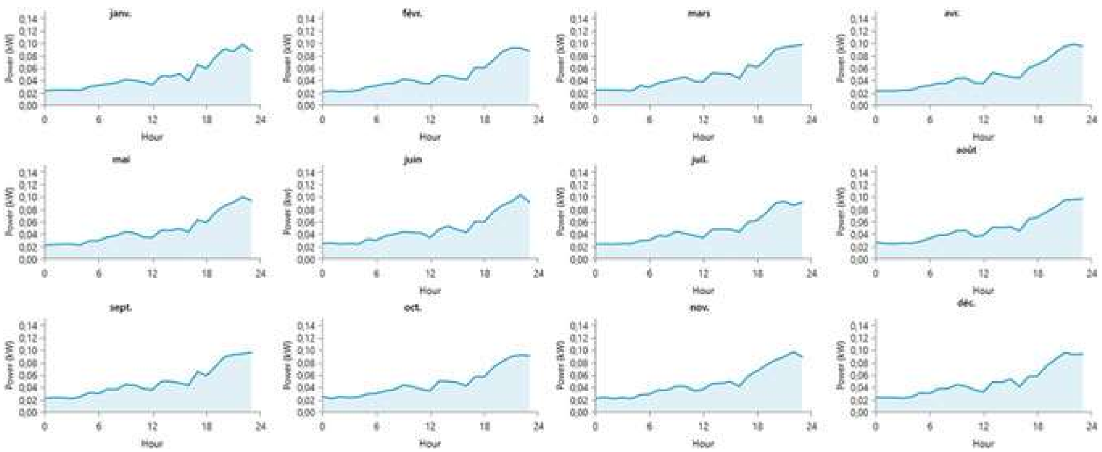

Fig. 5.12 Hourly average load variations in a year for all months

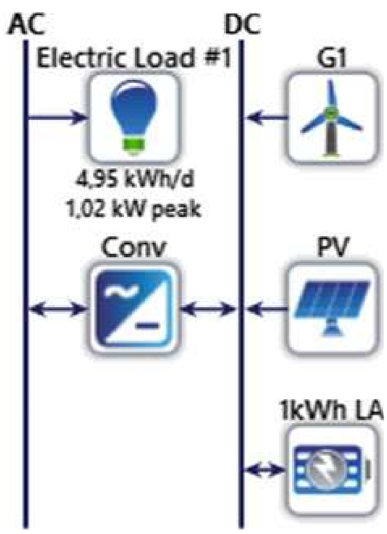

Fig. 5.13 Block diagram of PV/wind turbine/battery hybrid system

5.9 Conclusions

The most presented methods are well-known but still used in the design of system because it is the most important step in a project. This application using Homer software is based on economical performances which depend of course on real market prices and exact sizing of each component of a studied system.

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