Green Energy and Technology

Ramchandra Pode
Boucar Diouf

Solar Lighting

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Preface

Access to electricity considered as a fundamental human need is still very biased in the twenty-first century. Numerous developing countries are deprived of electricity, while such an issue is generally inexistent in developed countries; nevertheless, the energy sources that made the development possible are mainly based on fossil fuels that raise more and more environmental concerns.

Renewable energies are a good option to equilibrate this situation and provide a real opportunity for a better environment. Their successful implementation cannot be followed unless governments adopt adequate favorable policies that should necessarily go along with good education. Renewable energies should not be seen as a luxury, but a cost effective alternative that will bring jobs as well as improve living conditions.

One of the goals of the Millennium Development Program of the United Nations Organization is to provide regular electricity to 1.4 billion people around the world, mostly in the rural areas. Access to electricity and home lighting are considered essential for a decent quality of life. However, rural areas frequently lack the safe and uninterrupted electricity supply that is desired for the development of numerous economic activities. Grid expansion is a vital objective of several developing countries but is expensive and could be a long-term solution. However, the remoteness, isolation, and low electricity demand of many rural communities make them very unlikely to be reached by the extension of the power grid. Consequently, autonomous off-grid generation systems, such as photovoltaic or wind energies, seem to be the most suited to provide electricity services to these isolated rural communities.

This book has evolved from a number of years of intensive research on organic as well as inorganic LED lighting and practicing solar home systems. We feel that knowledge of the literature in the last couple of years has made a significant leap forward to warrant a comprehensive presentation. A large part of the book is based on the practical experience in solar home systems and energy efficient and future lighting devices such as LEDs and organic LEDs.

We acknowledge the open and intense discussion with many colleagues in the Physics and Information Display Departments of Kyung Hee University, Seoul

and participations in meetings and workshops on LED lightings and PV systems. Professor Syed Abdus Samad, Ex-Professor, Business Administration Division, Hankuk University of Foreign Studies, Seoul, South Korea and presently, Executive Chairman, Board of Investment, Government of Bangaladesh, Dhaka has made valuable suggestions and inputs while writing the research articles to enhance the acceptability of solar powered LED lighting and energy security which are now parts of this book.

We believe that the application of energy efficient lighting devices with solar home systems will experience significant growth in the years to come. We hope that this book will serve as a useful text and reference for academicians, business, and renewable energy engineering communities.

Seoul, June 2011

Ramchandra Pode
Boucar Diouf

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Chapter 1
Why Clean Energy?

1.1 Introduction

Energy plays the most vital role in the economic growth, progress and development, poverty eradication, and security of any nation. Uninterrupted energy supply is a vital issue for all countries today. Future economic growth crucially depends on the long-term availability of energy from sources that are affordable, accessible, and environmentally friendly. Security, climate change, and public health are significantly dependent on the energy as schematically shown in Fig. 1.1. Abundant, cheap, and clean energy are prerequisites for decent human living conditions and a healthy economy. In recent decades, the overwhelming increase in development activities have triggered the increasing demand for energy [1–4], resulting in further contributions to green house gas (GHGs) emissions. The world had already experienced its first and second energy crises due to the oil and gas scarcities in 1973 and 1979, respectively.

The recent International Energy Agency (IEA) World Energy Outlook Report shows that over 20% of the global population or 1.4 billion people lack access to electricity [5, 6]. Nearly 40% of the global population or 2.7 billion people, mostly in rural areas, rely on the traditional use of biomass for cooking. To meet the growth aspirations of billions of off-grid people, the development activities in the energy sector are expected to be accelerated globally. The world energy demand is projected to rise by 50% over the next 20 years, mostly because hundreds of millions of people in China, India, and other developing worlds will be buying cars and living more energy-intensive lives. The future projection of energy needs is displayed in Fig. 1.2. The production of fossil fuels, particularly oil, is going to have trouble keeping up with that demand. And even if we could meet that demand with fossil fuels, we would end up with irreversible climate change. At present, 80% of our energy comes from fossil fuels such as coal, oil, and natural gas and only 2% from wind and solar combined. The world needs to change the kind of energy we use, even as we need more and more of it.

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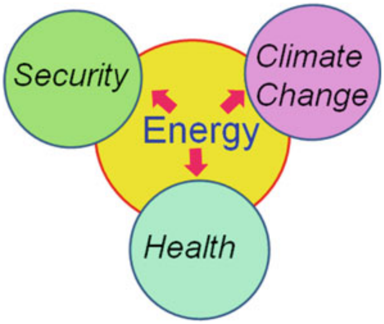


Fig. 1.1 Energy influences security, climate change, and public health

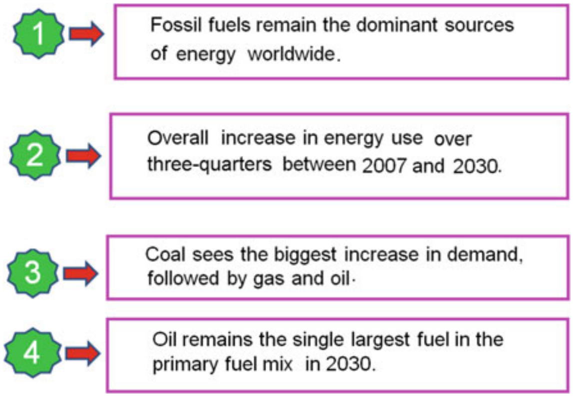


Fig. 1.2 Future projections of requirements of energy fuels

Lack of energy resources could jeopardize not only the economic progress but also the security and strategic interests of several countries. Adequate quantities of economically priced clean, sustainable and green fuels need to be made available to consumers. In a new paradigm, sustainable economic growth and industrial development without endangering the climate are envisaged.

Another concern regarding primary energy sources which has attracted attention of several developing and developed economies is that of energy security with uninterrupted supply of energy fuels. Indeed, this issue is imperative and needs to be addressed more seriously as these fuel sources are concentrated in a few countries. Unfortunately, primary fuel materials required to produce energy are not evenly distributed throughout the world. In fact, some countries in recent days are hopelessly marginalized by the global price volatility, increasingly competitive world demand, and associated geopolitical hazards. Faced with serious concern to energy security, competition for acquiring the overseas energy resources by developing and developed economies has significantly intensified in the recent years. Furthermore, environment pollution is influencing our health in many ways. Air pollution borne diseases include, (1) respiratory diseases, (2) gastric problems, (3) skin problems, (4) eye problems, (5) cardiac problems, and (6) others. Several poor countries do not have a robust health care system, like developed countries, and the majority of off-grid rural habitants are suffering from the air pollution borne diseases. An unhealthy workforce seriously affects the country's economic growth.

Consequently, energy, economics, environmental and climate change, and health care are intertwined issues. For a sustainable future economic progress and industrial growth, these issues must be addressed collectively. Furthermore, to avoid the next energy crisis and address the environment issue, existing windows of opportunities such as energy efficient technology and new and renewable technology need to be explored.

In this chapter, conventional energy sources, its impacts on health, environment and climate change and security, diversification of energy mix, and the feasibility of interchangeability of mix of energy sources, use of alternative fuels and estimation of CO_2 emission, and conclusions are discussed.

1.2 Present Scenario of Energy Mix

World Energy Outlook, IEA has projected that the world primary energy demand is increasing by 1.5% per year between 2007 and 2030, from just over 12,000 to 16,800 million tonnes of oil equivalent (Mtoe) with an overall rise of 40% [7]. Figure 1.3 shows the world energy mix in 2008 [8] and 2030 [9] in the Reference Scenario based on current policies. Assuming similar rates of consumption and the economic conditions in the future, World Oil indicates that oil reserves in the world would be depleted more or less in 43 years, coal in 417 years, and natural gas in 167 years [10]. The total *energy mix* size is projected to increase from 11,294.9 Mtoe in 2008 to 17,014 Mtoe in 2030 in the Reference Scenario with the current policies as estimated by the IEA [5]. Fossil fuels such as coal, oil, and natural gas remain the dominant sources of primary energy worldwide, accounting for the 50% overall increase in energy use between 2008 and 2030. In absolute terms, coal sees the biggest increase in demand over the projection period, followed by gas and oil. Although oil remains the single largest fuel in the primary fuel mix in 2030, its share will drop from 34% now to 30%. The energy mix of some industrialized and developing countries are listed in Table 1.1 [8, 11, 12]. Four developed countries namely Iceland, Norway, Sweden, and Finland have renewables contribution of 73, 60, 26, and 23% in the total energy mix, respectively. Whereas, France, Sweden, Switzerland, and Belgium have 40, 37, 24, and 22% of nuclear energy share in their energy mix, respectively. Interestingly, the energy mix of Iceland has the highest fraction of renewables (72.6%) of any country and that of only 27.4% of fossil fuel contribution. On the other extreme, the performance of the United States of America (USA) on the energy mix portfolio is not encouraging as it is strongly dependent on the fossil fuel (86%) as regard to 8 and 6% of nuclear and renewable energies, respectively. Also noteworthy are Australia (97%), Ireland (97%), and Indonesia (97.8%); their

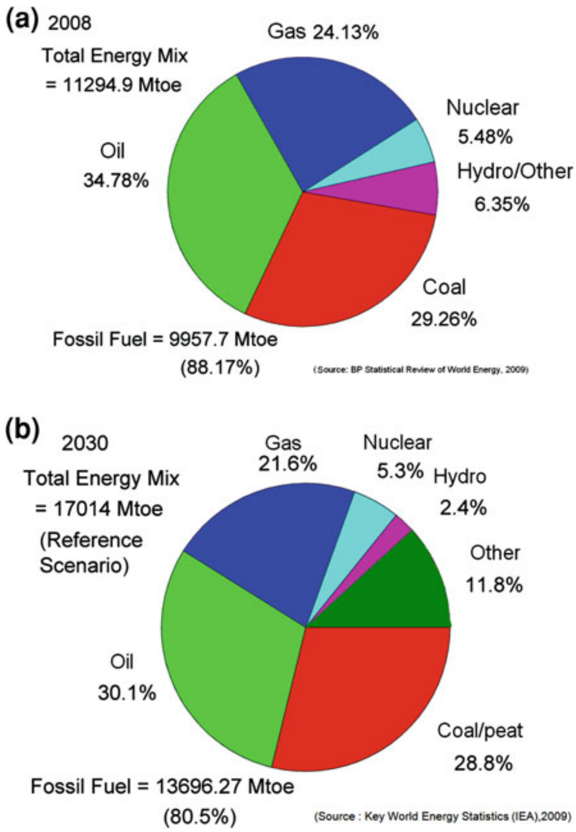


Fig. 1.3 **a** World energy mix in 2008, **b** in 2030 in the Reference Scenario based on current policies

economies are almost entirely reliant on fossil fuels. These results demonstrate that the interchangeability of the mix of energy sources model is practically feasible.

Global oil concentrations are shown in Fig. 1.4 [13] and Table 1.2 [8]. Around 60% of the world's proved oil reserves in 2008 were located in Middle East countries, while 57% of the world's proved gas reserves in 2008 were found in just three countries Russia, Iran, and Qatar as displayed in Fig. 1.5 and Table 1.2. While, the world's proved coal reserves are more evenly located around the globe, except the Middle East and South American Countries as listed in Table 1.2. Middle East and African countries are rich in energy resources which are sufficient to meet the current levels of the world energy demand. As a consequence, many developed and developing economies are investing in Latin American, African and Asian countries to secure energy resources. Indeed, the recent political interest of several countries in Africa illustrates their energy security concerns. Political instability and disruption of production and distribution chains due to accidents or natural events in key energy producing regions are further adding anxieties to consuming countries. Individual consuming countries continue to face specific energy security issues related to cost, geography, and political relationships with

Table 1.1 Energy mix of some industrialized and developing countries in 2008

Country	Energy mix				Reference
	Fossil (%)	Nuclear (%)	Renew-ables (%)	Other (%)	
Luxembourg	92	0	2	6	[11, 12]
United States	86	8	6	0	[11, 12]
Australia	97	0	3	0	[11, 12]
Canada	67	7	25	0	[11, 12]
Finland	59	16	23	2	[11, 12]
Belgium	75	22	2	1	[11, 12]
Ireland	97	0	2	1	[11, 12]
Netherlands	94	1	3	2	[11, 12]
Germany	84	12	4	0	[11, 12]
Denmark	85	0	14	1	[11, 12]
Japan	83	12	5	0	[11, 12]
Norway	37	0	60	0	[11, 12]
Austria	77	0	21	2	[11, 12]
United Kingdom	89	9	2	0	[11, 12]
Italy	90	0	7	3	[11, 12]
New Zealand	71	0	29	0	[11, 12]
Iceland	28	0	73	0	[11, 12]
France	52	40	6	2	[11, 12]
Bulgaria	71	22	5	2	[11, 12]
Portugal	83	0	15	2	[11, 12]
Sweden	37	37	26	0	[11, 12]
Switzerland	63	24	13	0	[11, 12]
Brazil	62.45	1.36	–	36.08 (hydro)	[8]
China	92.6	0.77	–	6.61 (hydro)	[8]
India	92.82	0.80	–	6.06 (hydro)	[8]
Indonesia	97.80	–	–	2.16 (hydro)	[8]
South Korea	85.32	14.22	–	0.37 (hydro)	[8]
World mean	**87**	**6**	**6**	**1**	–

producers. Diversifying oil and gas supply sources may be one strategic approach to enhance energy security for many counties, but does not address the climate change issue.

1.3 Climate Change

Energy use and supply is of fundamental importance to society and, with the possible exception of agriculture and forestry, has made the greatest impact on the environment of any human activity–a result of the large-scale and pervasive nature of energy-related activities. Although energy and environment concerns were originally local in character–for example, problems associated with extraction, transport, or noxious emissions–they have now widened to cover regional and global issues. The primary environmental impact of electricity consumption is the

Fig. 1.4 Global oil concentration

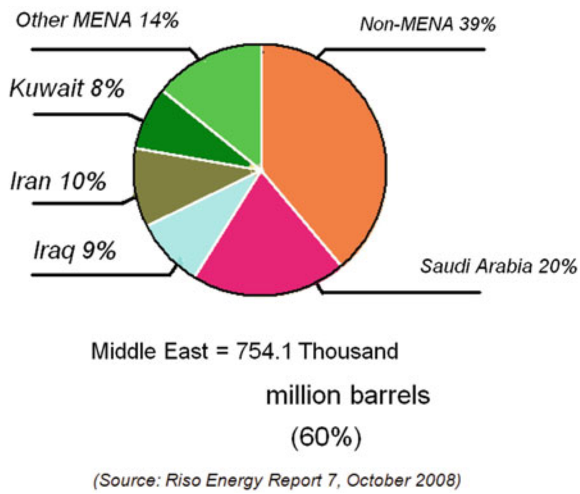
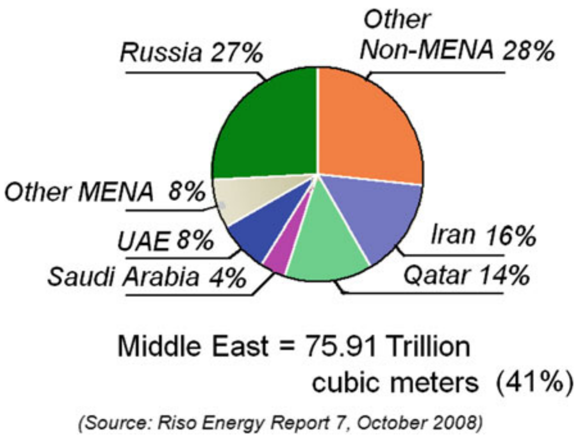


Table 1.2 Proved global oil, natural gas, and coal (including anthracite and bituminous coal) at the end of 2008

Region	Oil (Thousand million barrels)	Natural Gas (Trillion cubic meters)	Coal (Thousand million tonnes)
Asia Pacific	42.0	15.39	155.8
North America	70.9	8.87	246.1
South and Central America	123.2	7.31	15.0
Africa	125.6	14.65	320
Europe and Eurasia	142.2	62.89	272.2
Middle East	754.1	75.91	1.4

Fig. 1.5 World's proved gas reserves in 2008



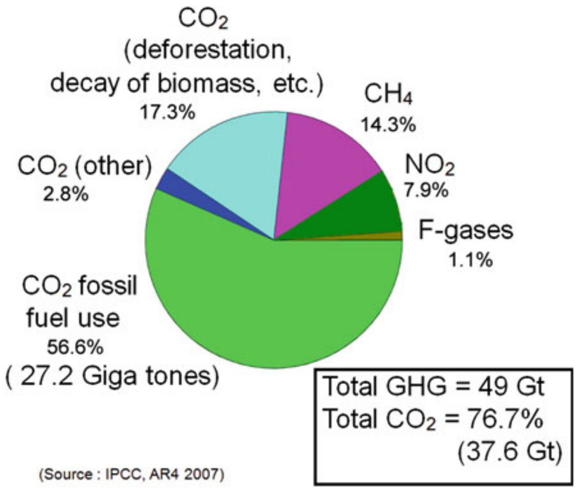


Fig. 1.6 Contribution to anthropogenic GHG emissions due to the various human activities

production of GHGs that contribute to global warming. Such problems have now become major political issues and the subject of international debate and regulation. It is for this reason that there is a need to address energy and environment issues together.

The main driver of demand for fossil fuels is the inexorable growth in the energy needs for power generation. The world net electricity generation increases by an average of 2.4% per year from 2006 to 2030 in the International Energy Outlook (IEO) 2009 reference case, a net increase by 77% [14]. Non-OECD countries are expected to contribute nearly 90% of the total world energy demand growth [14]. Population growth and mass industrialization in emerging economies are two main factors driving these figures [15]. Fossil fuels are expected to provide the bulk of primary energy in 2030 mainly due to the continued reliance on the existing coal-fired plants. Coal continues to provide a secure energy source for many consuming countries although there is a major concern about GHGs emissions. Figure 1.6 shows the contribution to anthropogenic GHG emissions due to the various human activities [16, 17]. The Use of fossil fuels contributes about 56.6% of all GHG emissions.

The global emissions of carbon dioxide from the three fossil fuels in 2008 are shown in Table 1.3 [18, 19]. Although China's total emission (21.67%) has taken over the US (20.22%), its annual per capita emission of 4.88 tonnes CO_2 is much lower than those of USA, Canada, and Australia at 19.96, 18.82, and 17.72 tonnes, respectively. As seen from the Table 1.3, India's annual per capita CO_2 emission is merely 1.17 tonnes which is much below the World average at 4.51 tonnes. Emissions from the three major developing nations of Brazil, China, and India account for 27.57% of the world total emission in 2008. While other countries designated here as the Rest-of-World account for 22.09% of the emissions. The per capita emission from this part of the world is also low at 2.42 tonnes CO_2 per person.

Table 1.3 Global emissions of CO_2 in 2008 and CO_2 emission per capita (IEA Statistics, CO_2 emissions from fuel consumption, 2010 edition) (Ref. [18, 19])

Country	Total CO_2 emissions (million tonnes)	CO_2 emissions from electricity and heat production (million tonnes)	CO_2 emissions per capita (metric tone/person)	
			2007	2008
Canada	550.9	119.3	17.33	16.53
United States	5,595.9	2,403.4	19.10	18.38
Brazil	364.6	41.2	1.81	1.90
Austria	69.3	15.2	8.36	8.31
Belgium	111.0	23.0	9.97	10.36
Bulgaria	48.8	30.0	6.56	6.40
Denmark	48.4	21.8	9.37	8.82
France	368.2	50.8	5.86	5.74
Finland	56.6	24.3	12.15	10.65
Germany	803.9	337.3	9.74	9.79
Iceland	**2.2**	**0.0**	**7.53**	**6.89**
Ireland	43.8	14.3	10.06	9.85
Italy	430.1	146.9	7.43	7.18
Luxembourg	10.4	1.1	22.35	21.27
Netherlands	177.9	57.2	10.84	10.82
Norway	37.6	0.8	8.08	7.89
Portugal	52	19	5.18	4.94
Russia	1593.8	873.9	11.11	11.24
Sweden	46	8	5.07	4.96
Switzerland	44	2	5.54	5.67
United Kingdom	511	195	8.54	8.32
Bangladesh	46.4	20.1	0.27	0.29
China	6,508.2	3,108.1	4.58	4.91
India	1,427.6	8,03.7	1.19	1.25
Japan	1,151.1	472.2	9.72	9.02
Nepal	3.3	0.0	0.11	0.12
South Korea	501.3	229.6	10.12	10.31
Kenya	8.6	2.3	0.22	0.22
South Africa	337.4	213.3	7.16	6.93
Iran	505.0	124.8	6.80	7.02
Kuwait	69.5	31.8	25.11	25.47
UAE	146.9	72.6	29.91	32.77
Australia	397.5	227	18.30	18.48
Indonesia	385.4	108.5	1.62	1.69
New Zealand	33.3	9.4	7.62	7.74

1.4 Environment and Health

Energy and clean environment are essential for sustainable development. The poor are disproportionately affected by any environmental degradation and lack of access to clean, affordable energy services. Proper environmental management is the key to avoiding the quarter of all preventable illnesses directly caused by environmental factors. The environment influences our health in many ways—through exposures to physical, chemical, and biological risk factors, and through related changes in our behavior in response to those factors. Air pollution borne diseases include respiratory diseases, gastric problems, skin problems, eye problems, cardiac problems, and others [20]. Thirteen million deaths annually are due to preventable environmental causes. Preventing environmental risk could save as many as four million lives a year, of children alone, mostly in developing countries.

Environment sustainability has become the critical issue across the world. Overwhelming evidence shows that human activities are affecting the environment. Environment-linked issues such as water quality, air pollution, and sustainability of agriculture have serious implications on public health. Figure 1.7 shows the impact of the environment on health. An unhealthy workforce is bound to (1) enhance medical expenditure, (2) reduce productivity, and (3) contribute to the lower economic growth of the nation. Catastrophic weather events, variable climates that affect food and water supplies, ecosystem changes are all associated with global warming and pose health risks. Climate and weather exert strong influences on health: increased deaths in heat waves, and in natural disasters such as floods, as well as changing patterns of life-threatening vector-borne diseases such as malaria and other existing and emerging infectious diseases are observed. The poor are the greatest sufferers as they do not and afford to have robust health care system as in the industrialized nations.

The World Health Organization (WHO) estimates that up to 25% of the global burden of disease is due to preventable environmental exposures. Children are especially vulnerable because they receive a higher dose than adults, with more extreme consequences. The unborn child’s health can also be affected because the environment can influence gene expression and organogenesis. The burden of disease is unevenly distributed, with children being the most vulnerable in developing and low-income countries. While children in such countries still have to cope with traditional threats, including lack of access to safe water, poor sanitation and hygiene, and infectious diseases, they suffer from emerging environmental exposures that threaten their health, such as the effects of rapid globalization, an upsurge in urbanization, transboundary chemical transport, and unsustainable consumption.

Table 1.4 shows the per capita power consumption in 2007 and the environment performance index (EPI) in 2009 in some countries [21, 22]. The EPI score was calculated by considering various factors such as environmental burden of disease, water resources for human health, air quality for human health, air quality

Fig. 1.7 Impact of the environment on health

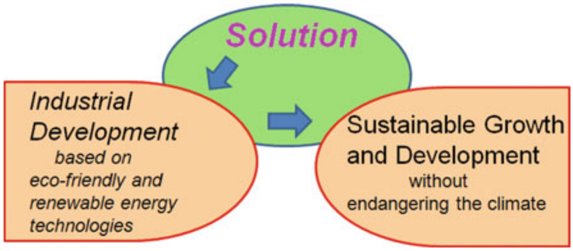


Fig. 1.8 Solution for sustainable development

for ecosystems, water resources for ecosystems, biodiversity and habitat, forestry, fisheries, agriculture, and climate change [22]. Table 1.4 shows that although Iceland's per capita electric power consumption is 36,853, it is ranked at first. As expected, developed countries with sufficient financial resources have better EPI index. However, most of world largest economies have poor EPI index. It seems that the environment performance index is significantly dependent on the *energy mix* to produce electricity. The solution for sustainable development without affecting public health and endangering the environment is to use clean eco-friendly renewable technologies with low-carbon emission, as schematically shown in Fig. 1.8. Failing to protect the environment, would impede not only the economic and industrial growths globally but also pose serious health hazards.

1.5 Renewable Energy

The emission of CO_2 per kWh electricity produced varies greatly among nations and depends on the mix of energy sources used to produce energy. Table 1.5 shows the "CO_2 emission" per kWh of electricity produced in some countries [19]. The lower value indicates that electricity is mainly produced by hydro or nuclear power plants.

Table 1.4 Energy consumption per capita (Ref [21]) and *Environmental performance Index* (*EPI*) (Ref. [22])

Country	Electric power consumption per capita in 2007 (kWh/capita)	EPI	
		Rank	Score
Canada	16,995	46	66.4
United States	13,638	61	63.5
Brazil	2,171	62	63.4
Austria	8,033	8	78.1
Belgium	8,614	88	58.1
Bulgaria	4,456	65	62.5
Denmark	6,670	32	69.2
France	7,772	7	78.2
Finland	17,162	12	74.7
Germany	7,184	17	73.2
Iceland	**36,853**	**1**	**93.5**
Ireland	6,263	44	67.1
Italy	5,713	18	73.1
Luxembourg	16,315	41	67.8
Netherlands	7,097	47	66.4
Norway	24,980	5	81.1
Portugal	4,860	19	73.0
Russia	6,317	69	61.2
Sweden	15,238	4	86.0
Switzerland	8,164	2	89.1
United Kingdom	6,123	14	74.2
Bangladesh	144	139	44.0
China	2,332	121	49.0
India	542	123	48.3
Japan	8,474	20	72.5
Nepal	80	38	68.2
South Korea	8,502	94	57.0
Kenya	151	108	51.4
South Africa	4,944	115	50.8
Iran	2,325	78	60.0
Kuwait	16,198	113	51.1
UAE	16,165	152	40.7
Australia	11,249	51	65.7
Indonesia	566	134	44.6
New Zealand	9,622	15	73.4

Countries with the highest figures rely mainly on coal. The CO_2 emission intensity per kWh of electricity produced, over the entire lifecycle by source is displayed in Fig. 1.9 [23]. The comparative CO_2 gas emission from electricity production from various energy sources in some countries is illustrated in Table 1.6 [24]. Fossil Fuels generate two-thirds of the world electricity, and produce one-third of global CO_2 emissions. Nuclear and renewable intensive

Table 1.5 CO_2 emission per kWh of electricity produced in some countries (Ref. [19])

Country	CO_2 emissions per kWh (kg of CO_2 per kWh)	
	2007	2008
Canada	0.205	0.181
United States	0.549	0.535
Brazil	0.073	0.089
Austria	0.202	0.183
Belgium	0.253	0.249
Bulgaria	0.515	0.489
Denmark	0.317	0.308
France	0.090	0.083
Finland	0.24	0.187
Germany	0.427	0.441
Iceland	0.001	0.001
Ireland	0.504	0.486
Italy	0.388	0.398
Luxembourg	0.328	0.315
Netherlands	0.405	0.392
Norway	0.007	0.005
Portugal	0.383	0.384
Russia	0.323	0.326
Sweden	0.040	0.040
Switzerland	0.023	0.027
United Kingdom	0.500	0.487
Bangladesh	0.567	0.574
China	0.758	0.745
India	0.928	0.968
Japan	0.450	0.436
Nepal	0.004	0.003
South Korea	0.455	0.459
Kenya	0.305	0.329
South Africa	0.845	0.835
Iran	0.536	0.582
Kuwait	0.645	0.614
UAE	0.831	0.842
Australia	0.907	0.833
Indonesia	0.692	0.762
New Zealand	0.272	0.214

energy mix seems to be the most suitable option for low-carbon emission electric power generation. CO_2 mitigation could be one of the options to reduce emission. Various techniques have been employed to suppress CO_2 emissions, as listed in Fig. 1.10.

Diversification of fuel sources is imperative to address energy security, climate change, and sustainable development issues. Furthermore, too much reliance on non-renewable sources to generate power is also unviable in the long run. Thus, it is essential to address energy crisis through the extensive utilization of abundant

Fig. 1.9 CO_2 emissions intensity over the entire life cycle by source

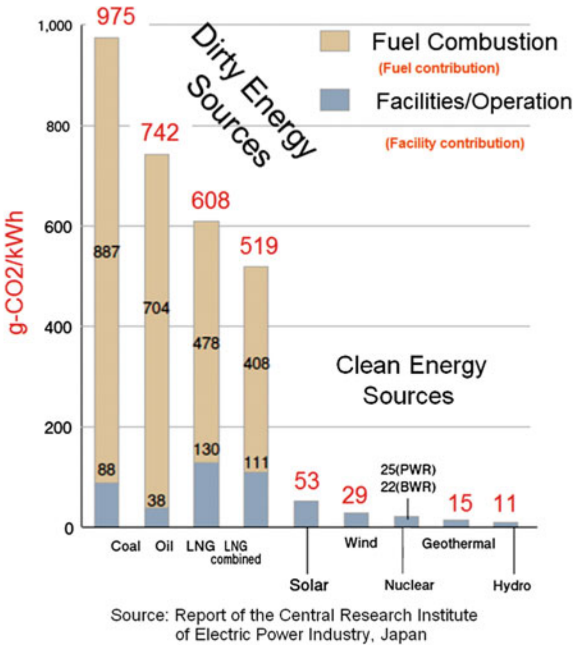


Fig. 1.10 CO_2 emission suppression measures

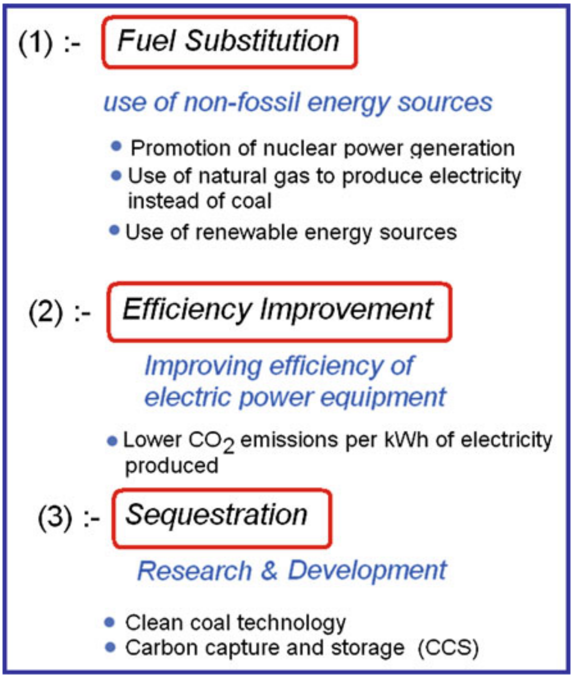


Fig. 1.11 Issues concerning renewable energy resources and technology

Are wind, water and solar energy resources sufficiently available to provide all the world's energy?

Whether efficient at producing usable energy as regards fossil fuels and biomass combustion.

Whether the technology needed to shift the world from fossil fuel to clean, renewable energy already exists.

Whether implementing that technology requires to overcome obstacles in *planning and politics*.

Table 1.6 Comparative CO_2 gas emission from electricity production (Ref. [24])

g/kW h CO_2	Japan	Sweden	Finland	UK: SDC	EU: ExternE
Coal	990	980	894	891	815
Gas thermal	653	1,170[a]	–	–	–
Gas combined cycle	–	450	472	356	362
Solar photovoltaic	59	50	95	–	53
Wind	37	5.5	14	–	6.5
Nuclear	22	6	10–26	16	19.7
Hydro	18	3	–	–	–

[a] peak-load, reserve
Japan: Central Research Institute of the Electric Power Industry, March 1995
Sweden: Vattenfall, 1999, popular account of its own LCA studies in Sweden
Finland: Kivisto, 2000
UK: Sustainable Development Commission report, March 2006
EU: Krewitt et al. 1998, ExternE data for Germany

renewable energy resources, such as biomass, solar, wind, and geothermal energies. Many countries have set ambitious targets for renewable energy. However, it is necessary to address issues concerning renewable energy resources and their use to produce electricity, as illustrated in Fig. 1.11. Are sufficient renewable resources to provide all the world's energy and technology to produce electricity from these resources available? What is required to change the mindset to overcome obstacles in planning and politics? Presently, renewable energy worldwide is still dominated by "old" renewables such as hydropower and traditional biomass that supply 6 and 9% of the global primary energy demand, respectively. Only around 2% of the world's primary energy is currently provided by "new" renewable sources such as wind, photovoltaics, and mini- and micro-hydro.

The sun is the source of all energies on earth. In an ancient civilization like India's, it has been worshiped as a god by all living beings. The sun's direct energy is inexhaustible and constantly renewable. Solar radiation is natural, free, and an abundantly available source of energy; there is no investment in receiving sunlight and no nation has the ability to solely control it. Both poor and rich nations equally receive the solar radiation emitted by the sun. Figure 1.12 shows the availability of solar and wind energies and the worldwide total consumption of energy [25].

1.6 Estimation of CO_2 Emission

For sustainable development without endangering the climate, the future energy mix is envisaged to be (1) Nuclear fuel intensive, (2) Natural Gas intensive, and (3) Renewable sources intensive. Here, the CO_2 emissions due to combustion of these fossil fuels in the energy mix are analyzed using a simple technique [26]. Although the obtained results do not account for the absolute emission figures as they depend on the fuel quality used and the preparation, the resulting trends give confident relative results. The CO_2 emission factors for the combustion of fossil fuels are:

$$\begin{aligned} \text{Oil} &\rightarrow 260\ \text{g}\ CO_2/\text{kW h} \\ \text{Natural Gas} &\rightarrow 195\ \text{g}\ CO_2/\text{kW h} \\ \text{Coal} &\rightarrow 330\ \text{g}\ CO_2/\text{kW h}. \end{aligned}$$

Since one tonne of oil equivalent (toe) is equal to 11,600 kWh, the CO_2 emissions per combustion of toe are:

$$\begin{aligned} \text{Oil} &\rightarrow 3.01\ \text{t}\ CO_2/\text{toe} \\ \text{Natural Gas} &\rightarrow 2.262\ \text{t}\ CO_2/\text{toe} \\ \text{Coal} &\rightarrow 3.828\ \text{t}\ CO_2/\text{toe}. \end{aligned}$$

By altering the energy mix, the CO_2 emission could be substantially mitigated. It may be mentioned here that any reduction of the contribution of fossil fuels to the total energy mix is accompanied by the increase of renewable and nuclear energy shares. The fossil fuel contribution variation of current energy mix (2008) from 97 (in Australia) to 28% (in Iceland) is practically feasible as shown in Table 1.1. Furthermore, the CO_2 emission could be manipulated by altering the contribution of different constituents of fossil fuels. Aggressive implementation of renewables and clean fuels to the energy mix not only reduce the overseas dependency for energy fuels but also help to (1) enhance the energy security, (2) mitigate CO_2 emission, (3) reduce environmental pollution, and (4) reduce health hazards.

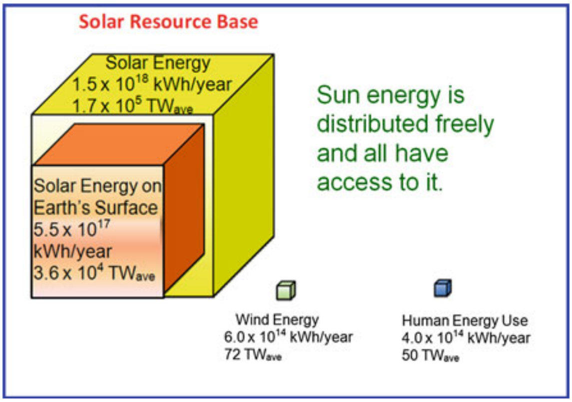


Fig. 1.12 Solar and wind energy potentials and total energy consumption worldwide

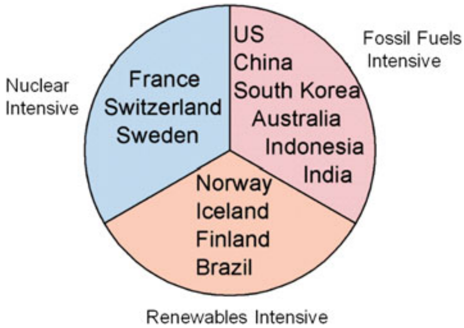


Fig. 1.13 Interchangeability of energy mix model

1.7 Conclusions

The future of human prosperity depends on how successfully two central challenges, namely (1) securing the supply of reliable and affordable energy, and (2) adopting a low-carbon, efficient and environmentally benign system of energy supply, are addressed. To address these concerns, it is essential to shift to energy sources that can substantially reduce CO_2 emissions compared with fossil fuels, rather than concentrating energy-saving efforts on the existing energy portfolio. In this regard, clean energies like renewable would be an important alternative.

Issues such as energy security, use of alternative fuels, and interchangeability of technology are vital to ensure that the mix of energy sources used in the economy is optimal and sustainable and that adequate quantities of economically priced clean and green fuels are made available to the consumers. Most of the technology needed to shift from fossil fuels to clean and renewable energy already exists. Furthermore, interchangeability of energy mix from fossil fuels to renewables is feasible and economical as demonstrated by the current energy mix of several countries (Fig. 1.13). Introduction of renewable portfolio in the future energy mix (1) eliminates combustion as a way to generate power for normal electricity use as well as for vehicles, (2) assures energy security, and (3) enhances the quality of life. If it allows carbon- and air pollution-emitting energy sources to play a substantial role in the future energy mix, environment- and health-related problems will only continue to increase.

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Chapter 2
Solar Photovoltaic Electricity

2.1 Solar Energy

2.1.1 Solar Photovoltaic Electricity

The direct conversion of light into electricity (Fig. 2.1) called photovoltaic (PV) effect was discovered by Antoine Cesar Bequerel in 1839.

The photovoltaic technology really took off with space applications in the 1940s. The terrestrial applications started developing with the oil crisis of the 1970s, launching a real technological boost. Photovoltaic technology is one of the most reliable and efficient off-grid solution to get electricity in remote places. Due to increasing demand and consecutive industrial development, the photovoltaic technology has grown today to maturity and is ready for a number of applications. The challenges remain in getting the cost lower and the efficiency higher, in order to be more competitive when compared with fossil fuels. Other components coming along with solar panels in a photovoltaic system have also shown tremendous development, especially batteries. In order to get the maximum out of a photovoltaic setup it is necessary to select the load as efficient as possible. This is another way of achieving a lower cost of photovoltaic electricity.

The calculation of the cost of a photovoltaic system will not only be "how much to pay up front" but also "how much energy can be converted and for how long?"; the capital investment. Solar cells can be wafer-based or thin-film-based, each technology with its pros and cons. Wafer-based solar cells generally made of silicon are more expensive but offer higher efficiencies. Thin film solar cells on the other hand are cheaper to fabricate but present lower efficiencies. Nevertheless, they present the advantages of being suitable for different other applications as the possibility of making them on flexible substrates.

Photovoltaic electricity is one of the main tools to achieve successful rural electrification in developing countries when the cost of expansion of the grid is

R. Pode and B. Diouf, *Solar Lighting*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-2134-3_2,

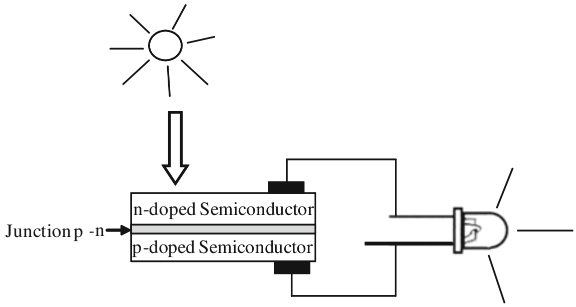


Fig. 2.1 Basic operation of a photovoltaic solar cell

much higher than the available budgets. It is a vector to improve the living and health conditions; it is also a great asset in environment protection by limiting the rejection of greenhouse effect gases.

Among the numerous applications of photovoltaic electricity the most appealing are certainly for low power electrical appliances.

Among those low power appliances, domestic lighting is certainly one of the most demanded. Lighting technology has known an important evolution from the carbon arc to the filament light bulb, the fluorescent tubes to the light-emitting diodes (LEDs) that are top of the line today. LEDs can cover a number of applications that were not covered before; especially because of the geometry and color range they can reach, and their power efficiency and life span which are continuously increasing.

In the following we will present the application of photovoltaic for lighting and the consequences of the choice of technology when sizing a photovoltaic stand-alone system.

2.1.2 The Photon: Energy, Wavelength and Frequency

Light can have a wave or particle behavior and will manifest in one form or the other depending on the experimental situation. In interference experiments light behaves as a wave while in photoelectric experiments light has a particle behavior; a light beam will behave as a bundle of particles.

When light or an electromagnetic radiation in general behaves as a stream of particles, these particles are called photons, while a wave is primarily characterized by its wavelength or frequency and its amplitude. Each photon in a monochromatic radiation will have an energy related to the wavelength or the corresponding frequency (the color) of the radiation. The photon energy is given by the Planck equation

$$E = h\nu = \frac{hc}{\lambda} \tag{2.1}$$

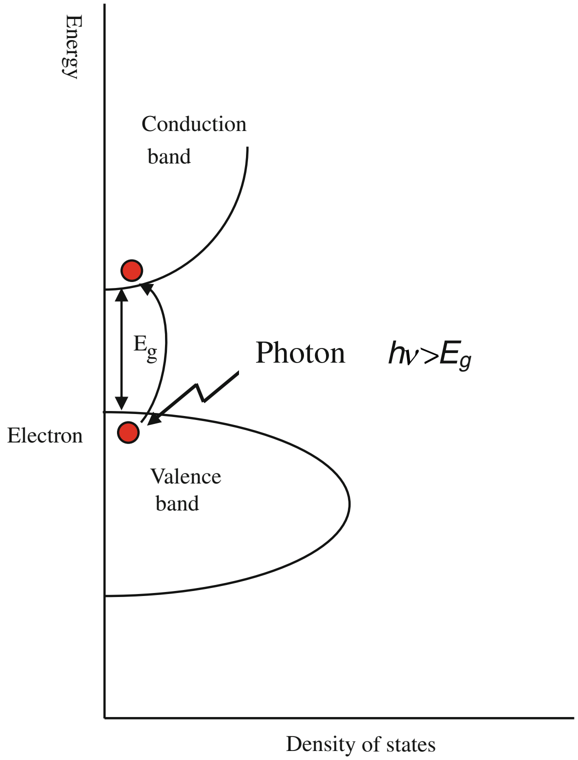


Fig. 2.2 Basic energy band diagram of a semiconductor

where h is a universal constant called Planck's constant:

$h = 6.625 \times 10^{-34}$ J s^{-1}

v is the frequency

λ is the wavelength.

The velocity of light in vacuum, generally symbolized by c, is a universal constant:

$c = 3 \times 10^{8}$ m/s.

Thus, the above equation allows an inter-conversion between the frequency or wavelength and energy of a photon for electromagnetic waves. The Planck equation gives the energy of a single photon when the color of the radiation (wavelength or the corresponding frequency) is known. The Planck equation also informs about light and semiconductors' interaction. By the band gap of a semiconductor one can know the corresponding color of light needed in order to send electrons from the valence band to the conduction band (Fig. 2.2). Table 2.1 shows the band gap of certain semiconductors.

The intensity of a light beam is the number of photons it contains. Thus, for a given wavelength increasing the intensity of the light will not change the energy of the individual photons but will just increase their number.

Table 2.1 Band gap of some semiconductors [1]

Material	Energy gap (eV)	
	0 K	300 K
Si	1.17	1.11
Ge	0.74	0.66
InSb	0.23	0.17
InAs	0.43	0.36
InP	1.42	1.27
GaP	2.32	2.25
GaAs	1.52	1.43
GaSb	0.81	0.68
CdSe	1.84	1.74
CdTe	1.61	1.44
ZnO	3.44	3.2
ZnS	3.91	3.6

The correspondence between energy in (eV) and wavelength expressed in (μm) is given by:

$$\lambda = \frac{1.24}{hv(eV)}(\mu\text{m}) \tag{2.2}$$

2.1.3 Solar Spectrum

The electric power generated by a solar cell is proportional to its area. The irradiance of the sun at the Equator level is about 1 kW/m^2 at 90 degrees, in other words a 1 cm^2 solar cell will receive about 10 mW. This irradiated power by the sun is not equally distributed for the different wavelengths composing the solar spectrum (Fig. 2.3). The solar spectrum shows a maximum intensity at the wavelength $\lambda = 0.5$ μm, this intensity falls to half at $\lambda = 1$ μm.

The absorption spectrum of a semiconductor depends on its band gap. If the band gap is bigger than the energy of the incident photon, there will be no transmission of an electron from the valence to the conduction band. If the energy of the photon is bigger than the band gap an electron will be transferred from the valence to the conduction band and the remaining energy will be released in the form of heat.

The atmosphere attenuates the sun's radiations before they reach the Earth's surface, mainly because of the absorption of infrared by water vapor and the absorption in the ultraviolet by the ozone layer. The air mass is defined as the level at which the atmosphere affects the sunlight received at the Earth's surface. The lower the air mass, the less will be the influence of the atmosphere.

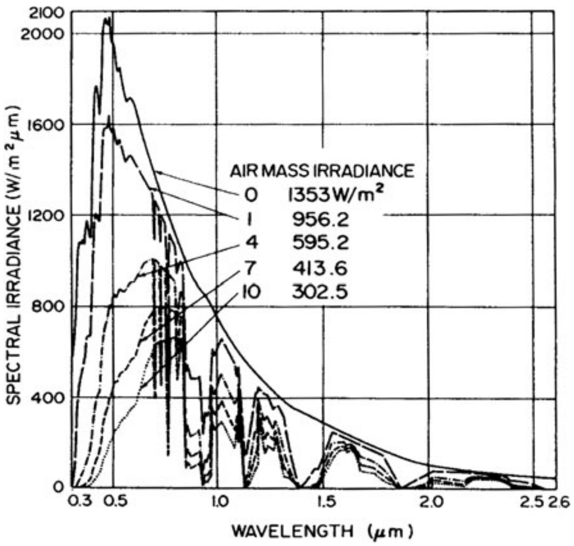


Fig. 2.3 Solar spectrum at different air masses

2.2 The Solar Cell

2.2.1 Structure of an Inorganic Solar Cell

A solar cell is generally made of thin film or a semiconductor wafer. Thin film solar cells can be made of organic or inorganic materials. Inorganic solar cells are made of a p-n junction; the most widely used inorganic solar cells are made of silicon. The silicon wafer is doped p- on the bottom side and n- on the top layer, the two regions forming an interface to make a p-n junction. At the junction level electrons will naturally migrate from the n-layer where their concentration is higher to the p-side, and the opposite for the holes, till the interfacial equilibrium is reached (*diffusion current*) leading to the creation of a zone free of charges called the depletion layer. It will result in a built-in electric field at the junction level, oriented from the n- to the p- side. The built-in electric field is the consequence of accumulation of charges of different signs at the two sides of the junction (Fig. 2.4). The top of the solar cell (n) is of low potential and the bottom (p) of high potential when the cell is exposed to light. The n-layer is made thin enough to let light penetrate to the junction level where it will be absorbed in the form of a photon whose energy will split into an electron and a hole (*that was original bounded in a pair*). In other words by absorption of a photon an electron will be transferred from the valence to the conduction band. This can occur only when the energy of the incident photon is greater than the band gap energy that characterizes the semiconductors of which the cells are made as presented in (Fig. 2.2). The built-in electric field will accelerate the two charges of opposite signs in opposite directions (Fig. 2.4), the electron is negatively charged and the hole positively

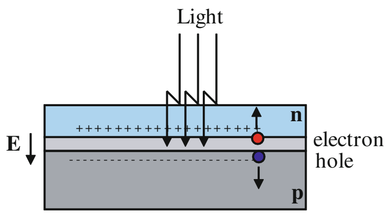


Fig. 2.4 Basic solar cell structure and effect of light

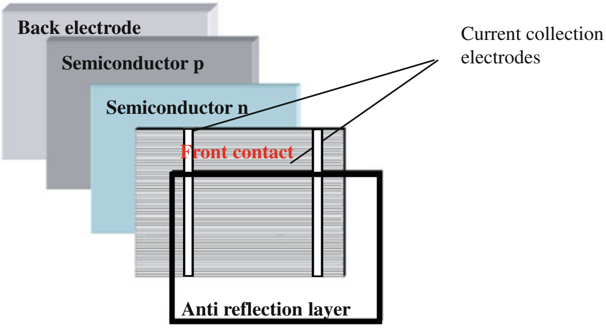


Fig. 2.5 Basic structure of a photovoltaic solar cell

charged. This is how an electric current is generated under illumination. Higher the number of photons that reaches the p-n junction, the more electron-hole pairs will be generated resulting in higher photocurrent. Also larger the exposed surface area, the more electron-hole pairs will be created, hence more important will be the electric current.

It is correct to say that, the amplitude of the electric current generated by absorption of photons in a solar cell of a given size at a given temperature is controlled by the incident light in two main ways:

- The intensity of the incident light (number of photons).
- The wavelength of the incident light (energy of individual photons or color of the light) in correspondence with the semiconductor band gap.

In practice, a solar cell will have the wafer with the p-n junction between front and back ohmic contacts to collect the current and a front anti-reflection coating to limit the losses due to reflection of light. The front contact to collect the current being metallic will be reflective. Thus it is necessary to find a good compromise in their design in order to minimize their light reflection. They are made of electrodes designed in fine lines generally called stripes and fingers. The complete structure of a wafer-based solar cell is presented in Figs. 2.5 and 2.6 presents readymade monocrystalline and polycrystalline silicon wafer-based solar cells.

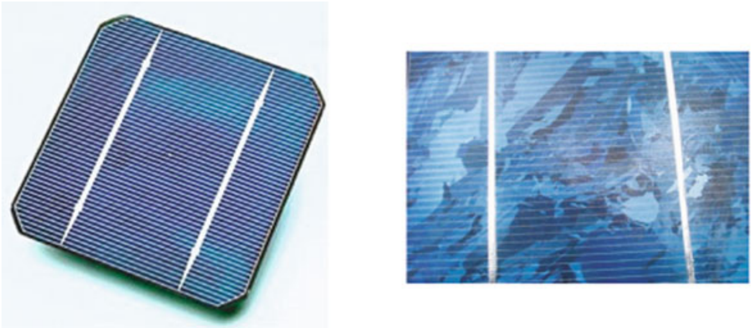


Fig. 2.6 Examples of silicon-based photovoltaic solar cells

The current measured when no load is connected to the cell is called the short circuit current. It is a characteristic of a solar cell with a perpendicular solar irradiation of 1,000 W/m^2 at a temperature of 25°C. The open circuit voltage of a solar cell is the voltage measured when there is no load connected to the solar cell. It is not very sensitive to the solar irradiance variation and reaches its maximum value even under low-light conditions. The open circuit voltage depends on the material the solar cell is made of. For silicon, the open circuit voltage is about 0.55 V.

2.2.2 Characteristics of Photovoltaic Solar Cell

Around the world, academic laboratories as well as industries are working with the objective of producing lower cost, higher conversion efficiency solar cells and finding new applications. Solar cells can be made in different forms with their pros and cons.

The semiconductors used in the fabrication of solar cells have different band gaps that give them different spectral responses to incident light. They display sensitivity according to the wavelengths of the absorbed photons. Each semiconductor has threshold energy, the band gap energy, above which absorption of photons will make electrons transit from the valence band to the conduction band (Fig. 2.2). Below that energy no photovoltaic effect will occur. The photovoltaic effect is not related to the light intensity but to its color (wavelength). Increasing light intensity will only proportionally increase the rate of photoelectron emission in the photovoltaic structure. In actual applications, the light absorbed by a solar cell is a combination of direct solar radiation, as well as diffused light bounced off of surrounding surfaces. A solar cell is coated with anti-reflective material to limit the light reflection at its surface and absorb the maximum amount of radiation possible (Fig. 2.5).

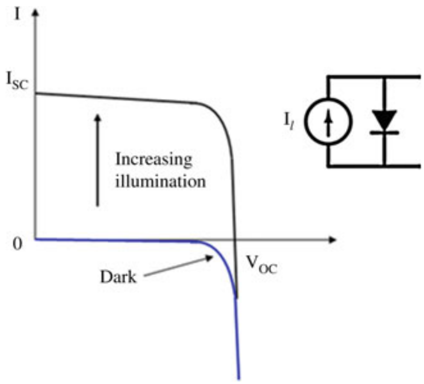


Fig. 2.7 I–V Curve of a solar cell and the equivalent electrical circuit

Photovoltaic cells can be arranged in a series configuration to form a module. The modules can then be connected in parallel or series configurations to form arrays. When connecting cells or modules in series, they must have the same current rating to produce an additive voltage output, and similarly, modules must have the same voltage rating when connected in parallel to produce larger currents.

2.2.3 Theoretical Current–Voltage Characteristic of Photovoltaic Solar Cell

A photovoltaic solar cell is modeled as a current source in parallel with a diode (Fig. 2.7). In the dark the current source appears switched off, so that the cell behaves as a simple diode. Under illumination, as the intensity of the incident light increases, an electric current is gradually generated by the cell as presented Figs. 2.7 and 2.8.

The total current I of an ideal cell is equal to the current photocurrent I_ℓ subtracted with the current flowing in the diode:

$$I = I_\mathrm{l} - I_0\left[e^{\frac{qV}{kT}} - 1\right] \tag{2.4}$$

where I_0 is the saturation current of the diode, q is the elementary electric charge 1.6×10^{-19} C, k is the Boltzmann constant, 1.38×10^{-23} J/K, T is the cell temperature in Kelvin and V is the solar cell's voltage.

It can be proven from the above equation that:

$$I_\mathrm{SC} = I_\mathrm{l} - I_0\left(\exp\frac{q(V + IR_\mathrm{S})}{nkT} - 1\right) - \frac{V + IR_\mathrm{S}}{R_\mathrm{SH}} \tag{2.5}$$

where n is the diode ideality factor (typically between 1 and 2), and R_S and R_SH represent the series and shunt resistances (Fig. 2.9).

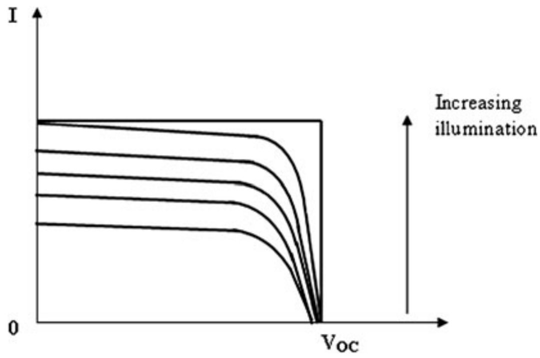


Fig. 2.8 I–V curves of a solar cell under increasing illumination, the square type shape represents the ideal behavior of the solar cell

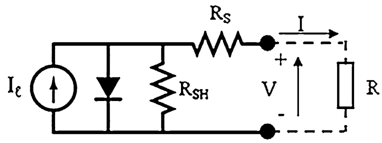


Fig. 2.9 Simplified equivalent circuit for a solar cell

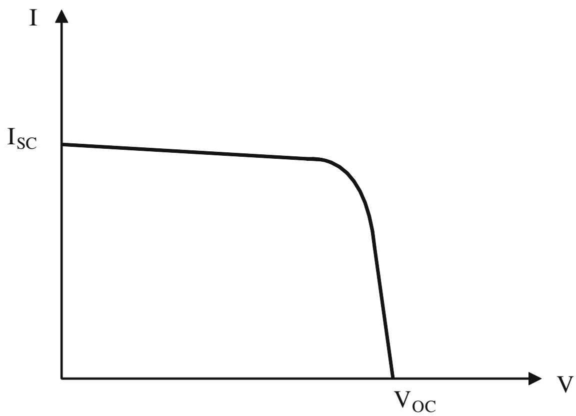


Fig. 2.10 Typical I–V curve of an illuminated solar cell

While operating, the efficiency of solar cells is reduced by the dissipation of power across internal resistances. These parasitic resistances are modeled as a parallel shunt resistance (R_{SH}) and series resistance (R_S).

The typical I–V curve of an illuminated solar cell has the shape shown in the Fig. 2.10 below. These curves can be obtained by two methods:

- The parameter analyzer method that uses a Measurement Source Unit (SMU), which is mostly used in laboratories. This method applies a voltage and measures the resulting current, as in the characterization of diodes or transistors. Laboratories use sun simulators also in the characterization of photovoltaic cells.

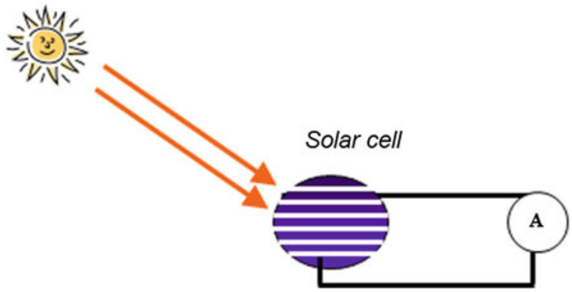


Fig. 2.11 Measurement of the short circuit current of a solar cell

- The variable load method, which is more affordable and portable, measures the current and voltage across a resistive load. Gradually changing the value of the resistance from open circuit to short circuit gives directly the power characterization of the solar cell.

2.2.4 Short Circuit Current

The short circuit current I_{SC} of a solar cell corresponds to the current measured when the solar cell is short circuited (Fig. 2.11), the voltage equals 0. Under illumination, the electric current flows from the bottom (+) of the cell to the top of the cell (−).

$$\mathrm{I}\ (\text{at } V = 0) = I_{SC} \tag{2.6}$$

I_{SC} is the maximum current value in the I–V curve of a solar cell under illumination. The larger the surface area of the cell, the greater will be the I_{SC}.

2.2.5 Open Circuit Voltage

The open circuit voltage (V_{OC}) of a solar cell is the voltage measured when there is no current passing through the cell as presented in Fig. 2.12. The top side of the solar cell is of negative voltage and the bottom is positive. V_{OC} is independent of the size of the solar cell, and is determined by the materials the cell is made of.

$$V(\text{at } I = 0) = V_{OC} \tag{2.7}$$

V_{OC} is also the maximum voltage possible across the cell in the I–V curve under illumination.

$V_{OC} = V_{MAX}$ for power quadrant

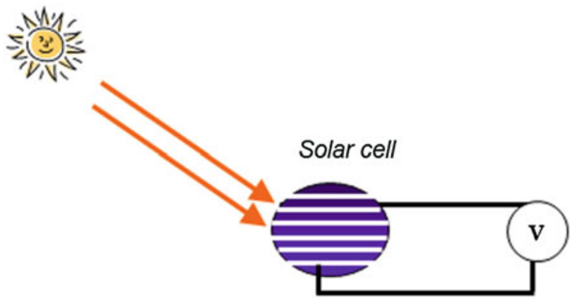


Fig. 2.12 Measurement of the open circuit voltage of a solar cell

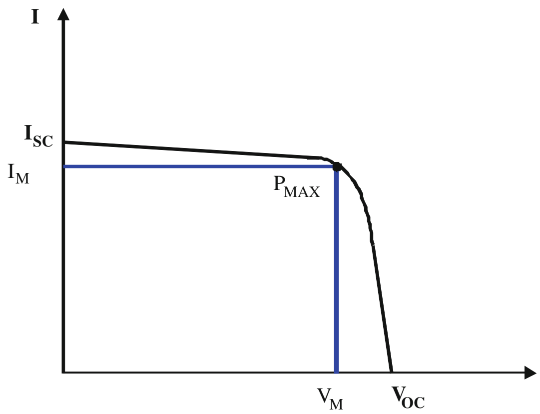


Fig. 2.13 Maximum power for an I–V sweep

2.2.6 Maximum Power

The electric power P produced by the cell in watts can be easily calculated along the I–V curve by the equation $P = \text{IV}$. At the I_{SC} ($V = 0$) and V_{OC} ($I = 0$), the power is zero. The maximum power, P_{MAX},will occur between these two points. The voltage and current at the maximum power point are denoted as V_M and I_M, respectively (Fig. 2.13).

2.2.7 Fill Factor

The Fill Factor (FF) is a measure of the quality of the solar cell. It is evaluated by comparison with the maximum actual power output, P_{MAX}, and with the theoretical maximum power output, $P_{Theorriical}$, which would be obtained if simultaneously the voltage was equal to the open circuit voltage and the current was equal to the short circuit current. The graphical evaluation of the FF is given by the ratio of the two rectangles in Fig. 2.14. The larger the FF; the better the quality of the solar cell.

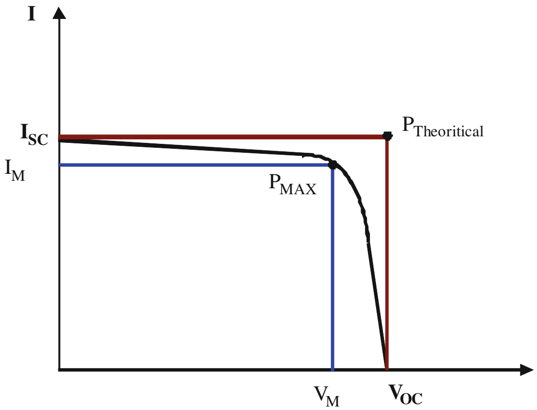


Fig. 2.14 Graphic evaluation of FF

$$\mathrm{FF} = \frac{P_{\mathrm{MAX}}}{P_{\mathrm{Theoritical}}} = \frac{I_{\mathrm{M}} V_{\mathrm{M}}}{I_{\mathrm{SC}} \cdot V_{\mathrm{OC}}} \tag{2.8}$$

A larger fill factor is desirable and corresponds to an I–V curve that is more square-like. Typical fill factors range from 0.50 to 0.9. Fill factor is also often represented as a percentage.

2.2.8 Efficiency of Photovoltaic Solar Cell

The efficiency of a photovoltaic solar cell is the ratio of the electrical power output P_{out}, compared to the solar optical power input (irradiance × surface area of the cell), P_{in}. P_{out} can be taken to be P_{MAX} since the solar cell can be operated up to its maximum power output; this gives the efficiency of the solar cell as:

$$\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \tag{2.9}$$

$$\eta_{\max} = \frac{P_{\mathrm{MAX}}}{P_{\mathrm{in}}} = \frac{\mathrm{FF} \cdot V_{\mathrm{OC}} \cdot I_{\mathrm{SC}}}{P_{\mathrm{in}}} \tag{2.10}$$

P_{in} is taken as the product of the irradiance of the incident light and the surface area of the solar cell, measured in W/m^2 or in suns (1,000 W/m^2). The efficiency of a solar cell, as its current and voltage, can be affected by ambient conditions, particularly the temperature, the intensity and the spectrum of the incident radiation as in the space applications. The efficiency of a solar cell should always be mentioned along with the test conditions.

2.2.9 Shunt Resistance (R_{SH}) and Series Resistance (R_S)

The efficiency of solar cells is reduced by the dissipation of power through internal resistances. These parasitic resistances can be modeled as a shunt resistance (R_{SH}) and a series resistance (R_S), as represented in Fig. 2.9. The shunt resistance is due to fabrication defects, the photogenerated current will find alternative paths rather than flowing through the cell's junction. An estimated value of R_{SH} can be determined from the I–V curve as detailed below. The shunt resistance will lower the open circuit voltage without changing the short circuit current.

The series resistance of a solar cell originates mostly from the contact between the metal connections, especially the front contact, and the semiconductor or the current in the emitter. The high-series resistance will reduce the short circuit current without affecting the open circuit voltage.

To model an ideal cell, the resistance in parallel with the current source, R_{SH}, would be infinite and would not provide an alternate path for current to flow, while R_S, the resistance in series with the current source, would be zero, resulting in no further voltage drop before the load.

Decreasing R_{SH} and increasing R_s will decrease the fill factor (FF) and P_{MAX}. If R_{SH} is decreased too much, V_{OC} will drop, while increasing R_S excessively can cause I_{SC} to drop instead (Fig. 2.15).

It is possible to approximate the series and shunt resistances, R_S and R_{SH}, from the slopes of the I–V curve at V_{OC} and I_{SC}, respectively. The resistance at V_{OC}, however, is at best proportional to the series resistance but is larger than the series resistance. R_{SH} is represented by the slope at I_{SC}. Typically, the resistances at I_{SC} and at V_{OC} will be measured and noted.

If incident light is prevented from reaching the solar cell, the I–V curve in dark can be obtained. It is important to note, however, that for real cells, these resistances are often a function of the light level, and can differ in value between the light and dark tests.

It is possible to approximate the series and shunt resistances, R_S and R_{SH}, from the slopes of the I–V curve at V_{OC} and I_{SC}, respectively.

In fact, Eq. (2.5) of the I–V curves of the solar cell:

$$I_{SC} = I_l - I_0\left(\exp\frac{q(V + IR_S)}{nkT} - 1\right) - \frac{V + IR_S}{R_{SH}}$$

gives for I_{SC} and V_{OC}:

$$I_{SC} = I_l - I_0\left(\exp\frac{qI_{SC}R_S}{nkT} - 1\right) - \frac{I_{SC}}{R_{SH}} \tag{2.11}$$

$$0 = I_l - I_0\left(\exp\frac{V_{OC}}{nkT} - 1\right) - \frac{V_{OC}}{R_{SH}} \tag{2.12}$$

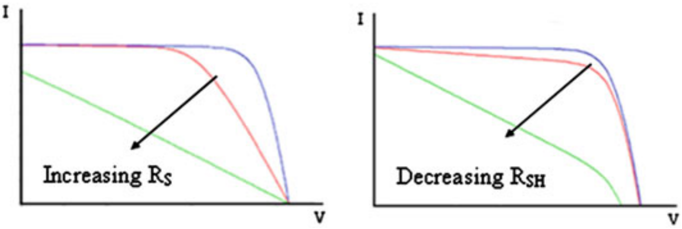


Fig. 2.15 Effect of changes of R_s and R_{SH} from ideality

In the regime where R_S is important, the combination of the above equations will give:

$$I_{SC}R_S = \frac{nkT}{q}\ln\left(\frac{I_0 qV_{OC}/ntT - I_{SC}}{I_0}\right) \tag{2.13}$$

The slop of the line I_{SC} as a function of $\ln(I_0 qV_{OC}/ntT - I_{SC})$ will give R_S. In the same way, in the regime where R_{SH} is important we will obtain:

$$\frac{V_{OC}}{R_{SH}} = I_{SC} - I_0 \exp\left(\frac{qV_{OC}}{nkT}\right) \tag{2.14}$$

The slop of the line V_{OC} as a function of $\left[I_{SC} - I_0 \exp\left(\frac{qV_{OC}}{nkT}\right)\right]$ will determine the value of R_{SH}.

2.2.10 Temperature Effects

Like other semiconductor-based devices, photovoltaic solar cells are sensitive to temperature. When there is a temperature increase, the band gap of the semiconductor decreases. Figure 2.16 describes the effect of increasing temperature on an I–V curve of a solar cell. The open circuit voltage is the parameter most affected by a temperature variation. When a photovoltaic cell is exposed to higher temperatures, the short circuit current, I_{SC}, increases slightly, while V_{OC} decreases more significantly.

Higher temperatures lead to a decrease in the maximum power output P_{MAX} of a solar cell. Since the I–V curve is sensitive to temperature variations, it is necessary to mention the parameters under which the I–V curve of a solar cell was realized.

2.2.11 Thin Film Solar Cells

Thin film solar cells can be made of organic or inorganic semiconductors with a polycrystalline or amorphous structure and deposited on electrically active or

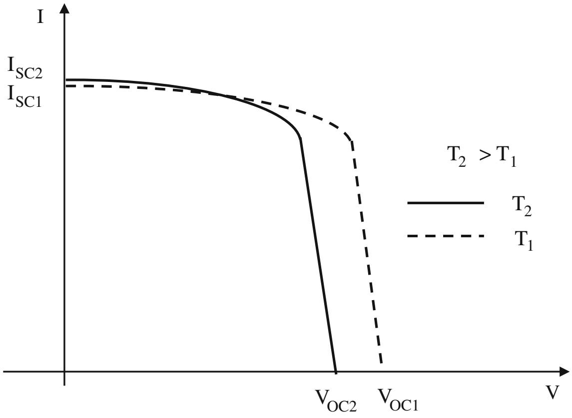


Fig. 2.16 Temperature effect on the I–V curves

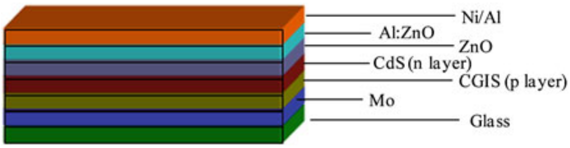


Fig. 2.17 Structure of a CIGS thin-film-based solar cell

passive substrates such as metal, glass or plastic [2, 3]. Thin film solar cell can be fabricated by techniques such as vapor deposition, plasma deposition, and plating or even screen printing. They present the great advantage of being lower cost and can also be made on flexible substrates so that they can cover applications unreachable with wafer-based solar cells. Among the main materials used to make thin-film-based solar cell are: amorphous silicon the most spread out [4, 5], copper indium selenide ($CuInSe_2$ or CIS) or with gallium for higher efficiency ($CuInGaSe_2$ or CIGS), Cadmium Telluride (CdTe) and Cadmium Selenide (CdS). Figure 2.17 represents the structure of a CIGS/CdS based thin film solar cell.

The drawback of film solar cells is their lower efficiency, generally under 10%, for inorganic thin films and about 5% for organic solar cells. They can also present problems of long-term instability that will affect even more their efficiency [6].

Figure 2.18 presents a rollable solar panel made of thin film on a flexible substrate. Table 2.2 illustrates the comparison between wafer- and thin-film-based solar cells.

2.2.12 Organic Solar Cells

Organic solar cells are made of thin films of carbon-based materials, called organic materials with a thickness in the range of 10–100 nm, these materials can show a p- or n-type semiconductor behavior [7–9]. They can be made of polymers or small molecules. Polymer solar cells [10] can be fabricated by techniques of spin

Fig. 2.18 Example of rollable thin film solar panel

Table 2.2 Comparison of wafer- and thin-film-based solar cells

	Wafer-based solar cell	
	Mono-crystalline Si	Polycrystalline Si
Pros	High efficiency	Good ratio efficiency/cost
Cons	Increasing cost of raw material	

	Thni- film-based solar cell			
	Amorphous Si (Si:H)	CIGS/CdS CIS/CdS	CdTe/CdS	Organic semiconductors (PPV/C_{60}) …
Pros	Low cost	Low cost		Low cost
Cons	Low efficiency	Low efficiency		Low efficiency

coating or ink-jet printing from a solution, while small-molecule solar cells are generally made by vacuum evaporation. There is a third type classified among organic solar cells based on titanium dioxide called dye-sensitized solar cells or after the name of their inventor: Grätzel cells [11, 12]. Organic solar cells can be fabricated on various substrates including flexible substrates such as plastics, giving them numerous fields of applications.

Organic solar cells were initially homo-junction, but they had very low efficiency, a fraction of a percent. Then in the mid 1980s hetero-junction solar cells were introduced [9], based on small molecules, which allowed reaching 1% of efficiency. The active part of these solar cells is a bilayer with an electron donor layer, as PPV or CuPc, where the light is absorbed and the electrons are generated before being transferred to the acceptor layer. Fullerene called C_{60} and derivates are of the most used electron acceptors. Bulk hetero-junction solar cells were also made, generally based on polymers.

In both cases, the active part of the solar cell, a homo- or a hetero-junction is sandwiched between two conductive electrodes with different work functions.

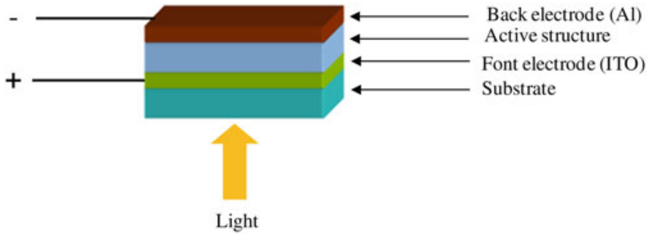
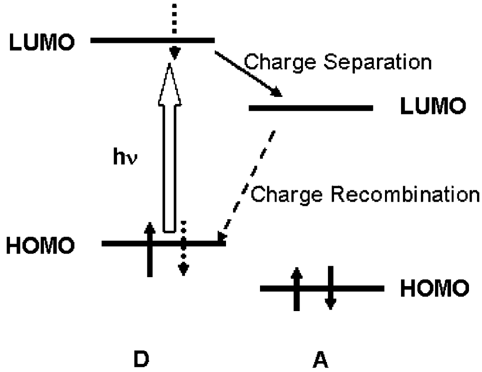


Fig. 2.19 Basic structure of an organic solar cell

Fig. 2.20 Principle of bilayer organic solar cells



A transparent front electrode to let the light in, generally ITO is used, and a metallic electrode as a back contact, generally Al, that plays also a role of reflector for the light that would have been transmitted through the device otherwise. Figure 2.19 represents the basic structure of an organic solar cell.

The efficiency of organic solar cells was improved by adding adjacent materials to the photoactive part, such as an electron transport layer and a hole transport layer in order to transmit more efficiently the photo-generated carriers to the electrodes.

The capacity of organic semiconductor to transport electric current is due to the sp^2 hybridization of carbon atoms. The p_z orbital of each sp^2 hybridized carbon atom will form π bounds with neighbors' p_z electrons of sp^2 hybridized carbon atoms. This overlap of p_z orbitals will allow electrons' neighbor to neighbor conduction.

The description of electric conduction in organic materials is different from that of inorganic semiconductors. In organic materials the concept of valence and conduction band is replaced with that of Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO). But as in the inorganic semiconductors, there is an energy gap between the HOMO and the LUMO. If a photon of sufficient energy is absorbed, an electron will transfer from a HOMO to a LUMO level, leaving a hole in the HOMO (Fig. 2.20).

This pair of charges called excitons, will be part of the electric current if they are effectively uncoupled and arrive at the electrodes, the hole at the anode (ITO generally) and the electron at the cathode (Al generally).

The fundamental difference in the principles of operation between organic and inorganic solar cells lies in the separation of carriers of the absorption of a photon. In inorganic solar cells, for wafer- or thin-film-based cells, there is a p-n junction with a built-in electric field that will split the electron and the hole and accelerate them in the opposite direction. In the case of organic solar cells, there is no built-in electric field to separate the generated pair of electron and hole. The exciton (pair electron–hole) needs to diffuse before arriving at the interface in the case of hetero-junction solar cells. This requires a certain energy compromise between the two materials and efficient charge separation occurs.

The solar cell is designed such that the light is absorbed in the organic material called the donor. An exciton (electron–hole pair) will be generated, transferring an electron from the HOMO to the LUMO level, in order to be separated at the interface and have an efficient transfer of the electron from the donor to the adjacent organic material called the acceptor, the acceptor should have a LUMO lower than the LUMO of the donor, so that the electron transfer will be energetically favorable. The organic solar cells, still suffer from low efficiency (maximum of about 5%) and long run stability as most thin film solar cells.

2.3 The Solar Panel

2.3.1 From the Solar Cell to the Solar Panel

A photovoltaic solar panel or module is made of similar cells assembled in series or parallel in order to achieve a given voltage or current output. The connected solar cells are then laminated generally with EVA (Ethylene Vinyl Acetate) between glass in the front, to let the light in, and generally a tedlar sheet at the back before being framed with aluminum.

When individual solar cells are chosen identical and connected in series, the resulting solar panel should have the same short circuit current as the individual cells and a voltage equal to the sum of their individual voltages. Nevertheless, the new weatherproof structure will have its efficiency slightly lower than the individual solar cells, partly because of the reflection of light, the connections between the cells and in the long run the aging of the encapsulant, the EVA film will have its transmission coefficient decreasing. Solar panels are generally guaranteed 25 years by manufacturers. The structure of a solar panel and connection of solar cells in series and parallel are shown in Figs. 2.21 and 2.22, respectively. Most of solar panels available on the market are of 6, 12, 24 or 48 V output. To charge a battery the voltage of the charger should be higher than the voltage of the battery to be charged, the electric current flows from high to low potentials.

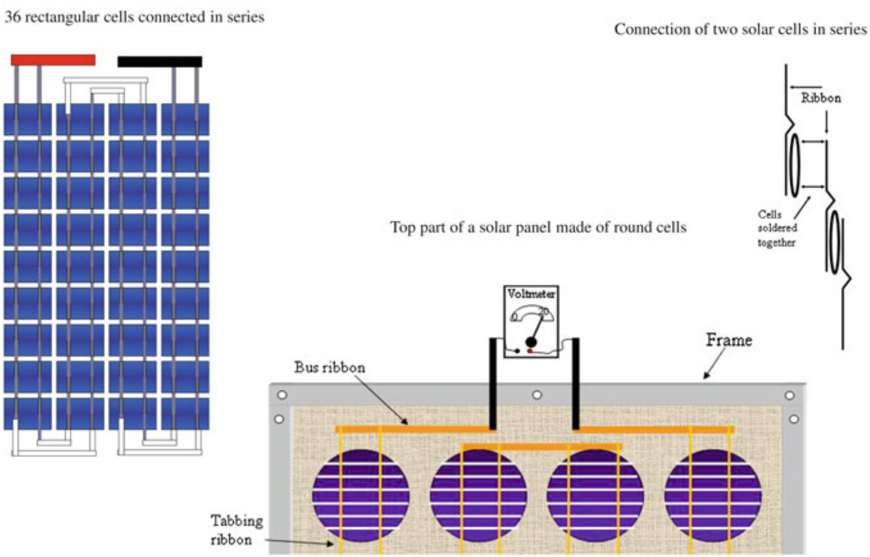


Fig. 2.21 Structure of a solar panel

Most low-power standalone systems are 12 V based. For 12 V applications, a silicon solar panel is made of 36 cells connected in series resulting in an open circuit voltage of about 20 V, considering about 0.5 V (0.5–0.55 V) open circuit voltage for the individual cells, the short circuit current depends on the size of the cells. A "12 V" lead-acid battery fully charged will display a voltage of about 14 V.

The charging current will depend on the power of the solar panel. The maximum charging current of a battery should not exceed the indications of the manufacturer for a good life span.

Solar cells are associated together to make a solar panel, and solar panels are associated together to make a solar array (Fig. 2.23).

Solar panels can be associated in series or in parallel depending on the need. In case they are associated in parallel, each of them should be equipped with a diode to avoid reverse current in any of the solar panels (Fig. 2.24).

2.3.2 *I–V Characteristics of Solar Modules*

Ideally, the current–voltage response of a solar module or array is similar to that of a solar cell. However, it is scaled up and the multiplying factor depends on the number of cells connected in series and in parallel. If (n) identical solar cells are connected in series making a block with I_{SC} and V_{OC} the short circuit current and open circuit voltage of the individual cells, and if (m) of those blocks are connected in parallel, the resulting I–V curve of the new entity as represented in Fig. 2.25, will have a short circuit current of $m \cdot I_{SC}$ and an open circuit voltage of $n.V_{OC}$.

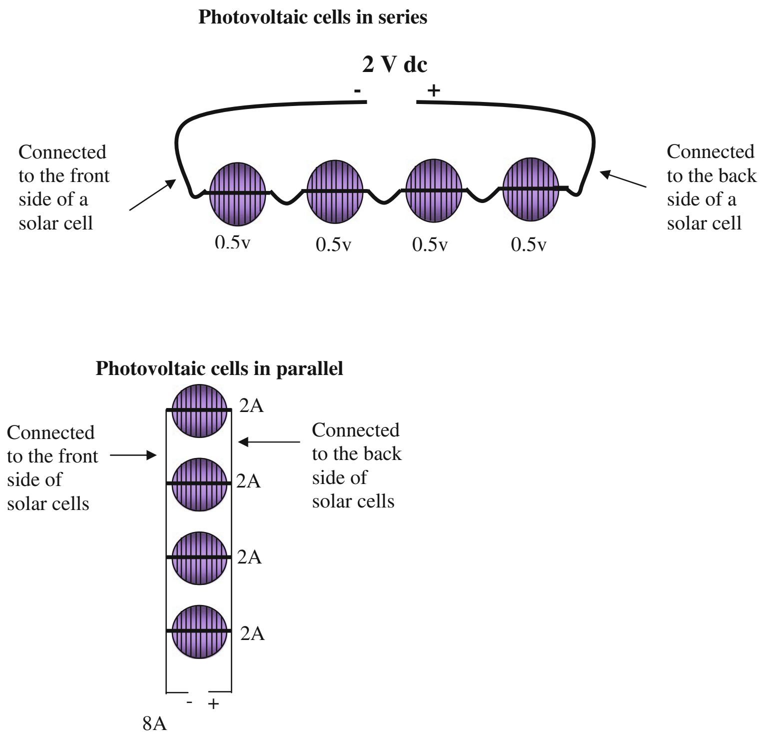


Fig. 2.22 Association of solar cells in series or parallel

2.3.3 Size of Solar Panel

The efficiency of a solar cell and the efficiency of a solar panel are defined for a solar irradiance of 1,000 W/m^2 at 25°C. A solar panel made of 15% efficiency technology (monocrystalline silicon) of 1 m^2 size will be of power $1{,}000 \times 0.15 = 150$ W. This shows that the size and the technology of a solar panel are the first very good indicators about the electric power it can generate. The short circuit current of the panel and the open circuit voltage will determine exactly what applications it can be open to.

2.3.4 Orientation of Solar Panel

A solar panel in order to produce a maximum of electricity needs to be oriented perpendicular to solar rays. At the equator level (latitude zero) the sun's radiations hit the ground perpendicularly, so that a solar panel will be installed flat parallel to

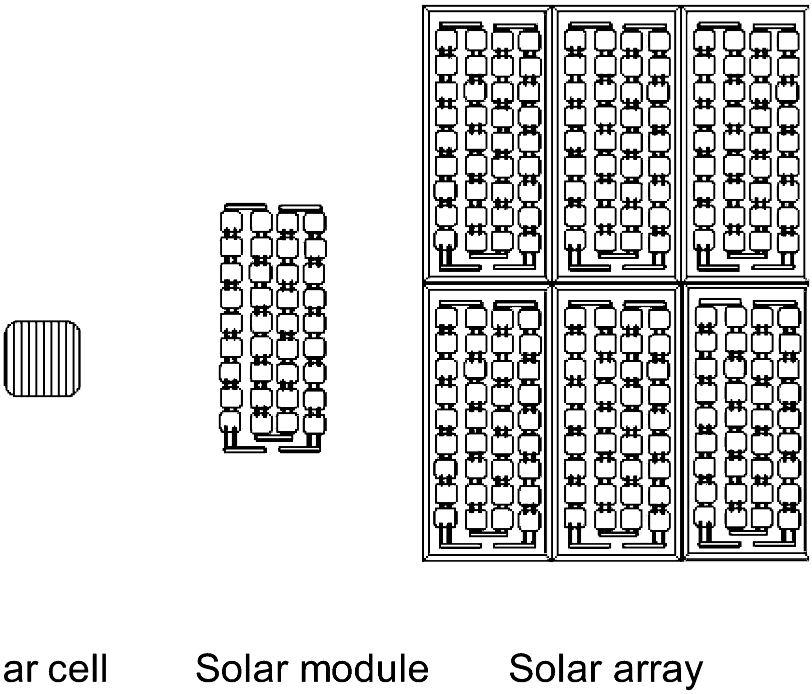


Fig. 2.23 From a solar cell to a solar array

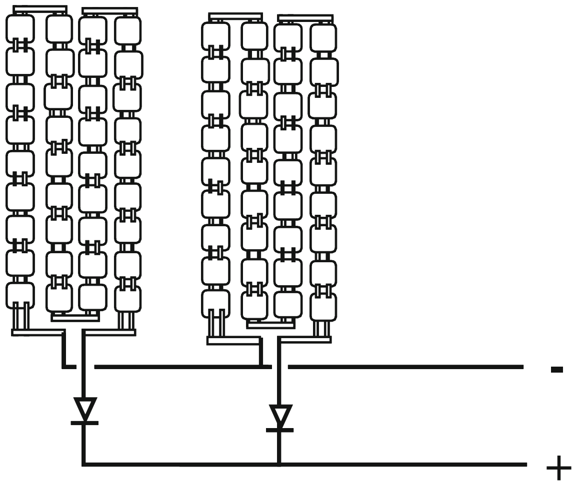


Fig. 2.24 Solar panels associated in parallel with blocking diodes

the ground. At other latitudes, the sun's radiations hit horizontally with an angle equal in average to the latitude of the location. Thus in order to receive the solar radiations perpendicular to the panel, the solar panel should be oriented with an

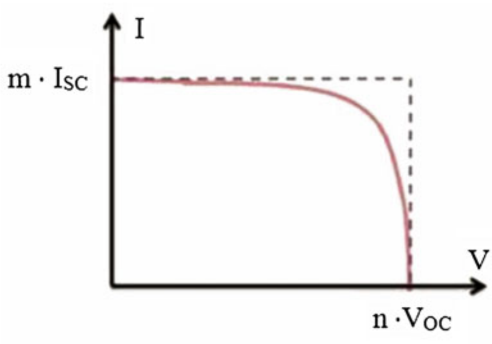


Fig. 2.25 I-V curve for modules

inclination angle equal to the latitude of the location (Fig. 2.26), toward the north in the southern hemisphere and toward the south in the northern hemisphere.

Nevertheless, the tilt of the earth's rotation axis responsible for the seasons should be considered to accurately orientate a solar panel throughout a year. To get the maximum of a photovoltaic panel installation, its orientation should be adjusted periodically. Devices such as sun trackers are sometimes used in low solar irradiance places to get the maximum output all day long. In case of a static and permanent installation the solar panel should be installed with an angle equal to the latitude of the location.

2.3.5 Solar Irradiance Data

In this section we present the solar irradiance, along with other influential meteorological parameters on the air mass, for 5 cities, one for each continent [13]:

Seoul (South Korea, Table 2.3), Dakar (Senegal, Table 2.4), Los Angeles (USA, Table 2.5), Toulouse (France, Table 2.6) and Melbourne (Australia, Table 2.7)—Data source: RETScreen.

2.4 Photovoltaic Systems

2.4.1 Standard Photovoltaic Standalone System

A standard standalone PV system is made of solar panels, batteries, a charge controller and a power inverter (Fig. 2.27).

The solar panels convert sunlight into electricity; the batteries store the electricity in a chemical form. A charge controller monitors the charge level of the battery. It will avoid the battery to be over charged or over discharged; the role of the power inverter is to convert the DC voltage of the battery to AC (Figs. 2.28 and 2.29).

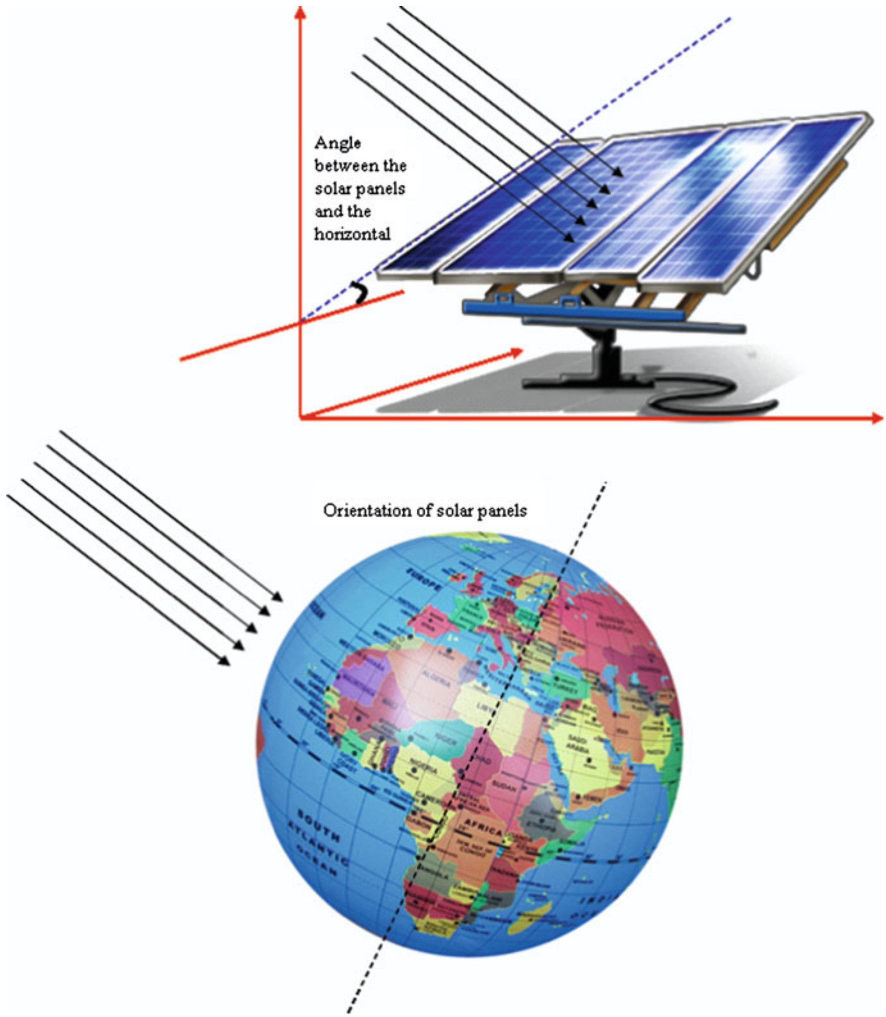


Fig. 2.26 Orientation of a solar panel

2.4.2 Solar Charge Controllers

Charge controllers monitor and manage the charge status of the battery. The simplest charge controller will simply disconnect the battery and the solar panel when the voltage of the battery reaches a certain high or low level of charge. For batteries like lead-acid batteries the voltage reflects the charge level.

Table 2.3 Solar irradiance Seoul, South Korea

	Unit	Climate data location		Project location
Latitude	°N	37.6		37.6
Longitude	°E	127.0		127.0
Elevation	m	86		86
Month	Air temperature (°C)	Relative humidity (%)	Daily solar radiation–horizontal (k W h/m^2/d)	Atmospheric pressure (kPa)
January	−3.4	56.8	1.94	101.4
February	−1.1	54.9	2.76	101.3
March	4.5	55.6	3.47	100.9
April	11.8	56.0	4.38	100.5
May	17.4	63.2	4.69	100.1
June	21.5	69.1	4.29	99.7
July	24.6	78.7	3.25	99.6
August	25.4	76.2	3.55	99.7
September	20.6	69.4	3.52	100.3
October	14.3	64.3	3.03	100.9
November	6.6	61.4	2.05	101.3
December	−0.4	57.8	1.70	101.4
Annual	11.9	63.7	3.22	100.6

Table 2.4 Solar irradiance Dakar, Senegal

	Unit	Climate data location		Project location
Latitude	°N	14.7		14.7
Longitude	°E	−17.5		−17.5
Elevation	m	24		24
Month	Air temperature (°C)	Relative humidity (%)	Daily solar radiation–horizontal (k W h/m^2/d)	Atmospheric pressure (kPa)
January	20.7	70.2	4.89	101.0
February	20.7	74.9	5.80	100.9
March	21.0	78.5	6.57	100.9
April	21.4	83.0	6.92	100.8
May	22.8	82.9	6.71	100.9
June	25.6	82.3	6.21	101.0
July	27.1	79.7	5.60	101.0
August	27.4	83.0	5.34	100.9
September	27.6	84.7	5.34	100.9
October	27.6	81.8	5.53	100.9
November	25.8	73.8	4.98	100.9
December	23.4	68.6	4.57	101.0
Annual	24.3	78.6	5.70	100.9

Table 2.5 Solar irradiance Los Angeles, USA

	Unit	Climate data location		Project location
Latitude	°N	33.9		33.9
Longitude	°E	−118.4		−118.4
Elevation	m	99		99
Month	Air temperature (°C)	Relative humidity (%)	Daily solar radiation–horizontal (k W h/m^2/d)	Atmospheric pressure (kPa)
January	13.8	66.0	2.81	101.5
February	14.0	69.2	3.65	101.4
March	14.5	73.5	4.80	101.3
April	15.7	72.0	6.06	101.2
May	17.0	75.9	6.41	101.1
June	18.4	76.6	6.61	101.0
July	20.3	77.4	7.14	101.0
August	20.7	77.0	6.54	101.0
September	20.3	76.1	5.30	100.9
October	18.6	72.9	4.19	101.1
November	16.1	64.3	3.16	101.3
December	13.8	61.9	2.62	101.5
Annual	16.9	71.9	4.95	101.2

Table 2.6 Solar irradiance Toulouse, France

	Unit	Climate data location		Project location
Latitude	°N	43.6		43.6
Longitude	°E	1.4		1.4
Elevation	m	154		154
Month	Air temperature (°C)	Relative humidity (%)	Daily solar radiation–horizontal (k W h/m^2/d)	Atmospheric pressure (kPa)
January	5.1	86.3	1.39	100.2
February	6.5	81.2	2.33	100.0
March	8.3	75.0	3.72	100.0
April	11.0	74.0	4.78	99.7
May	14.6	72.8	5.36	99.8
June	18.3	69.2	5.81	99.9
July	21.2	66.0	6.28	100.0
August	20.5	67.7	5.58	99.9
September	18.1	71.2	4.31	100.0
October	13.8	80.4	2.92	100.0
November	8.6	85.1	1.75	100.0
December	5.7	87.1	1.17	100.1
Annual	12.7	76.3	3.79	100.0

Table 2.7 Solar irradiance Melbourne, Australia

	Unit	Climate data location		Project location
Latitude	°N	−37.8		−37.8
Longitude	°E	145.0		145.0
Elevation	m	32		32
Month	Air temperature (°C)	Relative humidity (%)	Daily solar radiation–horizontal (K W h/m^2/d)	Atmospheric pressure (kPa)
January	20.4	60.7	6.67	99.6
February	20.7	60.5	5.95	99.9
March	18.7	62.2	4.52	100.0
April	15.8	65.1	3.16	100.3
May	13.3	70.4	2.19	100.3
June	11.5	72.3	1.68	100.3
July	10.7	70.7	1.87	100.1
August	11.5	66.2	2.56	100.0
September	13.1	64.4	3.61	100.0
October	15.0	61.1	4.96	99.8
November	16.9	60.0	5.80	99.5
December	18.7	59.2	6.39	99.4
Annual	15.5	64.4	4.10	99.9

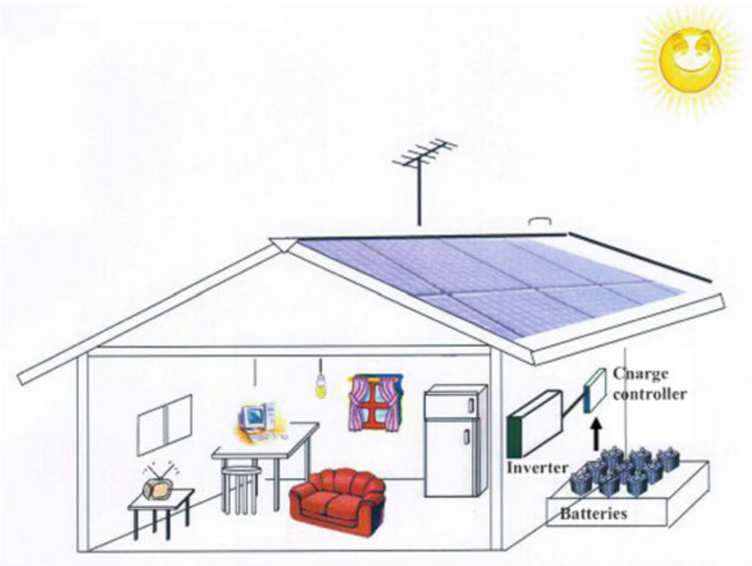
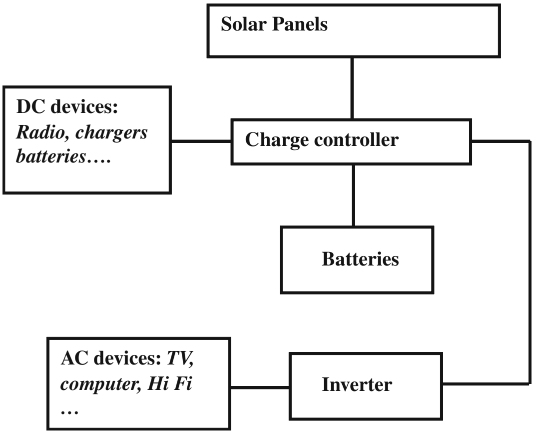


Fig. 2.27 Standalone solar house

Fig. 2.28 Structure of a standalone photovoltaic system



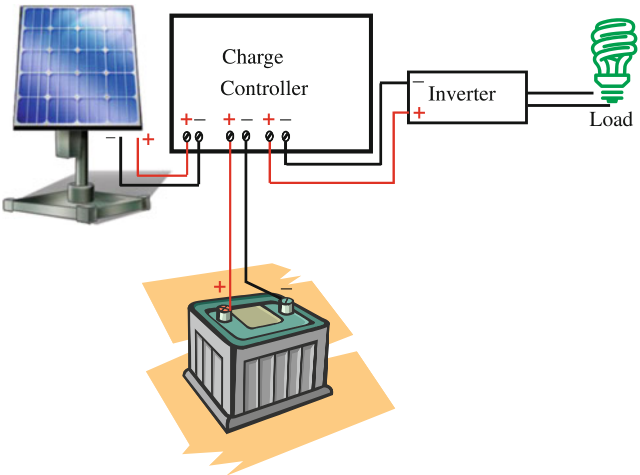


Fig. 2.29 Simple structure of a photovoltaic system for lighting

There are other types of controllers which are more sophisticated: the Pulse Width Modulation (PWM) and the Maximum Power Point Tracker (MPPT) controllers allow charging the battery closer its maximum capacity.

Solar charge controllers are necessary for most solar power systems that use batteries. The solar charge controller functions to control the power as it moves from the solar panels to the batteries. If overcharged, the life of a battery is reduced. The simplest type of charge controller functions to monitor the battery voltage and opens the circuit to stop the charging process once the voltage reaches a certain level. Older charge controllers accomplished this through the use of a mechanical relay.

Fig. 2.30 MPPT (*left*) and PWM (*right*) charge controllers

More recent charge controllers make use of pulse width modulation. This is a process in which, as the battery starts to reach a fully charged state, the amount of power being transferred to it gradually decreases. PWM extends the battery life even more, as it decreases stress on the battery. It can also keep batteries in a completely charged state, or floating, indefinitely. PWM chargers are more complex, but they tend to be more durable, as they do not use any breakable mechanical connection.

The most recent types of solar charge controllers use maximum power point tracking, or MPPT. This is an electronic tracking system that continuously compares the battery charge level with the output of the solar panel. It will then adjust the voltage and the current to be applied to the battery, conserving the same power from the solar panel, but charging the battery more efficiently.

In comparison to PWM controllers, MPPT charge controllers are more expensive, and their performance is significantly enhanced. Figure 2.30 shows pictures of MPPT and PWM charge controllers. Besides the type, charge controllers are characterized by the current they can control (5, 10, 15 … 50 A …) and the voltage under which they can control it, generally 12, 24 or 48 V which is the voltage of the solar module or array. They can be dual voltage with automatic switch, as 12 V/24 V. They also feature the operating temperature and efficiency, almost always above 95%. Their technical sheet will also show their power consumption. Most power controllers for 12 V applications will control a maximum current under 50 A. Generally high-power photovoltaic systems are based on higher voltages (24, 48 V…).

For their operation, charge controllers have a low voltage cut, under which no power will be supplied to the load (generally between 10.5 and 11 V for 12 V controllers) and a high voltage cut or full charge cut voltage above which they disconnect the batteries and the solar panels (generally between 13 and 14 V for 12 V controllers).

2.4.2.1 Example of Specifications of a Charge Controller

- Rated voltage: 12 V
- Max solar panel input current: 20 A
- Max solar panel work voltage: 23 V
- Max input solar panel power: 300 W
- Solar panel efficiency improvement: 10–30%
- Working efficiency rate: 95–97%
- MPPT regulator (maximum power point tracking)
- Full charge cut: 14 V
- Voltage drop: $\leq$ 400 mV
- Low voltage cut: 10.5 V
- Supply resume voltage: 12.6 V
- Temp compensation: -3 mV/cell
- Zero loaded losses: $\leq$ 45 mA/12 V
- Min. wire size: 1 $\sim$ 2 A/mm^2
- Dimensions: 188 $\times$ 118 $\times$ 55 cm (7.4 $\times$ 4.65 $\times$ 2.17)

2.4.3 Power Inverters

The power inverter converts the DC voltage of the battery or directly of the solar panel into an AC voltage generally 110–125 VAC or 220–240 VAC. There are different types of power inverters based on the shape of the converted signal: square wave inverters, modified sine wave inverters and pure sine wave inverters that are the most sophisticated.

The wave form has an influence only with some types of equipments. Among those devices susceptible to display problems when run by square wave inverter or a modified-sine wave signal are : equipment with variable speed motors, oxygen concentrators, fax machines, laser printers, high-voltage cordless tool chargers, electric shavers and garage door openers.

For the need of lighting the performances of modified sine wave inverters are generally satisfactory.

Power inverters are characterized also by their low- and high-cut off voltages, respectively under and above which they will stop functioning. Generally, inverters function between 10 and 15 V.

2.4.3.1 Peak or Surge Power and Continuous Power

Along with the shape of the output waveform, an inverter is generally characterized by two powers to be delivered: a peak (or surge) power and a continuous

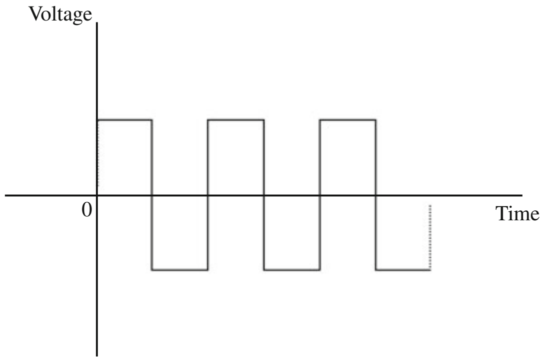


Fig. 2.31 Square wave voltage

power. The peak (or surge) power is the maximum power that the inverter can supply, but for only a short amount of time specified by the manufacturer. Some appliances, such as pumps, need a high start up power before operating at a much lower power. The surge power will also protect from overload.

The continuous power is the power under which the device will operate in the long run. It is generally the power under which name the inverter is designated.

2.4.3.2 Square Wave Power Inverters

These inverters were the first types of inverters made and are obsolete today. This is also the least expensive and least desirable type. The shape of the square wave is shown in Fig. 2.31. Square wave inverters are not adequate for most electronic devices.

2.4.3.3 Modified Sine Wave Power Inverters

Modified-sine wave inverters (Fig. 2.32) are the most popular and the most common types of power inverters on the market. Modified sine wave inverters deliver a power that is not exactly the same as electricity from the power grid, but consistent and efficient enough to run devices such as:

- Cellular phone chargers
- Laptops
- Computers
- Some fluorescent lights
- Most DIY tools, like drills and jigsaws
- Small fridges
- Hairdryers and electric shavers.

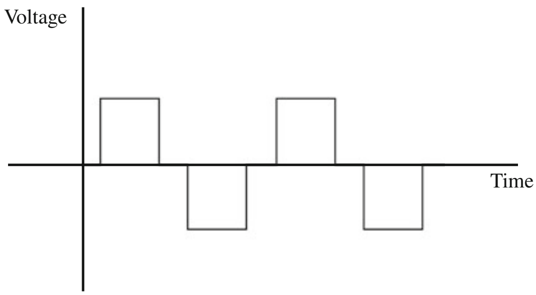


Fig. 2.32 Modified-sine wave voltage

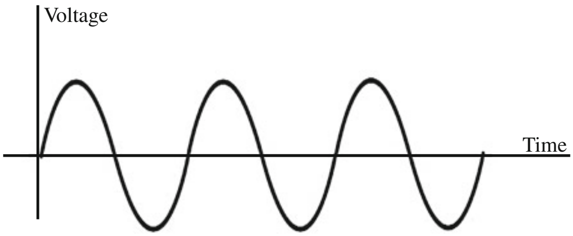


Fig. 2.33 Sine wave voltage

Fig. 2.34 Pure sine power inverter

However, some appliances that utilize motor speed controls may not work properly with a modified sine wave inverter.

2.4.3.4 Pure Sine Wave Power Inverters

Pure sine wave (true sine wave) inverters deliver the most consistent wave output. This type of power inverter produces the closest to a pure sine wave (Fig. 2.33) of all power inverters and in many cases produces cleaner power signal than the utility company itself. It will efficiently run any type of AC equipment.

Table 2.8 Example of technical datasheet of a power inverter

Specifications	1,500 W (max. 3,000 W) inverter -pure sine wave
Output continuous capacity	1,500 W
Output peak capacity	3,000 W
Output voltage	240 V AC
Output voltage stability	± 3%
Output frequency	50 Hz Frequency stabilized
Output signal form	Pure sine wave
Input rated voltage	12 V DC
Input voltage range	10–16 V DC
Input side connection	Terminal for battery cable
Standby current	< 0.8 A
Efficiency (full load)	max 90%
Total harmonic distortion (THD)	max 3%
Protection (output)	√
Output short circuit protection	√
Output overload auto shut down	√
Protection (input)	√
Low-voltage warning	10.5 ± 0.5 V DC
Low-voltage shut down	10.0 ± 0.5 V DC
Over voltage shut down	16.0 ± 0.5 V DC
Soft start	√
Cooling (load dependent) by Fan	40 ± 2°C on
Thermal protection	+60 + 10°C
Polarity protection by fuse	√
HI-POT (Isolation Test)	√
Operation-, Ambient temperature	− 15°C up to + 50°C
Storage temperature	− 30°C up to + 70°C
Dimensions (LxWxH)	42 × 19.3 × 9.4 cm
Net weight	6.2 kg
Certification	CE (EMC + LVD), E-Mark, RoHS, SGS (ISO 9001)

Pure sine wave inverters are the most expensive, but they also deliver the most reliable and consistent wave output. Some sensitive equipments require a sine wave, like certain medical equipment and variable speed or rechargeable tools like oxygen concentrators, fax machines, laser printers, variable speed motors and garage door openers. Figure 2.34 shows an example of pure sine power inverter. Table 2.8 shows an example datasheet of a pure sine power inverter.

2.4.4 Batteries

A battery is a device that stores electricity in chemical form. It is a direct current (DC) device described primarily by its voltage, capacity in ampere-hours (Ah) and technology (lead acid, nickel–cadmium, lithium polymer …). The most distributed batteries applied in photovoltaic systems are deep cycle lead-acid batteries.

Most solar photovoltaic systems use 12 V deep cycle batteries, 6 V batteries are also available. They can be associated in series to reach higher voltage, or combined in parallel for greater capacity without changing the voltage. The batteries used in photovoltaic systems are generally deep cycle batteries. The deep cycle batteries used in photovoltaic systems are designed to deliver low-to-medium current for a long period of time in contrast to car batteries that deliver a high current for a very short time, during ignition.

There are three main categories of lead-acid batteries technologies, based on the state of the electrolyte: flooded, gel and AGM (Absorbed Glass Mat). Deep cycle flooded or wet cells are the most common lead-acid batteries in the market. They can be sealed or not sealed. The sealed batteries require no maintenance and are recommended for non-experimented users.

Other types of rechargeable batteries as solid-state batteries are in the market as well and may be the best option depending on the applications but are costly: nickel–cadmium, nickel-metal hydride, lithium and lithium polymer etc. They different type of controllers. They may be used generally for very small size or portable systems. Table 2.9 compares the different types of batteries with their pros and cons.

2.4.4.1 Maintenance and Storage:

Batteries are inherent self-discharging devices. They have a self-discharging rate indicated as the rate of discharge per month. Thus, when in storage they need to be connected to a float charger or recharged periodically. They should generally be stored and charged in a dry and ventilated space at a temperature indicated by the manufacturer.

2.4.4.2 Peukert's Law: Capacity of a Battery

The capacity of a battery expressed in ampere-hours (Ah) is ideally the amount of current a battery can deliver during one hour or the number of hours the battery can deliver continuously one ampere. Peukert's law gives the capacity of a battery in relation to any discharging current and time of discharge:

$$C = I^k \times t$$

where, C is the capacity of the battery if the battery was to deliver 1 A constantly, I the actual current delivered by the battery, t the time and k the Peukert's constant, it is a dimensionless number generally between 1.2 and 2.

This law states that if the battery is discharged at a lower current, less than 1 A, it will run longer. On the other hand, if the battery is discharged at a higher current it will last a shorter time.

Table 2.9 Comparison of different type of batteries

Technology	Pros	Cons
Lead-acid	• low cost • Strongly built	• Low-energy density (ratio capacity/weight) • Auto discharge rate • Temperature sensitive
	• Capable of high currents • No memory effect • Good life span when correctly used • Recyclability	• Risks of sulfation when stored for a long period in discharged state
Nickel–Cadmium (Ni–Cd)	• Can support high charge or discharge currents • Affordable • Strongly built	• Memory effect • Density of energy • Difficult to recycle because of the Cadmium
Nickel-metal hydride (NiMH)	• Good density of energy • No memory effect	• Fragile because do not support overcharge, requires specific automatic chargers, more expensive than Ni–Cd
	• Can support important currents • Easy to store and transport • Recyclability	• Life span less than for Ni–Cd • Important auto discharge rate
Lithium batteries (Li), Lithium ion (Li-Ion) and Lithium ion Polymer (LiPo)	• High density of energy • Low auto discharge • No memory effect • Good lifespan	• Cost

For example, a battery of 50 Ah capacity can deliver 50 A continuously for one hour but if the discharging current was 100 A the operation time will be less than 30 min. Also, if the discharge current was 25 A it will run longer than 2 h.

2.4.4.3 Example of Datasheet of an AGM Deep Cycle Battery 6 V 25 Ah

Cell per unit	3
Voltage per unit	6
Capacity	225 Ah@10 h-rate to 1.80 V per cell@25°C
Weight	Approx. 32.0 kg

(continued)

(continued)

Maximum discharge current	2,250 A (5 s)
Internal resistance	Approx. 4.0 mΩ
Operating temperature range	Discharge: −20–60°C Charge: 0 to 50°C Storage: −20 to 60°C
Normal operating temperature range	25 ± 5°C
Float charging voltage	6.8–6.9 VDC/unit average at 25°C
Recommended maximum charging current limit	67.5 A
Equalization and cycle service	7.3–7.4 VDC/uni average at 25°C
Selfdischarge	Less than 3% per month at 25°C (Charge battery before storage)
Terminal	Terminal F14
Container material	A.B.S (UL94-HB)

2.4.5 Sizing Standalone Photovoltaic System

A PV project starts by considering two fundamental parameters: first, the energy need that will be determined by the load and the time of usage and second, the sun exposure that determines the amount of sunlight converted into electricity by the solar panels.

Let us consider a 20 W lighting system powered by a standalone photovoltaic system. Let us suppose that it is used for a study room and is automatically controlled to operate for exactly 10 h daily, that is, a daily need of 200 Wh of electric energy.

Let us suppose that our geographic location receives in average 6 h of sunlight everyday the year round with only 4 h of total light a day during the cloudy season. To meet our needs of electricity the whole year, the transformation of light into electricity needs to be based on the cloudy season. What size (power) of solar panel can achieve the transformation of light into 200 Wh of electric energy with only 4 h of sunlight: 200 Wh/4 h. It will require a 50 W solar panel.

What capacity of battery would be needed to store the electricity converted by the solar panel? The voltage of the battery should be chosen according to the voltage of the solar panel. For such a small system it is convenient to use a 12 V-based design. Thus a 12 V battery is supposed to store 200 Wh of energy which would be a capacity of 200 Wh/12 V, about 17 Ah. Nevertheless, if the system uses one of the best quality/price ratio technologies, the battery will be a flooded lead-acid battery, which imposes restrictions in its usage. A lead-acid battery should never be emptied over a certain level in order to have the expected lifetime mentioned by the manufacturer. Using it at 50% of its capacity is a correct alternative. Thus, the battery will be taken with a capacity of 34 Ah ($17/0.5 = 34$).

A charge controller will be necessary to maximize the lifetime of the battery by avoiding too low discharges or overcharges. For a 50 W–12 V solar panel a 12 V–5 A charge controller is a correct and standard choice (50 W/12 V < 5 A) and practically the panel charging voltage will be above 14 V in standard conditions of illumination.

Whether a power inverter to convert the DC voltage of the battery to AC will be needed or not depends on the operation voltage of the lighting system.

Remark When using a power inverter it is necessary to include the losses, considering for instance an efficiency of the inverter of only 90%. The efficiency is generally specified by the manufacturer.

Through this simple example we can consider the need of light from a different point of view by measuring the amount of light needed at a desk level in a study room. So far we did not mention about the technology of the lighting system.

It can be:

1. 20 W incandescent light (most likely too dim)
2. 20 W fluorescent light
3. 20 W LED light.

2.4.5.1 Comparison of the Three Lighting Systems

Now we can see the problem the other way around. In this case we need a certain amount of light (illuminance) in a study room and we need to know what lighting system to use. Depending on the chosen technology we will need a certain amount of electrical input power to feed the lighting system.

Let us consider a need of 500 lux at the desk level for our study room and try to find out what electric power consumption would be needed depending on the type of light source being used. The light source is labeled in lumens while the effective need in measured in lux but the relation between lumen and lux for a given light source and room geometry is not straightforward. Also, we have to consider a uniform or focused illumination, which will make the problem even more complex.

For that reason and to make it simple, let us consider that the most efficient lighting source, the 20 W LED, is enough to achieve the needed illuminance of 500 lux at the desk level in a uniform ambiance.

The electric power consumption will depend on the type and efficacy of the chosen light source. Here, let us consider the following correspondence to obtain the target illuminance of 500 lux at the desk level:

- LED lamp 20 W
- Fluorescent lamp 22 W
- Incandescent lamp 100 W

This reverse point of view allows sizing a system based on needs of illumination. Let us describe the resulting system depending on the chosen technology with a deep cycle lead-acid battery to use at 50% of its capacity:

1. *Photovoltaic system for a* 20 W *LED*–220 V *for* 10 h *of light daily*:

- With a 20 W LED, the daily energy need will be 200 Wh
- Solar panel for 4 h of sunlight: 200 Wh/4 h = 50 W
- 12 V lead-acid battery (200 Wh/12 V = 16.7 Ah) 16.7 Ah/0.5 ~ 34 Ah
- 12 V–5 A charge controller (50 W/12 V = 4.2 A)
- Inverter 75 W

2. *Photovoltaic system for a* 22 W − 220 V *fluorescent lamp for* 10 h *of light daily*:

- Daily energy need: 22 W × 10 h = 220 Wh
- Solar panel for 4 h of sunlight daily: 220 Wh/4 h = 55 W
- 12 V lead battery 18.3 Ah/0.5 ~ 37 Ah
- 12 V–7 A charge controller
- Inverter 75 W

3. *Photovoltaic system for a* 100 W–220 V *incandescent for* 10 h *of light daily*:

- Daily energy need: 100 W × 10 h = 1,000 Wh
- Solar panel: 1,000 Wh/4 h ~ 250 W
- 12 V lead-acid battery: 83.3 Ah/0.5 ~ 167 Ah
- 12 V−25 A charge controller
- Inverter 150 W

To build a very reliable system, a photovoltaic system should not only take into account the average of daily sunny hours, but also the completely cloudy days. For that reason a photovoltaic system should always be oversized in comparison with the daily needs of electricity allowing autonomy of two to three days depending on the needs.

An alternative is to couple the photovoltaic system with another source of energy for the days without sunlight. The grid or a generator can be reliable backup supplies.

Sizing a photovoltaic system should include all the losses due to the cabling, from the solar panel to the charge controller, from the controller to the batteries and the inverter and from the inverter to all the loads. It should also include losses due to the efficiencies of the electronic devices as the charge controller or the inverter, as well as the losses from the batteries as they will not restitute 100% of the energy they have stored. For these reasons the wiring should be kept as short as possible to improve the efficiency of a photovoltaic system. Other losses might come from voltage drop at the solar panel level when the temperature rises, as in the early afternoon, from the loose connections or bad orientation of the solar panel regarding the sun rays. In a good installation cumulative losses can easily reach up to 20% of the converted energy by the solar panels. To optimize the

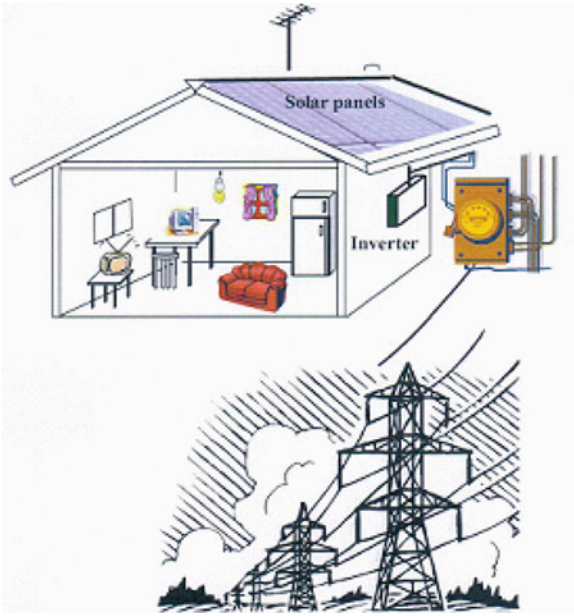


Fig. 2.35 Grid tie solar house

performance of a photovoltaic system the following points should be the guidelines:

The photovoltaic panel or array with the right voltage should be oriented correctly.

The wiring should be kept as short as possible with a correct gauge.

All other devices including the battery bank should be kept in cool and dry places.

2.4.6 Grid tie Photovoltaic Systems

A grid tie photovoltaic system is a system in which the electricity produced by the panels is directly injected in the grid through an adequate inverter (Fig. 2.35). In such a system the meter will turn backward when the amount of electricity produced is more important than the amount consumed and forward in the contrary. This gave the concept of net metering. The power companies will return credit to the costumer in various forms depending on the contract between them and the system's owner. In general there is no energy storage in a grid tie system; nevertheless certain grid tie inverters allow an output for a backup storage.

Fig. 2.36 Lighting photovoltaic kit

2.5 Solar Electricity and Rural Electrification

Production and distribution of electricity, in rural areas, is one of the major issues in number of developing countries. The lack of the ability to generate electricity keeps the people of many of these countries away from refrigeration benefits, lighting and telecommunication. In telecommunications, wireless networks can easily cover wide areas and theoretically be accessible, but devices such as cell phones need electricity to be charged in order to operate, similarly for computers (as for internet access). Access to electricity can improve living standards in rural areas in developing countries, and also open business perspectives for populations and make school work easier for students.

Generally, the solutions proposed are beyond the means and needs of the ordinary rural population. Solutions should be designed to target the primary basic needs as telecommunication and lighting. They should be very affordable, and easy to assemble and operate. They should provide knowledge and locally create jobs in order to lower labor and final costs.

Usually rural electrification involves standalone photovoltaic systems. Thus, the stored energy should be used as efficiently as possible. For lighting it makes it necessary to use LED or fluorescent lighting systems. An important advantage of LED for rural electrification is the possibility of high light output under a 12 VDC voltage. This will spare the need for an inverter to operate the lighting system making it cheaper and less sophisticated, so virtually less exposed to failure. This is a very important aspect in remote areas where getting a repair service can be a real challenge.

The Nopalu kit presented here, was developed for a rural electrification project in Senegal. A typical kit for rural electrification is shown in Fig. 2.36. The specifications of individual elements of the lighting photovoltaic kit are presented in Fig. 2.37.

The Nopalu kits developed by the authors are designed to be a solution that targets the specific needs of phone communications and lighting. They give up to

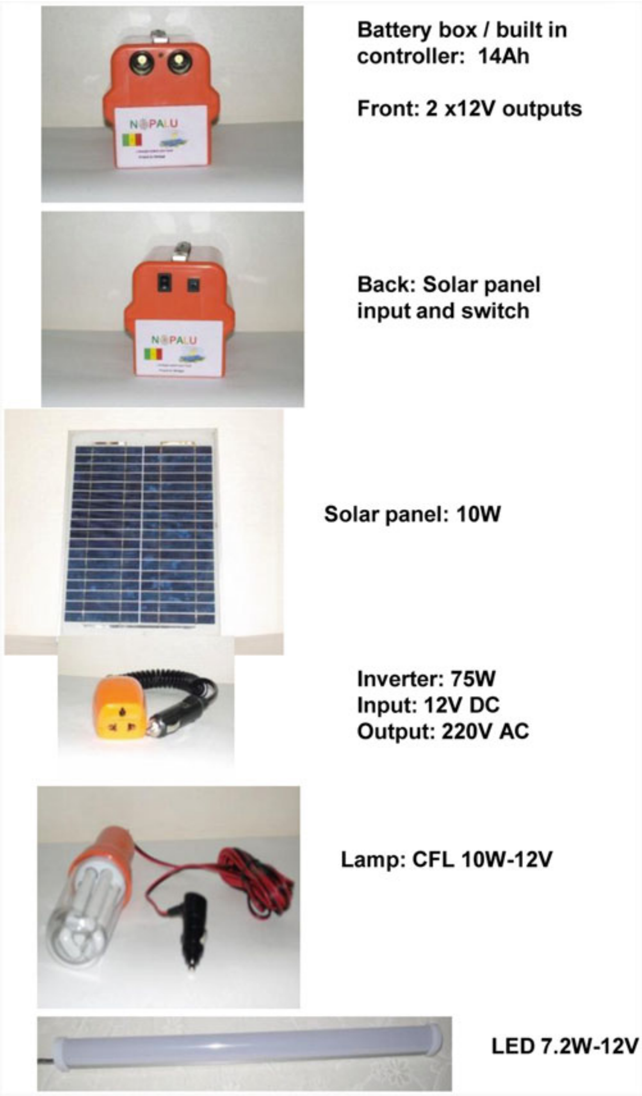


Fig. 2.37 Individual elements of the lighting photovoltaic kit

5 h of light for two lights and charge cell phones. These products are very compact photovoltaic systems, in kits, designed and built to supply electricity to low-power consumption appliances as for lighting and small electronics without any need of maintenance and no skill for setup and operation. They can also stand for power backups or primary power sources for laptops or other systems operating at low wattage under either DC or AC electricity.

These features in addition to their high quality, very competitive and attractive cost make these systems ideal solutions to solve the problems of rural electrification in developing countries as well as low-power standalone needs anywhere where the sun shines.

Solar energy or other green energies combined with power efficient devices, as LEDs, will eventually allow developing countries to have better access to energy for their populations in rural areas and advanced countries to lower their carbon footprint.

The potential of solar energy has proven itself and is being used worldwide. The development of renewable energies requires committed government policies but good education is needed for successful implementation.

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Chapter 3
Light Emitting Diodes

3.1 Elements of Photometry and Radiometry

3.1.1 Irradiance

Irradiance is a term used in radiometry. It measures the power of electromagnetic radiation per unit area. It is measured in W/m^2. In solar energy irradiance is referred to as insolation.

3.1.2 Radiance

Radiance is a term used in radiometry, and it is measured in $W/sr.m^2$. It is the radiant energy emitted per unit of time in a specified direction by a unit area of an emitting surface.

It is the flux per unit-projected area per unit solid angle leaving a source or any other source. If $d\Phi$ is the flux emitted into $d\Omega$ by a source element of projected area dA, the radiance is defined as $d\Phi/dA\ d\Omega$.

3.1.3 Luminous Intensity

Luminous intensity, used in photometry, is measured in candela (cd); it measures the power emitted by a light source in a certain direction. It depends on the wavelength of the emitted light because of the sensitivity of the human eye. As the human eye is most sensitive to light of 555 nm wavelength, lights with the same radiant intensity but different wavelengths will have a different luminous intensity.

R. Pode and B. Diouf, *Solar Lighting*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-2134-3_3,

3.1.4 Luminance

The term luminance is used in photometry; it is the intensity of a light source per unit area. It is measured in cd/m^2.

Luminance can characterize light emission or reflection from flat or diffuse surfaces. It measures how much luminous power an eye will perceive looking at the surface from a specific angle. Luminance is an indicator of how bright the surface will look. In this case, the solid angle of interest is the solid angle subtended by the eye's pupil. The sun has luminance of about 1.6×10^9 cd/m^2 at noon.

3.1.5 Luminous Flux

The luminous flux is measured in lumens (lm). It is a measure of the perceived power of light. It is wavelength dependent. One lumen is equal to the luminous flux produced by one candela of luminous intensity in one steradian solid angle. It is used to inform about the amount of light emitted by a light source. It is an indication we can find on light bulb packages in some countries. It tells the luminous efficacy of a light source.

The amount of light emitted by a source is measured in lumens. The definition of the lumen is based on the definition of the candela.

$$1 \text{ lm} = 1 \text{ cd.sr}$$

A sphere has a solid angle of 4π steradians, a light source that radiates uniformly one candela in all directions has a total luminous flux of $1 \text{ cd.}4\pi\text{.sr} = 4\pi \approx 12.57$ lm.

A candle emits about one candela in all directions. The candela measures the light intensity of a source of a certain wavelength. If we look at the amount of luminous intensity through a cone, a solid angle in steredian (sr), the luminous flux will be measured in lumens (lm). The lumen measures the power of light that perceives the human eye while the radiant flux measures (in watts) the total power of light emitted.

3.1.6 Measuring Units of Light Level: Illuminance

Illuminance is a term used in photometry. It is measured in lux (lx) in the international unit system or lm/m^2. It is wavelength dependent and measures the intensity of light. A light level or illuminance informs about how bright or dim is an ambiance, an environment or a work surface. It depends not only on the type and power of the light source but also on the distance between the light source and the surface of interest. The illuminance can also be measured in footcancles (of symbol: ftcd, fc or fcd).

The light level or illuminance is the total luminous flux incident on a surface. Illuminance is measured with a luxmeter. A foot candle is one lumen of light density per square foot; one lux is one lumen per square meter.

- 1 lux = 0.0929 foot candle = 1 lm/sq m
- 1 ftcd = 1 lux/10.752
- 1 lm/sq ft = 1 foot candle = 1×10^4 lux

The light level is a very good indicator of the efficiency of the power source. For applications, in general we proceed from a need of illuminance and find the lighting system and installation setup to match that need.

3.1.7 Common Natural Light Levels Outdoors

Table 3.1 shows the illuminance at ground level for different natural sources outdoors in a clear sky during the day with sunlight or at night with the moon and the stars. Illumination levels indoors from natural light sources are highly dependent on the architecture, the position inside the building, the size and number of windows and other parameters to be quantitatively described. Similarly for natural sunlight when the weather is cloudy, as the level to which the sky is covered should be well described and can be highly variable. These situations require specific evaluations for every case.

3.1.8 Recommended Light Level in Different Work Spaces

The outdoor light level on a clear day is adequate for almost any task. Inside buildings the illuminance is reduced depending on the architecture and the sun exposure and therefore additional light sources are often necessary. Most tasks require a light level between 300 and 500 lux, for detailed work it goes beyond 2,000 lux. Table 3.2 shows the required illuminance for different tasks.

3.1.9 Luminous Efficacy

The luminous efficacy of a light source is the ratio between the meausred amount of visible light it emits, in lumen, and the electric power (in watts) it consumes. The luminous efficacy is wavelength dependent as the luminous intensity (in lumens), which is based on the sensitivity of the human eye. It is measured in lumens per watt (lm/W). By definition, the maximum efficacy possible for a light

Table 3.1 Illumination at the ground level from different natural light sources

	Light source Sunlight	Illumination (lux)
Solar altitude (degrees)	90	129,000
	80	122,000
	70	114,000
	60	103,000
	50	87,400
	45	77,800
	40	67,500
	35	56,900
	30	46,300
	25	36,300
	20	27,400
	15	19,200
	14	17,600
	13	15,900
	12	14,300
	11	12,700
	10	11,100
	9.5	10,400
	9	9,610
	8.5	8,880
	8	8,170
	7.5	7,490
	7	6,840
	6.5	6,220
	6	5,620
	5.5	5,060
	5	4,540
	4.5	4,010
	4	3,550
	3.5	3,110
	3	2,690
	2.5	2,290
	2	1,920
	1.5	1,580
	1	1,270
	0.5	994
	0	759
Night	Full moon	0.11
	Quarter moon	0.011
	Starlight	0.0011

source is 683 lm/W; for monochromatic green light it is at 555 nm wavelength, the wavelength to which the human eye is most sensitive. The luminous efficacy of a light source, that is, the ratio between the output visible light and the input electric

Table 3.2 Average illuminance required for different tasks/places with artificial light

Activity	Illumination (lux)
Walkways	20–50
Corridors	100–150
Warehouses	150
Basic office work	250
Continuous reading	500
Supermarkets	750
Mechanical workshop	1,000
Detailed drawing work	1,500–2,000
Short time small size detailed work	2,000–5,000
High detailed task on long periods	5,000–10,000

power can also be described for an electromagnetic radiation as the ratio between the luminous flux and the radiant flux.

The lighting or luminous efficiency (not efficacy) is a dimensionless parameter equal to the ratio of the luminous efficacy of a light source x lm/W to the maximum luminous efficacy of a green light source at 555 nm, 683 lm/W.

Table 3.3 gives the luminous efficacy of different light sources.

Table 3.3 lists the luminous efficacy and efficiency for various light sources:

3.1.10 The Inverse Square Law

This law (Fig. 3.1) states that, the intensity of light (illuminance) radiated from a point source is inversely proportional to the square of the distance from the source as depicted in Fig. 3.1 (*it is valid for other linear waves*).

So if an object is moved twice further away from a point source it will receive only one-quarter of the illumination it was receiving prior to the displacement. A light source may be considered as a point source relative to an observer that is distant enough.

3.2 Semiconductors and p-n Junctions

Materials can be divided into three groups based on their ability to conduct electricity. Some of them can conduct electricity very well, thus they are called electric conductors. Metals are good conductors. Other materials which cannot conduct electricity at all are called insulators. For example, wood is an insulator. Between these two main groups there are semiconductors. Semiconductors are neither good conductors nor good insulators. Silicon is a semiconductor. By a process called doping the properties of semiconductors can be tuned in order to modify their electrical properties and match a desired conductivity.

Table 3.3 Lighting system luminous efficacies [1]

Category	Type	Overall luminous efficacy (lm/W)	Overall luminous efficiency
Combustion	Candle	0.3	0.04%
Incandescent	100–200 W tungsten incandescent (230 V)	13.8–15.2	2.0–2.2%
	100–200–500 W tungsten glass halogen (230 V)	16.7–17.6–19.8	2.4–2.6–2.9%
	5–40–100 W tungsten incandescent (120 V)	5–12.6–17.5	0.7–1.8–2.6%
	2.6 W tungsten glass halogen (5.2 V)	19.2	2.8%
	Tungsten quartz halogen (12–24 V)	24	3.5%
	Photographic and projection lamps	35	5.1%
Light emitting diode	White LED (raw, without power supply)	4.5–150	0.66–22.0%
	4.1 W LED screw base lamp (120 V)	58.5–82.9	8.6–12.1%
	5.4 W LED screw base lamp (100 V 50/60 Hz)	101.9	14.9%
	6.9 W LED screw base lamp (120 V)	55.1–81.9	8.1–12.0%
	7 W LED PAR20 (120 V)	28.6	4.2%
	8.7 W LED screw base lamp (120 V)	69.0–93.1	10.1–13.6%
	Theoretical limit	260.0–300.0	38.1–43.9%
Arc lamp	Xenon arc lamp	30–50	4.4–7.3%
	Mercury-xenon arc lamp	50–55	7.3–8.0%
Fluorescent	T12 tube with magnetic ballast	60	9%
	9–32 W compact fluorescent	46–75	8–11.45%
	T8 tube with electronic ballast	80–100	12–15%
	PL-S 11 W U-tube with traditional ballast	82	12%
	T5 tube	70–104.2	10–15.63%
	Spiral tube with electronic ballast	114–124.3	15–18%
Gas discharge	1,400 W sulfur lamp	100	15%
	Metal halide lamp	65–115	9.5–17%
	High-pressure sodium lamp	85–150	12–22%
	Low-pressure sodium lamp	100–200	15–29%
Cathodoluminescence	Electron stimulated luminescence	30	5%
Ideal sources	Truncated 5,800 K blackbody	251	37%
	Green light at 555 nm (maximum possible luminous efficacy)	683.002	100%

A semiconductor can be implemented with certain foreign atoms that will release excess electrons in it; in that case the doping is of n-type, and the doping material is called a donor. Phosphorous is an n-type dopant for silicon.

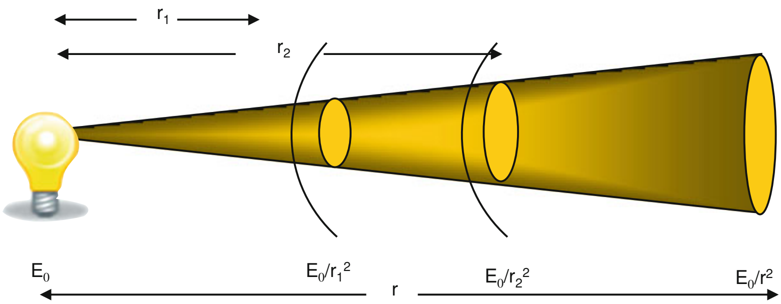


Fig. 3.1 Inverse square law representation

The electric current in the silicon-doped phosphorous is said to be a current of electrons. In a semiconducting material certain foreign atoms can be introduced as well that will capture part of the semiconductor's electrons; in that case the doping is said to be of p-type and the doping material is called an acceptor. The acceptor captures electrons from their original bounds creating vacancies called holes. The electric current is said to be holes current. Boron is a p-type doping atom for silicon.

When a p-type semiconductor and an n-type semiconductor are brought into contact they make a p-n junction. A p-n junction has specific properties different from that of the single p- or n-type semiconductors. A homojunction is a p-n junction made of the same material; when it is made of two different materials it is said to be heterojuction. The p-n junction is the basic building block of both inorganic solar cells and light emitting diodes.

In materials, electrons can belong to one of two categories called bands, depending on their energy. Electrons belonging to the valence band cannot participate in the conduction of the electric current as they are attached to atoms. Only the electrons belonging to the conduction band will take part in the conduction process; these electrons are not attached to individual atoms they are free to move through the whole structure.

In metals, the conduction and valence bands are adjacent without discontinuity. In insulators the conduction band is empty and there is a wide gap separating it from the valence band so that the electrons in the valence band cannot transfer to the conduction band under the application of a voltage, making the conduction of electricity impossible. In semiconductors, the situation is different because the gap between the valence and the conduction band is not two wide. In semiconductors electrons can be transferred easily from the valence band to the conduction band and become conducting electrons. Also, when a semiconductor is n-doped the excess electrons will come and populate the conduction band.

The band gap is measured in electron-volts (eV). The band gap in metals is 0 eV; in insulators it is generally greater than 5 eV and in semiconductors it is commonly between 1 and 3 eV as shown Table 3.4. The energy gap in a semiconductor controls almost all it's electrical and optical properties.

Table 3.4 List of band gaps of semiconductor materials [2–5]

Material	Symbol	Band gap (eV) at 300 K	Type of band gap
Aluminium phosphide	AlP	2.45	Indirect
Aluminium arsenide	AlAs	2.16	Indirect
Aluminium antimonide	AlSb	1.6	Indirect
Aluminium nitride	AlN	6.3	Direct
Cadmium selenide	CdSe	1.75	Direct
Cadmium sulfide	CdS	2.50	Direct
Cadmium telluride	CdTe	1.47	Direct
Diamond	C	5.5	Indirect
Gallium arsenide	GaAs	1.43	Direct
Gallium antimonide	GaSb	0.7	Direct
Gallium nitride	GaN	3.4	Direct
Gallium phosphide	GaP	2.26	Indirect
Germanium	Ge	0.67	Indirect
Indium antimonide	InSb	0.17	Direct
Indium nitride	InN	0.7	Direct
Indium phosphide	InP	1.35	Direct
Lead selenide	PbSe	0.27	Direct
Lead sulfide	PbS	0.37	Direct
Lead telluride	PbTe	0.29	Direct
Silicon	Si	1.11	Indirect
Silicon carbide	SiC	2.86	Indirect
Zinc selenide	ZnSe	2.82	Direct

Depending on their band gap semiconductors will be used for different technological applications, as for light emitting diodes and solar cells. The band gap of semiconductors will determine the color of the LED (Fig. 3.2).

A p-n junction is a polarized device; the electric current can flow through it in one way only, that is when the electric potential applied on the p side of the junction is higher than that applied on the n side. The p-n junction is then forward biased and is conductive. In the opposite case, the applied voltage is positive on the n side and negative on the p side, the junction is said to be reverse biased and the electric current is blocked.

Figure 3.2 depicts the band structure of a direct band gap semiconductor. In fact, semiconductors can be divided into two groups: direct band gap semiconductors and indirect band gap semiconductors. They have different responses under electrical excitation for radiative recombinations between electrons and holes: electroluminescence or under the absorption of a photon as in the photovoltaic effect. For electroluminescence direct band semiconductors have a faster response. While for a photon absorption direct band gap semiconductors require less thickness than indirect band gap semiconductors, this is the reason why thin film solar cells are generally made of direct band gap semiconductors. Gallium arsenide (GaAs) is a direct band gap semiconductor, while silicon (Si) is an indirect band gap semiconductor. Table 3.4 shows a list of semiconductors with their band gap and nature of band gap.

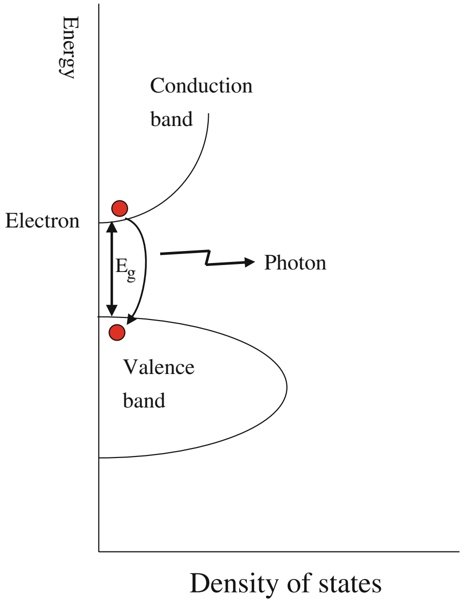


Fig. 3.2 Semiconductor band diagram showing the emission of a photon by transition of an electron from the conduction to the valence band

3.3 Light-Emitting Diode (LED) and Lighting

3.3.1 Light Emitting Diodes (LEDs)

LEDs are bipolar and polarized devices that emit light when connected to an adequate DC power supply. They are generally made of wafer p-n junctions and called solid-state light sources because of their nature. LEDs come in different colors, shapes and sizes.

Semiconductor p-n junctions emit light under an applied adequate voltage as a result of the electrons and holes recombination to produce photons. At room temperature without an external power source the thermal excitation will not result in perceivable light because of the low concentration of carriers. An external power supply across the junction, as a voltage or current source, is necessary to increase the concentration of carriers in order to have an emission of light important enough to be perceivable.

LEDs can be made so that light will be emitted in two geometries, surface emission or edge emission (Figs. 3.3, 3.4). In surface emission geometry the light is emitted perpendicular to the p-n junction and will be in two directions, the direction of perception and the direction of the substrate. The light emitted in the direction of the substrate is either reflected or absorbed depending on the nature of the substrate.

LEDs are generally made of very thin layers of semiconductors; one layer is n-doped with an excess of electrons, while the adjacent layer is p-doped with a deficit of electrons.

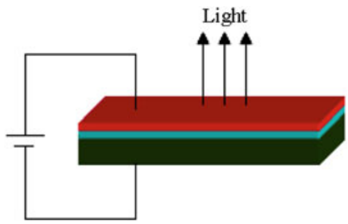


Fig. 3.3 LED surface emission

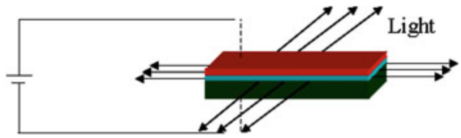


Fig. 3.4 LED edge emission

When a correct voltage is applied the electrons from the n region and holes from the p region of the diode will drift to combine. Their recombination can result in the generation of light. When the recombination of an electron and a hole results in a photon it is called a radiative combination and produces light, otherwise the recombination is said to be non-radiative and will produce heat. the more electron–hole pairs radiatively combine the more important will be the number of emitted photons, hence the brighter will be the resulting light. This phenomenon is known as injection electroluminescence. The brightness of an LED is current controlled, as described above. The color of the light depends on the band gap of the semiconductors.

The number of photons generated inside the semiconductor (n_{phi}) composing the generated light inside the material is compared with the number of injected electrons (n_e) to recombine with holes to generate light. This ratio defines the internal quantum efficiency. The internal quantum efficiency can reach up to 90% and depends on the epitaxial structure of the material.

$$\eta_{int} = \frac{n_{phi}}{n_e}$$

The number of photons extracted and emitted outside the semiconductor (n_{phe}) is compared to the number of photons generated inside the semiconductor; this ratio is called the extraction efficiency. The extraction factor can generally be as low as 2%.

$$\gamma_{ext} = \frac{n_{phe}}{n_{phi}}$$

The extraction efficiency is limited by internal refection and the difference in refractive index between the semiconductor and the encapsulation material.

The ratio of emitted photons with the injected electrons is the external quantum efficiency.

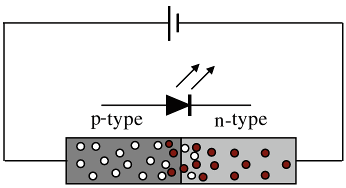


Fig. 3.5 LED structure and light generation

$$\eta_{ext} = \frac{n_{phe}}{n_e}$$

It can be estimated by the ratio between light power output from the LED and applied electric power across the LED, which is the product of its current and voltage.

LEDs are attractive for different reasons; these colored lights are very power efficient and have a very long lifetime. LEDs are made of specific semiconductors, gallium arsenide (GaAs), gallium phosphide (GaP), or gallium arsenide phosphides (GaAsP), zinc sulfide (ZnS) or silicon carbide (SiC) are often used as substrates. The color of the emitted light (wavelength) is controlled by the chosen semiconductor and the doping materials: commonly zinc or nitrogen.

In order to power the device contacts are deposited to connect electric wires. They are generally deposited by photolithography and made of gold or silver. LEDs are then encapsulated in transparent plastics whose optical properties will partly determine the characteristics of the light output. These plastics, that can be colored, are chosen diffusive or clear with a geometry that will shape the light beam.

It is now possible to make wafers with increasing purity and uniformity. This will affect the brightness, power efficiency and life span of LEDs, how bright and efficient LEDs can be made and how long they will last. As they get better, they are appropriate for increasingly demanding applications, such as lighting. The modern LED can last up to 100,000 h compared to the average short lifetime of an incandescent light bulb in the range of 1,000 h. This makes them suitable for applications where it is difficult or impossible to replace parts, such as undersea or outer space applications.

Remark: This life span of LEDs is obtained in laboratory test conditions and will not apply exactly in other conditions. The LED life span is very much dependent on the conditions of use especially temperature and humidity. In reality, about 50,000 h of life span for LEDs used in lighting applications should be expected (Figs. 3.5, 3.6).

Generally on catalogs one can find information about LEDs such as:

- Dominant wavelength (color).
- Peak wavelength: it is the wavelength at the maximum spectral power. It does not necessary determine the color of the LED. Two LEDs can have the same peak wavelength and have different colors.

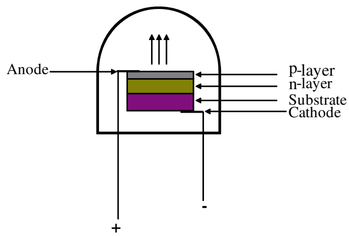


Fig. 3.6 LED architecture

- Luminous intensity.
- Spatial distribution of light (viewing angle or beam angle).

3.3.2 *LED Materials and Evolution*

Holonyak and Bevacqua presented in 1962 the first visible light LED, a red LED, based on III–V materials (combinations of elements from groups III to V in the periodic table of elements) while working at General Electric in Syracuse, New York in the USA [6]. Visible light LEDs involve semiconductors of band gap greater than 1.8 eV and less than 3.1 eV corresponding to a wavelength between 0.7 and 0.4 μm, respectively.

It is in the 1960s that the first LEDs were developed and made commercially available. They were based on GaAsP (gallium arsenic and phosphorus) and generated red light at 655 nm with a luminous intensity of about 1–10 mcd at a current of 20 mA. These light sources found their applications primarily in indicators. After GaAsP, GaP (gallium phosphide) red LEDs were developed to obtain a higher efficiency, but there was no revolution in their applications.

In the 1970s new colors of LEDs became available: green based on GaP, orange and yellow based on GaAsP (gallium arsenic phosphide).

In the 1980s GaAlAs (gallium aluminum arsenide) LEDs were developed as a result of an active research [7]. The efficiency was higher, driving voltage lower for better power usage. Also, research in the domain of laser diodes allowed the development of InGaAlP (indium gallium aluminum phosphide) to have the production of red, yellow, orange and green LEDs based on the same basic technology for better light output and life span.

In the 1990s the high brightness blue LEDs were developed. The blue LEDs could be developed based on GaN (gallium nitride), SiC (silicon carbide) and ZnSe (zinc selenide) because of the width of their band gaps. Nevertheless, SiC was not a good candidate because of its indirect band gap and ZnSe blue LEDs were developed, but not commercially available because of their short life span. The research on GaN started in the 1970s eventually led to the success of blue LEDs in the 1990s with a better material process developed by Nakamura and his team in Japan [8, 9]. In 1993 Nichia Industries delivered the world's first blue LED which completed the RGB set (red green blue) that are the primary colors in the display industry. But the greatest revolution will be the possibility to generate white light based on blue LEDs using color combination or coating blue LED chips with a phosphor layer: Yttrium Aluminum Garnet (YAG).

As aforementioned, the majority of LEDs are made based on III–V compound semiconductors. LEDs can also be based on group IV materials such as silicon (Si) and carbon (C) for SiC LEDs or II–IV compounds such as ZnSe to generate the blue light. Nevertheless such materials easily show defect formations resulting in LEDs with shorter life spans. In comparison LEDs based on Al_yGa_{1-x-y} In_xN alloys have direct band gaps and higher material stability.

The life span of an LED is the number of hours of operation after which the LED loses 30% of its brightness. LEDs are today given a life span in the range between 50,000 and 100,000 h if used in conditions specified by the manufacturer compared to the range of 1,000 h for incandescent lamps and 10,000 h for fluorescent lamps. In operation, the life span of an LED is very much dependent of the base material (InGaN, InGaAlP, GaAlAs…) and the environment, especially the humidity and temperature that impose adequate packaging (as encapsulation) for a good heat evacuation Table 3.5 summarizes some LEDs characteristics.

3.3.3 Shockley Diode Equation

A semiconductor diode is made of a p-n junction based on a crystal semiconductor like silicon. The symbol of a diode is represented in Fig. 3.7.

The Shockley ideal diode equation gives the I–V characteristic of an ideal diode. It is also called the diode law and is written as:

$$I = I_S\left(e^{V_D/nV_T} - 1\right) \tag{3.1}$$

where

I is the diode current,

I_S is the reverse bias saturation current (or scale current),

V_D is the voltage across the diode,

V_T is the thermal voltage

and n is the ideality factor, also known as the quality factor or sometimes emission coefficient. It varies between 1 and 2 depending on the fabrication process and semiconductor material and in many cases is assumed to be approximately equal to one.

The thermal voltage V_T is approximately 25.85 mV at 300 K. Its temperature dependence is stated as:

$$V_T = \frac{kT}{q} \tag{3.2}$$

where k is the Boltzmann constant, T is the absolute temperature of the p-n junction and q is the charge of an electron.

Table 3.5 Typical LED characteristics

Wavelength (nm)	Color name	Fwd voltage (Vf @ 20ma)	Intensity 5 mm LEDs	Viewing angle	LED dye material
940	Infrared	1.5	16 mW @50 mA	15°	GaAlAs/GaAs–Gallium Aluminum Arsenide/Gallium Arsenide
880	Infrared	1.7	18 mW @50 mA	15°	GaAlAs/GaAs–Gallium Aluminum Arsenide/Gallium Arsenide
850	Infrared	1.7	26 mW @50 mA	15°	GaAlAs/GaAs–Gallium Aluminum Arsenide/Gallium Aluminum Arsenide
660	Ultra Red	1.8	2,000 mcd @50 mA	15°	GaAlAs/GaAs–Gallium Aluminum Arsenide/Gallium Aluminum Arsenide
635	High Eff. Red	2.0	200 mcd @20 mA	15°	GaAsP/GaP–Gallium Arsenic Phosphide/Gallium Phosphide
633	Super Red	2.2	3,500 mcd @20 mA	15°	InGaAlP–Indium Gallium Aluminum Phosphide
620	Super Orange	2.2	4,500 mcd @20 mA	15°	InGaAlP–Indium Gallium Aluminum Phosphide
612	Super Orange	2.2	6,500 mcd @20 mA	15°	InGaAlP–Indium Gallium Aluminum Phosphide
605	Orange	2.1	160 mcd @20 mA	15°	GaAsP/GaP–Gallium Arsenic Phosphide/Gallium Phosphide
595	Super Yellow	2.2	5,500 mcd @20 mA	15°	InGaAIP–Indium Gallium Aluminum Phosphide
592	Super Pure Yellow	2.1	7,000 mcd @20 mA	15°	InGaAlP–Indium Gallium Aluminum Phosphide
585	Yellow	2.1	100 mcd @20 mA	15°	GaAsP/GaP–Gallium Arsenic Phosphide/Gallium Phosphide
4500 K	"Incan-descent" White	3.6	2,000 mcd @20 mA	20°	SiC/GaN–Silicon Carbide/Gallium Nitride

(continued)

Table 3.5 (continued)

Wavelength (nm)	Color name	Fwd voltage (Vf @ 20ma)	Intensity 5 mm LEDs	Viewing angle	LED dye material
6500 K	Pale White	3.6	4,000 mcd @20 mA	20°	SiC/GaN–Silicon Carbide/Gallium Nitride
8000 K	Cool White	3.6	6,000 mcd @20 mA	20°	SiC/GaN–Silicon Carbide/Gallium Nitride
574	Super Lime Yellow	2.4	1,000 mcd @20 mA	15°	InGaAlP–Indium Gallium Aluminum Phosphide
570	Super Lime Green	2.0	1,000 mcd @20 mA	15°	InGaAlP–Indium Gallium Aluminum Phosphide
565	High Efficiency Green	2.1	200 mcd @20 mA	15°	GaP/GaP–Gallium Phosphide/Gallium Phosphide
560	Super Pure Green	2.1	350 mcd @20 mA	15°	InGaAlP–Indium Gallium Aluminum Phosphide
555	Pure Green	2.1	80 mcd @20 mA	15°	GaP/GaP–Gallium Phosphide/Gallium Phosphide
525	Aqua Green	3.5	10,000 mcd @20 mA	15°	SiC/GaN–Silicon Carbide/Gallium Nitride
505	Blue Green	3.5	2,000 mcd @20 mA	45°	SiC/GaN–Silicon Carbide/Gallium Nitride
470	Super Blue	3.6	3,000 mcd @20 mA	15°	SiC/GaN–Silicon Carbide/Gallium Nitride
430	Ultra Blue	3.8	100 mcd @20 mA	15°	SiC/GaN–Silicon Carbide/Gallium Nitride

Fig. 3.7 Diode symbol

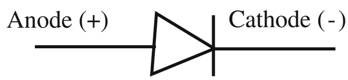
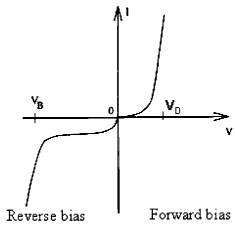


Fig. 3.8 I–V characteristics of a p-n junction diode



This model does not represent the reverse breakdown. For forward bias voltages V_D across the diode is important compared to the thermal voltage V_T, the current voltage dependence is well approximated from Eq. 3.1 by:

$$I = I_S e^{V_D/(nV_T)} \tag{3.3}$$

3.3.4 Current–Voltage Characteristic of LEDs

An LED or in general a diode's I–V characteristic can be divided into four domains of operations (Fig. 3.8), two regions under reverse bias and two regions under direct or forward bias. The structure of the curve is determined by the transport of electrons and holes through the depletion region of the diode under an applied external voltage.

If an external voltage is applied across the diode with the same polarity as the built-in potential, the depletion layer which is an insulator will have its width increased preventing any significant electric current to flow through the junction. The diode is said to be under a reverse bias: the applied potential on the p side is lower than the applied potential on the n side of the junction. At very large reverse bias, beyond the breakdown inverse voltage V_B, a process called reverse breakdown occurs which causes a large increase in the current that generally damages the diode permanently. The second region under reverse bias (V negative but less than V_B in absolute value) has only a very small reverse saturation current. However, this current is temperature dependent, and at sufficiently high temperatures, a substantial amount of reverse current can be measured.

On the other hand, if the polarity of the external voltage opposes the built-in potential, the diode is said to be under direct or forward bias; the applied electric potential on the p side is higher than the potential on the n side. In this case, recombination can occur when the applied voltage (or electric field) exceeds the built-in voltage (or electric field), V greater than V_D in Fig. 3.8, resulting in substantial electric current through the p-n junction. In the third region the forward voltage is low; V is less than the threshold voltage V_D, where only a small forward current is conducted. The fourth region comes in when the potential difference is increased above V_D, defined as the threshold voltage or diode forward voltage drop, where the diode's current becomes appreciable and the diode is said to be switched on. The current depends exponentially on the voltage above V_D. The value of the threshold voltage depends on the nature of the base semiconductor, for silicon diodes the switch on voltage is about 0.7 V but it is different for other type of diodes.

3.3.5 Driving LEDs

3.3.5.1 Constant-Current Driver Circuit

The electronic circuit powering LEDs should have an important consideration when evaluating LED lights. Many simple driver circuits provide a constant voltage, meaning that the output current varies with the LED's voltage. A constant-voltage driver can cause early LED failure as shown in the current voltage dependence in Fig. 3.8. As the LED's temperature increases, its threshold voltage drops, causing a constant-voltage driver to supply more current in response to the decreased LED voltage; this is because of the band gap decrease in semiconductor with increasing temperature. A current over a certain limit will damage the LED.

Proper LED driver circuits supply a constant DC current, holding steady as the LED voltage changes with temperature. LEDs are inherently dimmable as their brightness is a function of their current.

LEDs are current-driven devices whose brightness is proportional to their forward current. Forward current can be controlled in two ways. The first method is to use the LED I–V curve to determine what voltage needs to be applied to the LED to generate the desired forward current. This is typically accomplished by applying a voltage source and using a ballast resistor. However, this method has several drawbacks. Any change in LED forward voltage creates a change in LED current.

The second preferred method of regulating LED current is to drive the LED with a constant-current source. The constant-current source eliminates changes in the current due to variations in forward voltage, which translates into a constant LED brightness. Generating a constant-current source is fairly simple. Rather than regulating the output voltage, the input power supply regulates the voltage across a current-sense resistor. The power-supply reference voltage and the value of the current-sense resistor determine the LED current. Multiple LEDs should be connected in a series configuration to keep an identical current flowing in each LED. Driving LEDs in parallel requires a ballast resistor in each LED string.

3.3.6 Driving LEDs with an AC Voltage

An LED under an alternative current (AC) voltage will conduct only during the positive part of the cycle, when the bias appears as forward bias. During that positive portion of the cycle the LED will conduct, so it emits light only when the voltage is higher than its threshold voltage. The period of light emission will consequently last less than half of the cycle; the brightness also might reach its peak only if the maximum of the AC voltage equals the voltage that can force enough current in the LED for its maximum brightness.

Second, even when the LED is conducting, the average voltage will be far less than the peak voltage. For a sine wave voltage, the average voltage of the positive half is about 36% lower than the peak voltage. When using an AC signal which amplitude equals the peak voltage, in the negative portion of the cycle it is necessary to compare that voltage with the maximum reverse voltage that would permanently damage the LED. This can be overcome by combining an extra diode that will impose a new threshold voltage.

Another solution is to incorporate a full-wave bridge rectifier circuit that makes both halves of the cycle positive to drive the LED when the voltage reaches its threshold value. It is also possible to operate jointly two LEDs in reverse-parallel, so that one emits light during the positive half of the cycle, and the other generates light during the negative half. This increases twice the light output, since both halves of the cycle are being used. Furthermore, using a square wave AC instead of sine wave AC would allow reaching almost 100% of brightness when using two reverse-parallel LEDs.

One can find in the market LED drivers that will convert the AC voltage into DC, specially made for LEDs, with voltage compensators to overcome the heat effects. AC LED lamps also have a built-in converter. However, the use of converters will result in some loss.

Seoul semiconductor in South Korea has developed direct AC LEDs without any additional electronic circuitry. In their approach different regions of the chip will switch ON or OFF depending on the part of the cycle. Other companies such as the Lynk Labs have developed more or less equivalent systems.

The research is ongoing for new approaches to drive LEDs directly and efficiently with AC power.

3.3.7 Power LEDs

LED-based lights have been on the market for a few years. The first generations of LED lights were not powerful enough for general illumination. New, high-power LEDs allowed manufacturers to design LED lights with enough power to fit lighting applications.

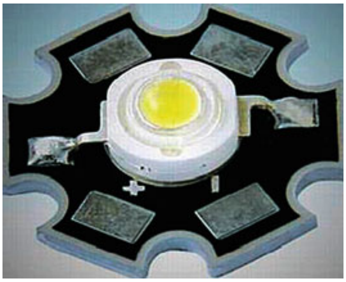


Fig. 3.9 Typical power LED mounted on a metal plate for heat evacuation

High-power LED chips have power ratings greater than 1 W and are identifiable by a large metal pad at the bottom of the LED package Fig. 3.9. Metals are good heat conductors, this metal pad provides a direct path for heat to escape the LED, usually by means of an adjacent heat sink. An LED's lifetime is specified as the time for its light output to degrade to 70% of its initial output. Manufacturers specify 70% lifetimes between 50,000 and 100,000 h. However, to achieve the LED's predicted lifetime rating, the light must operate within the manufacturer's temperature limits. Operating LEDs at high temperatures reduces their lifetime.

To guarantee the LEDs' rated life (the expected average operating life), manufacturers accurately test their devices under drastic control conditions in order to ensure the life span they predicted. Low-quality LEDs shows a shorter lifetime due to poor process control as in the semiconductor fabrication.

As for the processor of a computer, high-power LEDs must be cooled with a heat sink combined with a fan if necessary. Because LEDs do not radiate any heat, the metal pad provides the only path for heat to leave the LED. The heat wasted in the LED propagates from the LED die through the circuit board, the metal slug, into a heat sink and then out into the surrounding air.

3.3.8 About LED Light

3.3.8.1 High Efficiency

LEDs are current-driven devices that require current limiting when driven by a voltage source. In most applications, it is desirable to drive LEDs with a constant-current source. The current source is used to regulate the current through the LED regardless of power supply (voltage) variations or changes in forward voltage drops.

LEDs are no longer just used for providing the pretty red and green indicator lights on electronic equipments. Advances in technology have allowed LEDs to be used as practical sources of illumination. The primary benefits of LEDs are durability and efficiency. When driven properly, a power LED can last up to 100,000 h without degradation in the light output. The typical efficacy of a power LED, measured in lumens per watt, is between 50 and 80 lm/W. This is several times greater than incandescent light sources and comparable with fluorescent

Fig. 3.10 Example of LED light bulb with E27 base

lights. Since the LED is a solid-state device, it can withstand shock and vibration that would damage a filament bulb or glass envelop.

For a highly efficient LED control, LEDs must be driven with a constant-current source. Most LEDs have a specified current level that will achieve the maximum brightness for that LED without premature failures. An LED could be driven with a linear voltage regulator configured as a constant-current source. However, this approach is not practical for higher power LEDs due to power dissipation in the regulator circuit. A switch-mode power supply (SMPS) provides a much more efficient solution to drive LEDs.

An LED will have a forward voltage drop across its terminals for a given current drive level. The power supply voltage and the LED forward voltage characteristics determine the SMPS design that is required. Multiple LEDs can be connected in series to increase the forward voltage drop at the given driving current level.

3.3.8.2 Directionality of LED Light

The light output from an LED is directional, within a certain angle rather small, so as to create a light bulb with a 360^0 distribution effect as with an incandescent light bulb, LED chips need to be assembled and oriented in different direction. Figure 3.10 shows a typical 360^0 LED light bulb.

3.3.8.3 LED Light Diffusion

Bear power LEDs generate harsh light that is too bright in comparison with the surrounding bringing discomfort or even pain in the eyes when directly stared at. It makes necessary the integration of power LEDs in home lighting to diffuse the light emitted by power LEDs. Any material that can diffuse or spread out LEDs' light in order to give a softer light that can be used. Depending on the application the diffuser can be made of coated or structured glass, and clear or opaque plastics.

3.3.8.4 Color Rendering Index

The perception of objects' colors by the human eye depends on the source of illumination. The same object might appear in a different color in daylight or under a low-pressure sodium lamp. The color rendering index (CRI) of a light source is rated on a 100 scale. It informs about the fidelity in the appearance of the colors as the light source may allow the human eyes to perceive them. It measures the ability of a light source of restituting faithfully the color of an object. A high color rendering index is desirable for a light source as much as its efficiency for a good acceptance.

The color rendering index of incandescent light sources is almost 100, it can reach 95 for fluorescent lights while for LEDs it is in the range of the 80s. It is very poor for low-pressure sodium (HPS) lamps, under 25.

The CRI was first defined in 1974 by the CIE (Commission Internationale de l'Eclairage) but scientists have established other methods of evaluation [10]. In fact in 2007 the CIE mentioned that is not recommended to use it with white LEDs. Nevertheless, in general in order to evaluate the color rendering of a light source, it is compared to a reference light source that is supposed to render the colors perfectly and is given a CRI of 100.

Remark: CRI has been used to compare different light sources, but in 2007 [11, 12] CIE expressed its reserve regarding its use with white light LEDs and suggested that a new metric should be developed.

CIE Technical Report 177:2007, *Color Rendering of White LED Light Sources*, states, "The conclusion of the Technical Committee is that the CIE CRI is generally not applicable to predict the color rendering rank order of a set of light sources when white LED light sources are involved in this set." For the simple reason that the predicted CRI for white LED both phosphor- and RGB-based did not correspond with the reality of the observer who would appreciate a good color rendering.

3.3.8.5 Color Correlated Temperature

This concept comes from the black body radiation. By association the color of a heated metal will change with its temperature. As the metal gets hotter, it starts as red and changes gradually to orange, yellow, white and then blue–white. This corresponds with incandescent lamps but is not appropriate for other light sources such as fluorescent lights or LEDs. For these light sources the concept of correlated color temperature which is not at all an indication of the temperature of the light source, but just a comparison of their appearances is used.

In the lighting industry, the color correlated temperature, expressed in Kelvin, of a light source is described by its warmness or coolness. It may sound confusing but, higher color temperatures (3,600–5,500 K) are considered cool, while lower color temperatures are considered warm (2,700–3,000 K). Cool light is generally chosen for visual tasks due to its ability to restitute higher contrast than warm light. While warm light is generally indicated for indoor applications.

According to the definition, the color correlated temperature of a light is different from the definition of the color of light. The definition of the color of light can be based on a first approach on the coordinates on three axes of pure spectral colors considered as primary color 700.0 nm for red, 546.1 nm for green and 435.8 nm for blue. If X, Y and Z are the axes of the three colors then a color will be evaluated by its weight x, y and z on each axis, respectively as:

$$\text{Color} = xX + yY + zZ$$

This is based on the conception of an equal energy distribution to obtain white light while mixing the colors red, green and blue.

The Commission International de l'Eclairage (CIE) has defined in 1931 the first accepted standard definition of a light color in relation to the wavelengths it contains. This system known as the CIE color model can be considered as an evolution of what is known as the Maxwell triangle. The CIE theory is based on the fact that human eyes contain in the retina three types of color sensors called cones, which respond differently depending on the wavelength. The responses of these three types of color receptors are measured using three variables X, Y and Z.

3.3.8.6 White LEDs

White LED brought the real revolution in the lighting industry and was made possible with the creation of blue and UV LEDs. By nature of semiconductors, there is no unique band gap that can emit white light. In order to generate white light from LEDs two main processes are used in inorganic LEDs: wavelength mixing and wavelength conversion. White LEDs made from wavelength mixing are based on three colors; Red, Green and Blue are mixed. This technique presents the advantage of offering the control of the tone of the white light by changing the proportion of the different colors.

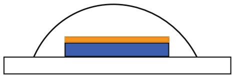


Fig. 3.11 White LED with the phosphor on the die

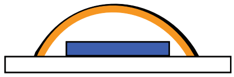


Fig. 3.12 White LED with the phosphor on the epoxy

Fig. 3.13 Five millimeter round diameter LED with in a clear package

In the phosphor-based white LEDs the process is based on wavelength conversion due to the photoluminescent properties of phosphor. In general white light is made from blue or near-ultraviolet LED whose radiation is absorbed by a phosphor-coated surface before being reemitted in a white color similar to fluorescent lights (Figs. 3.11, 3.12). The phosphor can be deposited on the LED die directly or on the plastic housing as shown in Figs. 3.11 and 3.12.

Generally, commercially available white LEDs are based on InGaN blue LEDs coated with a cerium (Ce) doped yttrium aluminum garnet (YAG) phosphor, YAG:Ce [13]. In order to use LEDs for general lighting and make them good replacements for incandescent and fluorescent lamps, the most important requirement that LEDs should fulfill besides efficiency and life span, is a good color rendering. Good color rendering of LEDs should be combined with their good power efficiency. In the very first white LED, a 5 mm package, the phosphor was dispersed within an epoxy resin that surrounded the blue LED die (Fig. 3.13).

The main difference between a blue and a similar white LED is the phosphor dispersed within the epoxy surrounding the die or over the die itself. The color of LED lamps is completely controlled by the selection of the appropriate phosphors, giving the required control over the lamp color for many general illumination applications. However, achieving this goal will require optimization of all aspects of white LED lamps including the phosphor efficiency.

The efficacy of solid-state lighting based upon InGaN LEDs has improved by more than ten times over the last decade: the efficacy of cool white LEDs can surpass those of linear fluorescent lamps (more than 100 lm/W) and warm white LED 1 W LEDs surpass compact fluorescent lamp efficacies (more than 50–80 lm/W). For 2015, the US department of Energy plans the efficacy of warm white packages to

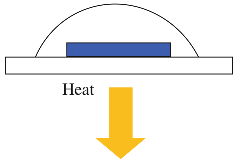


Fig. 3.14 LED heat evacuation

reach 138 lm/W; this will be a significant technical achievement that would lead to a greater market penetration of solid-state lighting. As may be expected, the inclusion of a small amount of red phosphor with YAG:Ce improved the CRI to acceptable range (a color rendering index higher than 80) and increased the light conversion. The phosphors and phosphor blends of interest have excitation frequencies in the desired range of near-UV and blue (380–450 nm) and emit in bands across the visible spectrum.

3.3.8.7 Temperature Deterioration and Aging of LEDs

The reliability of a lighting system is in the lumen power maintenance and color variation minimization. As the market of white high brightness LEDs is continuously growing, LEDs with several watts of input electric power are available. This makes them ideal candidates to replace classic lighting systems. The self-heating of these devices is also increasing with the power input.

In contrast to incandescent and fluorescent lights the heat generated in an LED is not radiated as part of the its monochromatic spectrum (Fig. 3.14). One of the weak points of LEDs is the necessity of heat management. Overheat of an LED will result in junction deterioration, the epoxy color changing and deterioration leading to transmittance reduction and refractive index variation of the phosphor. The consequences are a lower lumen output and the modification of spectral properties (color); in other words lower brightness and color variation. A microscopic analysis shows that the effects of temperature stress on the LED packaging is the carbonization of the plastic package of the device.

To maintain the high light output of an LED and ensure a long life span, it is necessary to efficiently evacuate the heat.

Incandescent light bulbs convert about 8% of the input electric power into visible light, and the rest is radiated in the form of heat. For fluorescent lights the ratio is about 21% of the input electric power that is converted into light and the rest into heat. For LEDs, 15–25% of the input electric power is turned into light, the rest heats up the device itself and needs to be effectively evacuated.

3.3.9 Haitz's Law

Haitz's Law (Figs. 3.15, 3.16) is considered to be the LED equivalent of Moore's Law, which states that the density of transistors on integrated circuits doubles

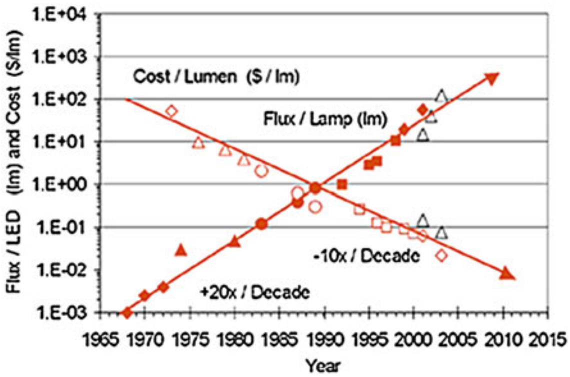


Fig. 3.15 Haitz' Law [14]

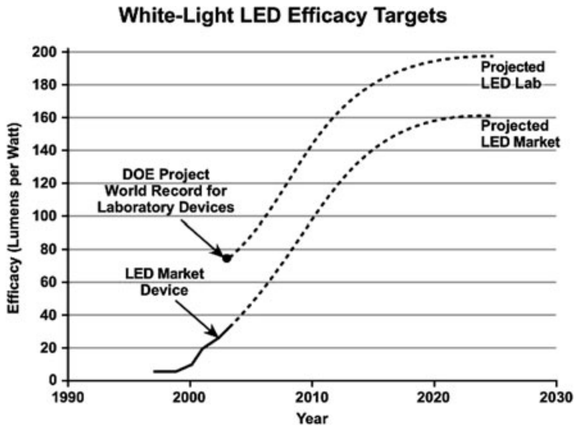


Fig. 3.16 Haitz' Law for white light [15]

every 18–24 months. Moore's Law announced in 1965 has so far been verified. Haitz's Law presented in 2000 has also been proven accurate so far. The materials and processes to make LED will be continuously improving leading to more efficient lighting devices. Through Haitz's law one can assume that LEDs will be brighter and of lower cost, so more and more competitive compared to other light sources such as fluorescent lighting. It states, as we can see from the graphs in Figs. 3.15 and 3.16 that every 10 years the price of LEDs will decrease by a factor of 10, while their performances will improve by a factor of 20.

3.3.10 LED Lamps

LED chips can be made with light efficacy reaching 100 lm/W, equivalent of fluorescent lamps and their efficiency 80% better than incandescent light bulbs. LED chips can be associated in different forms to make lamps in order to replace different household lamps with different type of bases as halogen lamps,

Fig. 3.17 LED lamps for replacement of E27 screw base lamp (*left*) MR16 Halogen lamp (*middle*) and fluorescent tube (*right*)

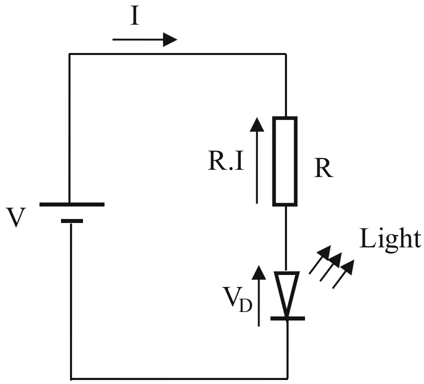


Fig. 3.18 Simple LED circuit diagram

incandescent lights, compact fluorescent light bulbs and fluorescent light tubes (Fig. 3.17). Lamps made from LEDs are equipped with electronic circuitry in order to turn the AC voltage to DC. Also, there is a heat evacuation system to avoid high heat that would destroy the lamp. LED lamps are generally made in different levels of color correlated temperature from cool white 6,400 K to warm white 2,700 K.

3.3.11 Basic LED Circuit

The most basic LED circuit (Fig. 3.18) consists of an LED powered by a DC voltage in series with a current limiting resistance R. The LED is specified by its driving voltage V_D and maximum current I_m given by the manufacturer. V_D will be the voltage drop between the two poles of the LED. For a certain level of brightness, if the current I ($I < I_m$) is supposed to flow through the diode, the resistor value R is determined as follows:

$$V = R.I + V_D \tag{3.4}$$

$$R = (V - V_D)/I \tag{3.5}$$

For maximum brightness, the resistance is, R_{min} and the current is I_m, hence:

$$R_{min} = (V - V_D)/I_m \tag{3.6}$$

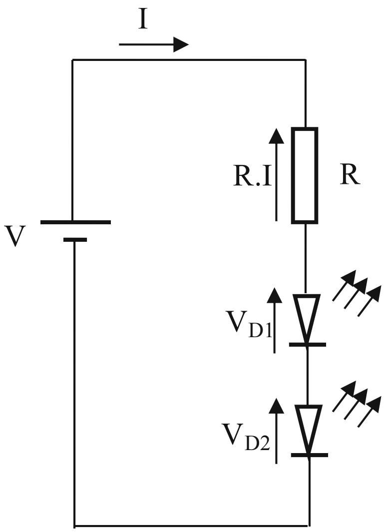


Fig. 3.19 LEDs in series

V is the voltage of the power supply, as a 9 V battery. The LED voltage drop (V_D) is the voltage drop across the LED. Typically, this is between 1.5 and 4 V depending on the color of the LED. A red LED typically drops 1.8 V, but voltage drop normally rises as the light frequency increases, a blue LED may drop around 3.3 V. The LED current rating (I_m) is the manufacturer rating of the LED (although the above formula requires the current in amperes, this value is usually given by the manufacturer in milliamperes, such as 20 mA).

When LEDs are placed in series (Fig. 3.19) the rule to calculate the limiting current stays the same but in this case we have to add the different voltages of the different LEDs.

When connected in parallel each LED should have its current limiting resistance connected in series with it (Fig. 3.20).

3.3.11.1 Table of technical data for LEDs

LED suppliers provide catalogs with technical data that specify their parameters of operation. The three most important information are the color, the maximum brightness current I_f and the driving voltage V_f. Table 3.6 shows the typical technical data for some 5 mm diameter round LEDs.

3.3.12 Solar LED Street Light

Street lights commonly use high discharge lamps as high pressure sodium lamps or mercury lamps. The evolution of LED technology makes it possible to replace

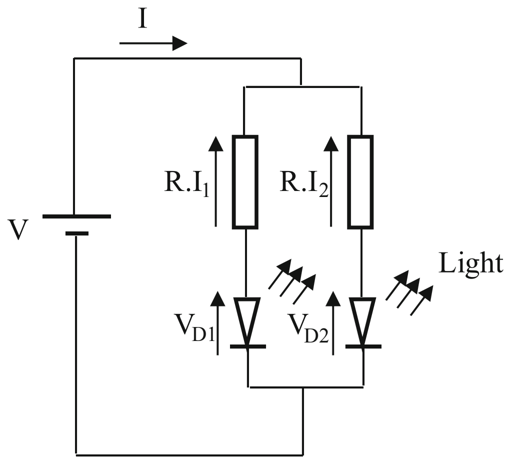


Fig. 3.20 LEDs in parallel

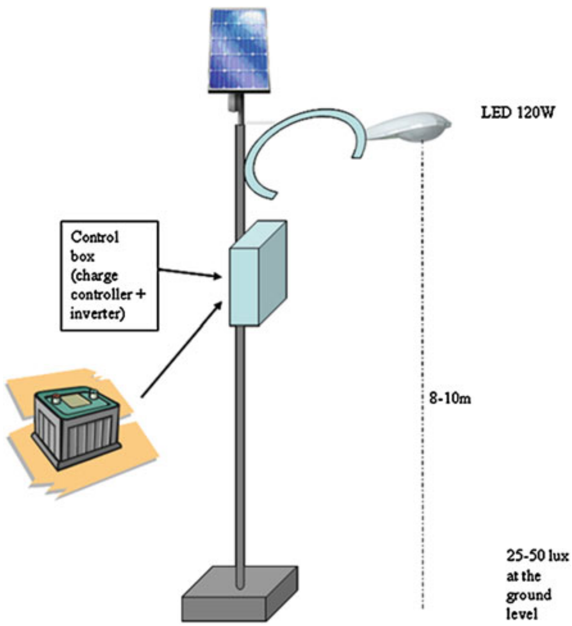
Table 3.6 Example of common technical data for some 5 mm round LEDs with diffused package

Type	Color	I_{Dmax}	V_{Dtyp}	V_{Dmax}	V_{Rmax}	Luminous intensity	Viewing angle	Wavelength
Standard	Red	30 mA	1.7 V	2.1 V	5 V	5 mcd @ 10 mA	60°	660 nm
Standard	Bright red	30 mA	2.0 V	2.5 V	5 V	80 mcd @ 10 mA	60°	625 nm
Standard	Yellow	30 mA	2.1 V	2.5 V	5 V	32 mcd @ 10 mA	60°	590 nm
Standard	Green	25 mA	2.2 V	2.5 V	5 V	32 mcd @ 10 mA	60°	565 nm
High intensity	Blue	30 mA	4.5 V	5.5 V	5 V	60 mcd @ 20 mA	50°	430 nm
Super bright	Red	30 mA	1.85 V	2.5 V	5 V	500 mcd @ 20 mA	60°	660 nm
Low current	Red	30 mA	1.7 V	2.0 V	5 V	5 mcd @ 2 mA	60°	625 nm

I_{Dmax} is the maximum forward current
V_{Dtyp} is the typical forward voltage
V_{Dmax} is the maximum forward voltage
V_{Rmax} is the maximum reverse voltage
1 mcd = 10^{-3} cd = 1 millicandela
Viewing angle: standard LEDs have a viewing angle of 60°; others emit a narrower beam of about 30°

250 W mercury lamps with 120 W LEDs lighting systems. For a number of municipalities, public lighting represents an important portion of their budget which they need to lower. LED street lighting as a capital investment is an opportunity to achieve that goal of cost reduction.

Fig. 3.21 Example of solar LED Street light



Advantages of LED street lights:

- Lower energy consumption
- Lower maintenance cost
- Longer life span
- Good automatic control
- Fast response
- Environment friendly
- Better illuminance uniformity
- Higher color rendering giving better night visibility
- No mercury or lead hazards

Solar street lights (Fig. 3.21) reduce cost and maintenance of street light, and keep away power outage problems, with only the battery (if lead-acid) to be changed periodically (about every 3–5 years).

Sizing a solar LED street light:

Example:

Objective: 25–50 *lux at the ground level with lamp at* 8–10 *m of the ground*

LED 120 W

Operation duration daily: 10 h

Energy need daily: $120 \times 10 = 1200$ Wh

Solar panel for 4 h of daily sunlight: 300 W

Battery lead-acid 12 V: 100 Ah/0.5 = 200 Ah

Charge controller 12 V-30 A

Inverter 200 W

Fig. 3.22 LED lamp with an E40 screw

In this example the system will be running on a daily basis without extra autonomy. In a commercial system the customer should have the option of choosing the number of days of autonomy depending on how critical the weather is.

The opening angle of the LED light beam will control the distance between the two light poles in order to have 100% coverage at the ground level.

If the same system was to use a mercury lamp of 250 W, the amount of energy needed daily would be:

250 W $\times$ 10 h = 2500 W h

Solar panel for 4 h of sunlight daily: 625 W

Battery: 210 A h/0.5 = 420 A h

Controller 12 V-50 A

In this case besides the cost increase there is a real problem of space to instal the solar panels or to store the batteries. This gives another advantage to LEDs for street lighting applications.

Along with the LED a solar street light can use a smart controller to further reduce the energy consumption. The most basic smart controller will turn the light ON at dusk and switch OFF at dawn; this can be done by sensing the current or voltage from the solar panel. Other controllers are additionally equipped with a timer that will switch the light OFF after a certain number of hours of operation. The smartest controller will dim the LEDs gradually and periodically depending on the environment and the neighborhood for instance, to switch it completely OFF at dawn. For example the LED will operate at full power for the first 4 h after dusk before being 30% dimmed after 2 h and 30% dimmed again after 2 h and switch OFF at dawn. LED street lights can be based on DC system, 12, 24 V generally in the case of solar street lighting, in this case there is no need for an inverter.

The design of LED street lights depends on the usage of LED lamps equipped with a heat sink and a base as an E40 base (Fig. 3.22) in which case they can replace existent lamps; the system can also be a system in which the LED and the heat sink are built in the fixture making only one block (Fig. 3.23). In either case the LED light does not use a reflector as in other lighting systems such as HPS lamps, thus reducing the efficiency loss.

Fig. 3.23 Street light fixture with buil-in LEDs and heat sink

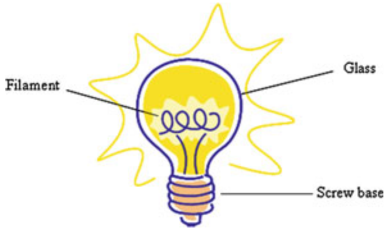


Fig. 3.24 Incandescent light bulb

LED street lights can use high power LEDs, as 1 W single chip LED or lower power LEDs in different numbers to achieve the same power. In both cases they need an adequate lensing system for good expansion of the beam.

3.4 Other Ways of Making Light from Electricity

3.4.1 Incandescent Light Sources

An incandescent light bulb is made of a thin glass enclosure that envelops a tungsten filament, through which an electric current passes (Fig. 3.24). In general it is a bipolar and non-polarized device. The glass envelop is filled with an inert gas such as argon to reduce evaporation and prevent oxidation of the filament. While running through the tungsten filament, the electric current heats it up to typically 2,000–3,300 K (below tungsten's melting point of 3,695 K). For a given drawn amount of current, the filament temperature will depend mostly on its size. It radiates on a continuous spectrum but only a small portion of the radiation belongs to the visible range. Most of the consumed energy is radiated in the form of heat.

Higher power incandescent light bulbs are three-way light bulbs. They have two filaments and three feeding contacts in their bases. The two filaments share a common ground, and can be lit separately or together. The incandescent light bulb or incandescent lamp produces light by heating its tungsten filament to a high temperature until it glows. The hot filament is protected from air by the glass bulb that is filled with inert gas or evacuated.

Incandescent bulbs are produced in a wide range of sizes, light output and voltage ratings, from 1.5 V to about 300 V. They require no external regulating equipment, require low-manufacturing cost and work equally well on either alternating current or direct current. As a result, the incandescent lamp was widely used for household and commercial lighting, for portable lighting such as table lamps, car headlamps and flashlights, and for decorative or advertising lighting.

Incandescent light bulbs are gradually being replaced in many applications with fluorescent lamps or LEDs. These newer technologies improve the ratio of visible light to heat generation. Approximately 90% of the power consumed by an incandescent light bulb is emitted as heat, rather than as visible light.

A tungsten filament in its solid state radiates most of the consumed electric power in the infrared region. Even if the radiated visible light increases with the filament's temperature, at high temperatures (under melting point), a lot of the radiation is either infrared or ultraviolet. The theoretical limit of higher luminous efficacy for a tungsten filament at its melting point is about 52 lm/W.

Compared to LEDs or a fluorescent lamp, an incandescent light bulb produces more heat and therefore consumes more electric power for the given quantity of light (expressed in lm). LEDs or fluorescent lamps produce light by luminescence, rather than by heating a tungsten filament to incandescence as it is for incandescent light bulbs.

Tungsten halogen lamps are also incandescent light sources. Nevertheless, they are an improvement compared to standard incandescent light bulbs. They have a higher efficiency, up to 20% and greater life span.

In classical incandescent lamps the failure comes from the fact that the tungsten filament evaporates over time, getting thinner and thinner and eventually breaks. In halogen lamps the halogen gas makes the evaporated material to redeposit on the filament giving it a longer life span. These lamps are more expensive than the standard incandescent lamps and are generally used in commercial applications or outdoor lighting.

3.4.2 Fluorescent Light Sources

In a fluorescent light source electricity is used to excite mercury vapor, which produces ultraviolet radiations that will make a phosphor to fluoresce resulting in the production of visible light. It is called a gas discharge lamp. Fluorescent lamps are equipped with ballast in order to operate.

Fluorescent lamps have been mostly made in tubes but are also available in compact fluorescent lamp (CFL) form in order to replace incandescent light bulbs for more efficient energy consumption and environment issues. In its compact form, CFL, with an E27 screw base, can fit the fixture on to replace them without any mount modification (Fig. 2.25).

Fluorescent light sources have a higher conversion rate of electric power input into visible light output than incandescent light bulbs. Fluorescent light sources can reach up to 100 lm/W compared to the higher theoretical limit rated at 52 lm/W for incandescent light bulbs. So for a given amount of light output (in lm) a

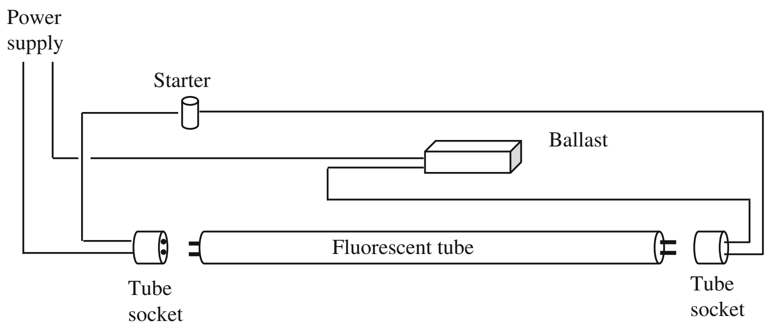


Fig. 3.25 Fluorescent light tube setup

fluorescent light bulb will produce less heat and consume less electric power. Their longer life span up to 10,000 h and power efficiency makes them cost effective.

Nevertheless fluorescent lamps present a certain number of disadvantages.The first one is its hazardous aspect because of the mercury they contain in the glass envelop that is rather fragile. The mercury imposes specific requirements for disposal and recycling. Fluorescent lamps emit a certain portion of ultraviolet (UV) light to which some people are sensitive. It can also affect art works or displays by its effects on colors. They will age rapidly if they are frequently turned ON and OFF because of the erosion of the electron-emitting surface of the cathodes every time the lamp is put into operation.

The efficiency of fluorescent lamps decreases with increasing temperature. They operate ideally at room temperature. Also, they may present difficulties when operated at very low temperatures that weather sensitivity will limit their applications, such as street lighting in very cold areas.

3.4.3 High-Intensity Discharge Lamps

High-intensity discharge (HID) lamps are commonly used in outdoor applications or large areas indoors. They present among the highest efficacy and life span. Their principle is based on an electric arc to produce intense light under an adequate voltage. The most common HID lamps are: mercury vapor which is the oldest one and less efficient, and high pressure sodium and metal halide lamps. Most of HID lamps radiate a significant amount of ultra violet rays that are harmful to human beings and animals.

3.4.4 Low Pressure Sodium Lamps

Low pressure sodium lamps are similar to fluorescent light sources in principle. They are the most efficient electrical lights and have a long life span, but suffer of very poor color rendering. For this reason they are mostly used only in places where color does not matter, and everything appears in a yellow or gray tone.

To compare the cost of light sources, one needs to go beyond the initial cost and consider the efficiency, life span and environmental impact. The initial cost of an incandescent bulb is very attractive compared to the cost of a florescent lighting device or an LED. To be accurate, a comparison of incandescent lamp operating cost with other light sources must be taken into consideration along with other parameters such as their different luminous efficacy (lm/W), illumination requirements and spatial constraints, aging effect and life span, and of course health and environment issues.

Challenges in making LEDs include:

- Choosing the right semiconductors for an effective radiative recombination of carriers and the emission of the right wavelength.
- Getting the light out of the semiconductor: overcoming total internal reflection and reabsorption.
- Making the right packaging for the diode: adequate light extraction and beam shaping and good heat sink for high-intensity applications for longer life span and stable chromaticity.

The evolution of LEDs' is not at its end and industries are in active research to improve LEDs luminous efficacy, color rendering, life span and cost to make them complete replacements of classical lighting systems. The coming years should witness a deeper market penetration by combination of a price drop, a better power efficacy and light quality and the continuous increase of environment concerns.

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Chapter 4
OLED Lighting Technology

4.1 Introduction

Since their discovery more than 50 years ago, organic light emitting diodes (OLEDs) have been viewed as holding significant benefits, particularly for use in display technologies. OLED technology is fast becoming a viable choice for energy efficient next-generation lighting. After the discovery of an efficient bilayer OLED technology in the mid 1980s, the device architecture was studied intensively [1–18]. Materials systems commercially available in the late 1990s showed that the OLED technology was considered as a possible next lighting technology [19–28]. Since 2000, there has been continual increase in the technology development of OLED for lighting, largely driven by traditional lighting companies such as Philips, Osram, General Electric (GE), and Panasonic, as well as technology providers such as Universal Display, Cambridge Display Technology, Kodak, and Novaled pushing their technology know-how beyond the display sector. This improvement in technology and product development has led to an explosive growth in the number of OLED lighting patents being filed as well as scientific and technical publications.

OLED-based solid-state lighting (SSL) is a candidate technology that offers significant gains in *power efficiency*, *color quality*, and *lifetime* at lower cost and less environmental impact over traditional incandescent and fluorescent lightings [29, 30]. The introduction of OLEDs light sources for general lighting applications will address issues like environmental pollution as it contains no toxic materials/gases and energy consumption and is likely to cause a major paradigm shift in the lighting industry.

4.2 What Makes WOLEDs Attractive

While solid-state inorganic light emitting diodes (LEDs) comprise point light sources, OLEDs could be used for power-efficient large area light sources or for general illumination with their revolutionary thin, flat, transparent, lightweight,

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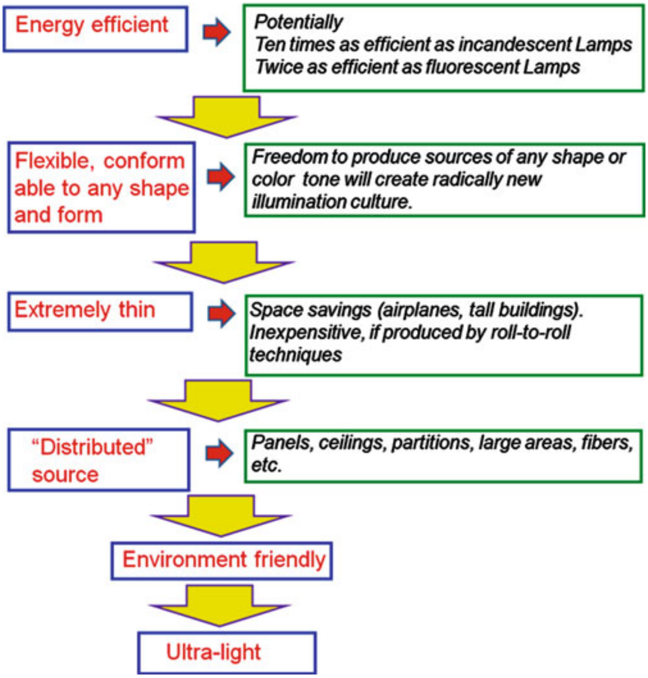


Fig. 4.1 Favorable features of OLEDs lighting

and flexible properties. They consume up to 70% less energy compared to conventional light sources, meaning that OLED lighting could also help to reduce energy consumption. Hence, it is hardly surprising that OLEDs are increasingly being seen as prime candidates for the next generation lighting. Figure 4.1 shows the favorable attributes of OLED lighting.

More recently, with the EU's objective of cutting at least 20% in CO_2 emissions by 2020, and studies by the European Union Joint Research Center (JRC) showing a huge potential for saving energy by creating better energy efficiency forming the backdrop, the lighting industry has gradually started to regard OLEDs as promising alternatives to conventional light sources.

For widespread commercialization and acceptance in the future, the development of 6×6 in, 45 lm/W (LPW) OLEDs that operate at a brightness of 1,000 cd/m^2 with an expected lifetime of >10,000 h are desirable. The device should produce high illumination quality light, i.e. it should have a color point located near the black body locus (<0.01 CIE units), a color temperature in the range 2,700–6,500 K, and a color rendition index, CRI >90. Therefore, the future goal and direction of researchers is to develop novel OLED designs and materials to produce a white OLED with energy efficacy better than the current designs by a factor of at least three.

Ultimately, the design should promise to achieve OLEDs with efficacies >100 LPW and outstanding color and spectral performance at low intrinsic manufacturing cost. Achieving this ultimate goal (>100 LPW) requires combining the control of the physics associated with devices grown by vapor deposition techniques, with the materials design flexibility and wide range of processing conditions that are possible using polymer materials.

4.3 OLED Light Source Overview

4.3.1 OLED Emission Principle

An organic light emitting device (OLED) is a heterostructural device consisting of an organic emitting layer (ETL), electron transport layer (ETL) sandwiched between an anode, generally transparent indium tin oxide (ITO), and a low work function cathode which is calcium, magnesium, or lithium fluoride-aluminum (Fig. 4.2). When a voltage is applied to the transparent electrodes, the current flow through the organic layers generates light as the electrons and holes recombine in the emissive layer. Figure 4.3 shows the principle of operation of multilayer OLEDs. Depending on the choice of organic materials for the emissive layer, OLEDs can be designed to emit any color, including white light with various color temperatures. This, in combination with high luminous efficacy and long lifetimes, reputedly makes OLEDs ideal candidates for architectural lighting applications.

The essential requirements for next-generation OLEDs for lighting applications are high brightness, reduced cost, and low power consumption. An efficient driving scheme, suitable efficient device configuration, and solid-state encapsulation are some of the technological options available in realizing these features.

Tang in 1982 and Tang and VanSlyke demonstrated that poor performance of the monolayer early device was dramatically improved in two-layer devices simply by addition of one hole transport layer (HTL) in the device structure [31]. Organic electroluminescent devices having improved power conversion efficiencies by doping the emitting layer were also realized around the same time by the Kodak group. Subsequently, heterostructure configurations to improve the device performance were implemented by inserting several layers such as buffer layer between anode and HTL, ETL, hole blocking layer (HBL), or interlayer between cathode and ETL in the device structure [2, 3]. Such multilayer structures often enhance the drive voltages of OLEDs. Usually, the operating voltage for higher brightness was much higher than the thermodynamic limit, e.g., 2.4 eV for a green device. Chemical doping with either electron donors (for electron transport materials) or electron acceptors (for hole transport materials) can significantly reduce the voltage drop across these films. Multilayer structure devices with either HTL- or ETL-doped layer show improved performance, but the operating voltages were still rather higher than the thermodynamic limit. Subsequently, Leo and his

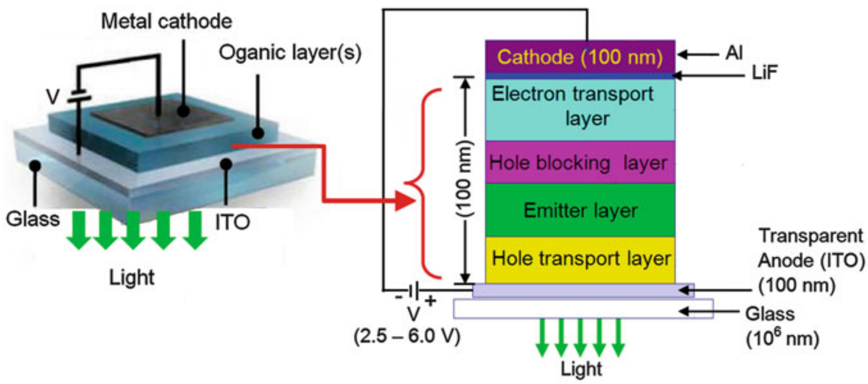


Fig. 4.2 Heterostuctural device structure of typical OLEDs

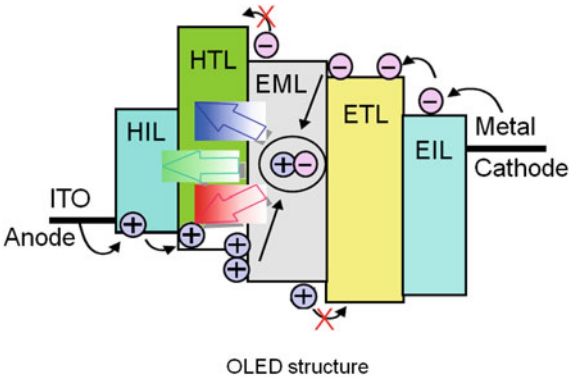


Fig. 4.3 Principle of operation of the multilayer OLEDs

group proposed the concept of p-type doped HTL and n-type doped ETL [32–34]. These pin structure devices show high luminance and efficiency at extremely low operating voltages. Indeed all these devices have multilayer structures with high current and power efficiencies, but thin emitting layer. Nevertheless, the narrow thickness of the emitting layer in pin PHOLEDs and the complex design architecture of phosphorescent OLEDs are not desirable from the manufacturing perspective.

To date, lighting applications of OLEDs have been hindered by two major factors: (1) relatively limited life (about 5,000 h to the L50 (50% decrease in output)) compared with about 20–50,000 for conventional high brightness (HB) LEDs and (2) significant lower light output than HB LEDs (about 25 lumens versus 100–150 + lumens). However, the radically different physical form of OLEDs from conventional LEDs have advantages for future lighting technology and make them the next disruptive technology in SSL.

4.3.2 *OLED Types*

4.3.2.1 Classification by Emission Layer Formation Process

The organic material, serving as a light emitting layer, is available in two types according to the molecular weight of the organic compound used: low-molecular type and high-polymer type. The two types of organic materials offer no distinct difference in the principle of light emission but involve some differences in terms of manufacturing the electroluminescent (EL) element.

Small Molecular Type

The principle of light emission was discovered first for the low-molecular type of organic materials, which have been placed into practical application based on the earlier advanced development [31]. The vacuum thermal evaporation process was used for deposition of thin film layers of small molecule organic materials on the required areas by using a shadow mask [35]. The multilayer structures of fluorescent and phosphorescent OLEDs are shown in Fig. 4.4.

In practice, however, this method requires higher temperatures for deposition to convert the low-molecular type organic material into a gaseous state, during which the metallic shadow mask will expand, creating a potential problem of an unevenly formed organic film layer. The temperature influence becomes even more significant for larger panel sizes (requiring larger shadow mask sizes). Therefore, at present, upsizing EL panels using low-molecular type organic materials are considered difficult to implement.

Polymer Type

On the other hand, for the high-polymer type of organic materials, the mainstream manufacturing process of EL panels includes the ink jet method or spin coating, taking advantage of the high degree of solubility of these organic materials in liquid [36–39]. The device structure of polymer organic light emitting diode (P-OLEDs) is displayed in Fig. 4.5. This ink jet method applies the organic materials to the areas requiring pixels, precisely allowing for micro-level control of the formation of the film layers. The method features higher efficiency of material consumption and is expected to be more suitable for upsizing and cost reduction compared to the methods used for the low-molecular type of organic materials.

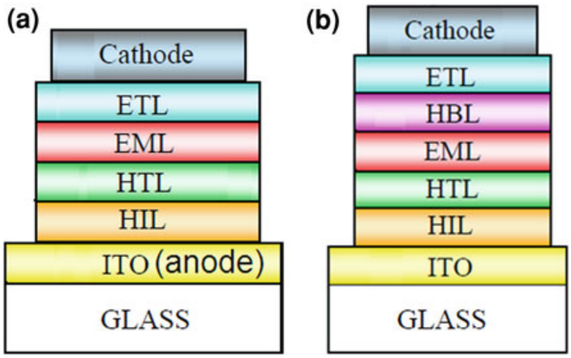


Fig. 4.4 Small molecule-based OLED fabricated using vacuum thermal deposition process **a** fluorescence and **b** phosphorescence

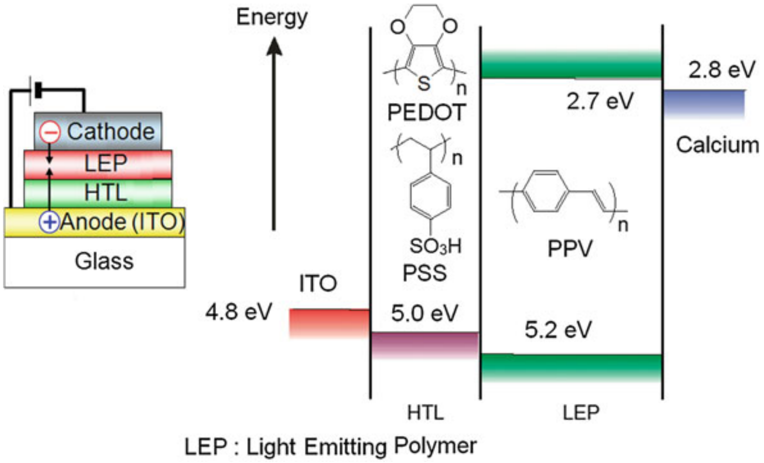


Fig. 4.5 Device structure of light emitting polymer

4.3.2.2 Classification by Emission Mechanism of Emitting Material

Fluorescence OLEDs use only singlet state (25%) for light emission, thus 75% of the charges injected from electrodes undergo non-radiative decay process which has a negative effect on the device stability. Figure 4.6 shows the emission mechanism of fluorescence OLEDs.

In recent years, PHOLEDs are gaining a dominant position in the field of OLED devices owing to their superior efficiency, which makes them suitable for high performance high brightness displays and SSL [40–42]. The upper limit in the external quantum efficiency of 5% observed in fluorescent small molecule organic devices [2, 3] has been overcome by harvesting both the singlet and triplet excitons to produce a large emission of photons in PHOLEDs [2, 3]. Iridium (III) and platinum (II) complexes are well-known phosphorescent emitters. The iridium (III) complexes have been shown to be the most efficient triplet dopants for high

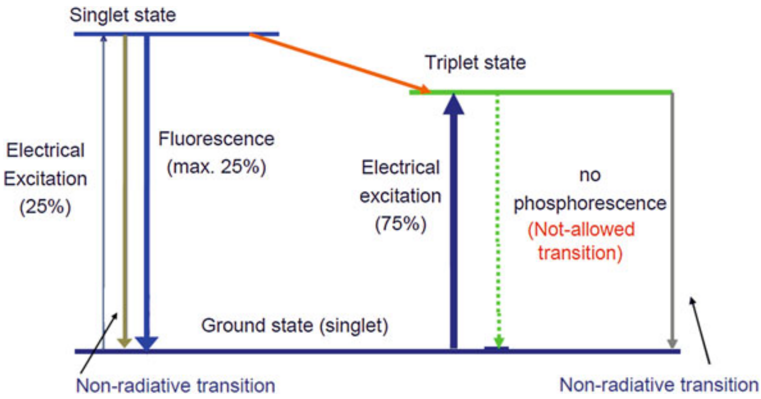


Fig. 4.6 Fluorescence emission mechanism of OLEDs

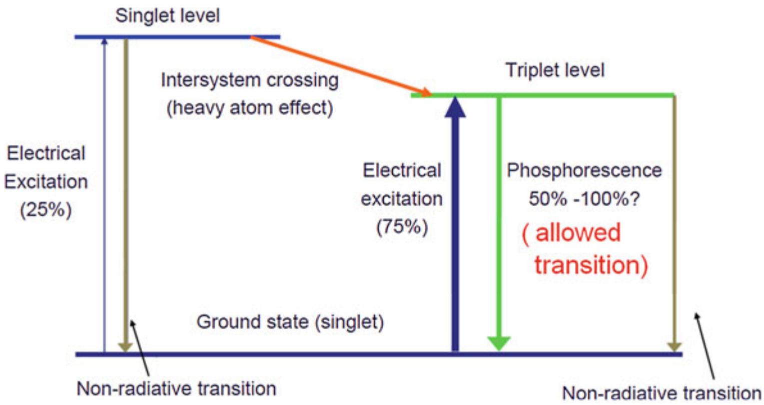


Fig. 4.7 Phosphorescence emission mechanism in phosphorescent OLEDs

efficiency OLEDs [43, 44]. The phosphorescence emission mechanism in phosphorescent OLEDs is shown in Fig. 4.7. To produce high quantum efficiency in phosphorescent OLEDs, the excited energy of the phosphorescent emitter has to be confined within the emitter itself. This has been achieved using multilayer device architectures comprising electron/hole injection and transport layers with wide-energy-gap host and carrier-transporting materials [45, 46].

4.3.2.3 Classification by Drive Method

Passive Matrix OLED

In the passive matrix-type OLED (PMOLEDs) panel, current-carrying conductor wires are laid in the horizontal (X electrodes) and vertical directions

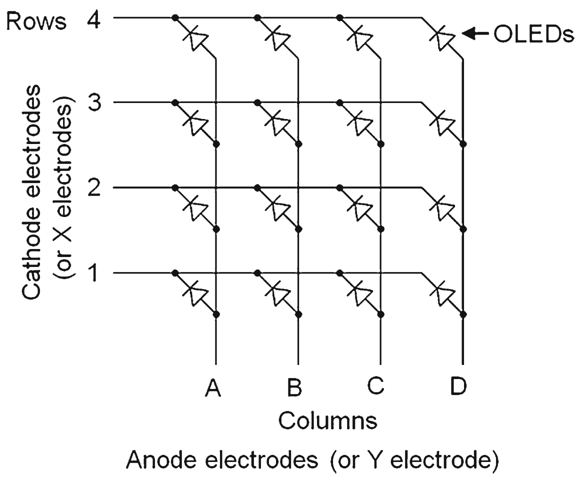


Fig. 4.8 Low cost passive matrix arrays of OLEDs. A pixel on the PMOLED is illuminated when it is selected by the X–Y electrode signals

(Y electrodes), through which an electric current is fed with fixed timing causing the pixels at the intersections to illuminate as shown in Fig. 4.8 [47]. The passive matrix type, also known as simple matrix type, features a relatively simple structure allowing for panel production at lower costs, although it also has the disadvantage that the emission of light is limited to the period of time when the electric current is fed and thus a larger amount of current must be supplied to maintain a certain level of brightness. Furthermore, PMOLEDs have high power consumption and the limitation to realize high resolution display because of the inherent huge amount of parasitic capacitance and high resistance of electrode. Larger screen sizes and increased number of trace wires cause the duration of light emission from each pixel to become significantly reduced, thereby leading to problems, including the inability to assure the required useful life. However, the PMOLED driving scheme is useful for panels of smaller sizes and lower resolutions (smaller number of scanning lines).

Active Matrix OLED

The active matrix-type driving scheme requires formation of complicated circuits, although it provides the advantages of allowing faster response time and higher resolution, and also of reducing drive voltages and low energy consumption even in larger screen sizes compared to the passive matrix type, and moreover it provides for longer useful life.

Active matrix OLEDs (AMOLEDs) incorporate transistors controlling each pixel individually, having wider range of applications from high resolution small area to large area displays. In order to supply power to the AMOLED, additional power supply lines and power control transistors are required on each pixel [48, 49]. Therefore, one pixel of AMOLED needs at least two transistors and one

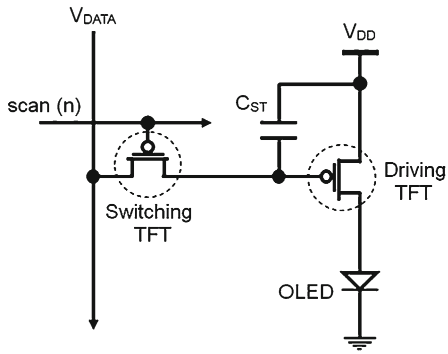


Fig. 4.9 Conventional pixel circuit of AMOLED which consists of two TFTs and one capacitor

storage capacitor (C_{ST}) as shown in Fig. 4.9. The role of a switching thin film transistor (TFT) is digitally controlling the input signals, and that of a driving TFT is analogically modulating the power supplied to the OLEDs. The brightness of AMOLED is monotonically increasing with the increase of the supplied current from the driving TFT.

4.3.2.4 Classification by Light Channel

Bottom or Top Emission

Bottom emission devices use a transparent or semi-transparent bottom electrode to get the light through a transparent substrate. Top emission devices [50–52] use a transparent or semi-transparent top electrode emitting light directly. A major disadvantage of a bottom emitting structure is that the emission aperture shares the substrate with the device electronics, potentially limiting the pixel aperture. This can be avoided by using top emission organic light emitting devices, where (a) light escapes from the device through the transparent cathode and encapsulation, (b) permits larger pixel apertures, and (c) all electronics circuitry could be placed at the bottom as shown in Fig [50–54]. Top-emitting OLEDs are better suited for active matrix applications as they can be more easily integrated with a non-transparent transistor backplane. The device structures of typical bottom- and top-emitting OLEDs are displayed in Fig. 4.10.

Transparent OLEDs

Transparent OLEDs (TOLEDs) use transparent or semi-transparent contacts on both sides of the device to create displays that can be made to be both top and bottom emitting (transparent). TOLEDs can greatly improve contrast, making it much easier to view displays in bright sunlight (Fig. 4.11). This technology can be used in Head-up displays, smart windows, or augmented reality applications.

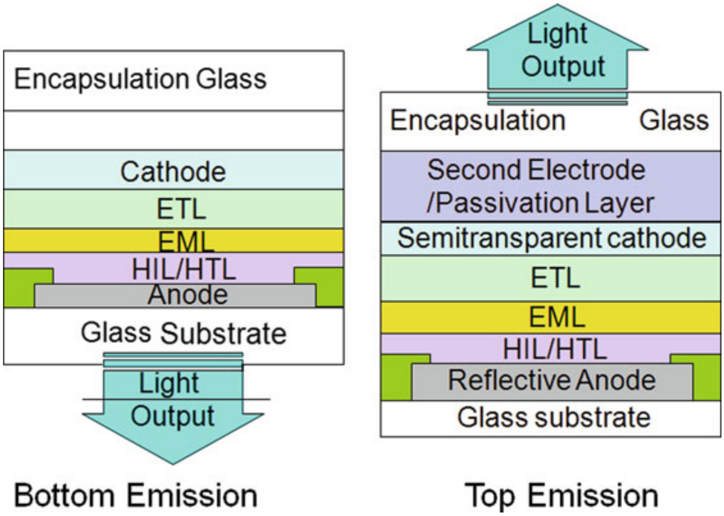
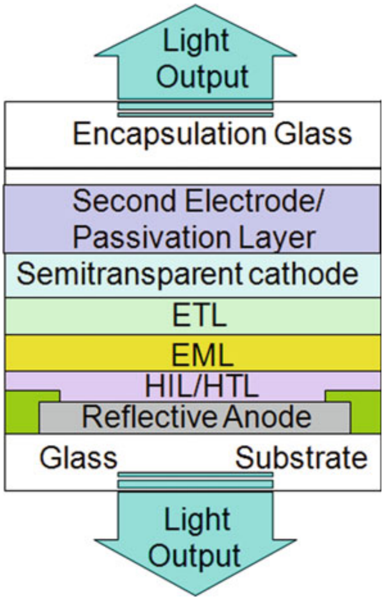


Fig. 4.10 Device structures of bottom- and top-emitting OLEDs

Fig. 4.11 TOLED device structure



A high performance transparent white OLED panel using Novaled materials presented in Finetech Japan 2010, boasts a transparency of 60–70% as displayed in Fig. 4.12 [55]. Recently, Novaled and Universal Display displayed transparent flexible lighting and display products with very high quality of light and CRI index up to 95 at the Consumer Electronics Show 2011 (CES-2011) in Las Vegas [56].

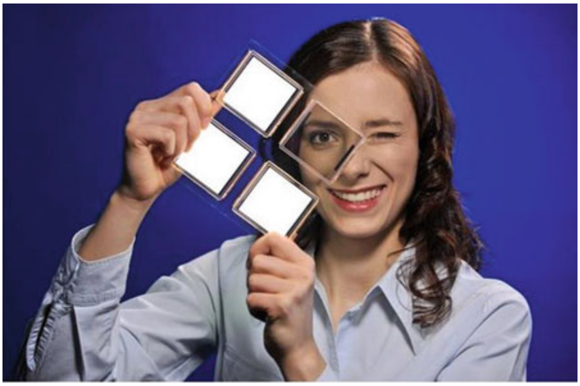


Fig. 4.12 High performance transparent white OLED with Novaled materials (Source: Novaled)

Sony developed a flexible, TOLED display [57]. Transparent AMOLED could be used for high resolution, full color heads-up displays [58–61].

Inverted OLED

One of the unique selling propositions of OLEDs is their potential to realize highly transparent devices over the visible spectrum. This is because organic semiconductors provide a large Stokes–Shift and low intrinsic absorption losses. Hence, new areas of applications for displays and ambient lighting become accessible, for instance, the integration of OLEDs into the windshield or the ceiling of automobiles. In contrast to a conventional OLED, in which the anode is placed on the substrate, an Inverted OLED (IOLED) uses a *bottom cathode* that can be connected to the drain end of an n-channel TFT, especially for the low cost *amorphous silicon* TFT backplane useful in the manufacturing of AMOLED displays. A *bottom cathode* is followed by the formation of an ETL, light emitting layer, HTL/hole injection layer, and finally the anode [62, 63]. The output light is collected through the semitransparent *bottom cathode* as shown in Fig. 4.13. The main challenge in the realization of fully transparent devices is the deposition of the top electrode. To obtain uniform light emission over the entire viewing angle and a low series resistance, a transparent conducting oxide (TCO) such as ITO is desirable as top contact as well. However, the sputter deposition of ITO on the top of organic layers causes damage induced by high energetic particles and UV radiation. An efficient process to protect the organic layers against the ITO radio frequency (rf) magnetron deposition process of ITO for an IOLED was reported by Meyer et al. [64]. The average transmittance exceeds 80% in the visible region. The configuration of inverted topside-emitting OLED is shown in Fig. 4.14 [65, 66]. Novel Alq_3/LiF/Al or Ag bottom cathode structure for inverted top-emitting OLEDs was reported by Chen et al. [67]. The emission of light via the conductive transparent top contact is considered necessary in terms of integrating OLED technology to the standard Si-based driver circuitry.

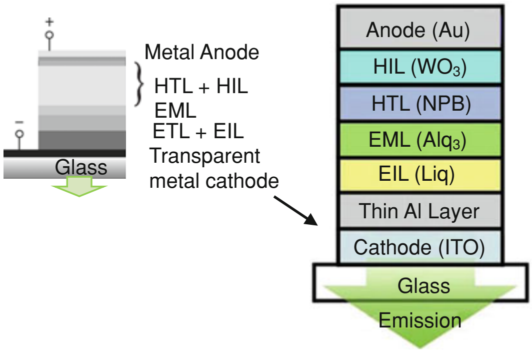


Fig. 4.13 Inverted bottom emitting OLEDs

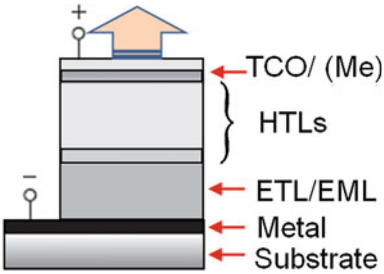


Fig. 4.14 Inverted topside-emitting OLED configuration

4.4 Characteristic of OLED Light Source

4.4.1 Optical Characteristics

OLED manufacturers today typically quote three parameters for their white light products: luminous efficacy (lm/W), luminance (cd/m^2), and lifetime (hours). The first two are familiar, but some care needs to be taken with lifetime values. Specifications of light sources are listed in Table 4.1.

As defined in Illuminating Engineering Society (IES) LM-80-08, the rated lumen maintenance life Lp is the "elapsed operating time over which the LED light source will maintain the percentage, *p*, of its initial light output" [68]. For lighting and display purpose, the L50 (50% lumen maintenance) value is used, while for architectural lighting the L70 (70% lumen maintenance) value is required.

Recently, the state of the art for commercially available WOLED lighting panels featured 15 lm/W luminous efficacy, 1,000 cd/m^2 luminance, and an L70 lifetime of 5,000 h. OLED technology is advancing rapidly. For example, OLED manufacturer Visionox [69] has demonstrated prototype desk lamps featuring WOLEDs with 40 lm/W and an L70 lifetime of 50,000 h.

Table 4.1 Specifications of light sources

Quantity	Description	Unit
Energy efficiency	Visible radiation flux per electrical power	%
Efficacy	Radiation power per electrical power	lm/W
Color point	Coordinates in the CIE diagram	*x,y*
Color temperature	CIE coordinates on black body line	K
Color rendering	Comparison of color impression from the test chart	—

4.4.2 Color Issues

WOLEDs typically employ different electro phosphorescent materials to generate red, green, and blue lights. By balancing the light output from each material, the OLED manufacturer can adjust the correlated color temperature (CCT) over a wide range. To meet the expectations of the architectural lighting market, this range should be within the range of 2,700–6,500 K as mentioned by the American National Standards Institute (ANSI C78.377) [70]. The major concern with this approach is that each electro phosphorescent material has a different L70 lifetime, with blue OLED materials typically half that of red and green OLED materials. As the OLED lighting panels age, there will inevitably be significant color shifts.

For WOLED panels, there is no color control. As a result, the panels may exhibit unacceptable color shifts long before their L70 lifetime is reached. (A rough calculation indicates that this may happen after a lumen depreciation of only two to three percent.) Such a color shift in the lighting panel is unacceptable. However, the ANSI C78.377 standard permits white light LEDs to have variations in chromaticity within the limits of 7-step MacAdam ellipses [70]. ANSI C78.377 implicitly recognizes the technical difficulties of chromaticity ("color") binning for semiconductor LEDs, which is why it allows 7-step MacAdam ellipses.

One potential solution to the problem of color shifts is to employ narrow stripes of red, green and blue OLED materials with separate electrical drivers for each color and optical feedback, similar to what is done with high-end SSL luminaires with RGB LEDs. However, this takes away from the simplicity of OLED panels.

4.5 White OLED

4.5.1 WOLED Basic Structure

White color could be obtained by combining three primary colors, red, green, and blue as displayed in Fig. 4.15. In OLED lighting, white light emission can be achieved by mixing either three primary colors (red, green, and blue) [30, 71] or two complementary colors from different emitters [72–75]. Figure 4.16 shows the white light emission using two and three color mixing configurations. For lighting

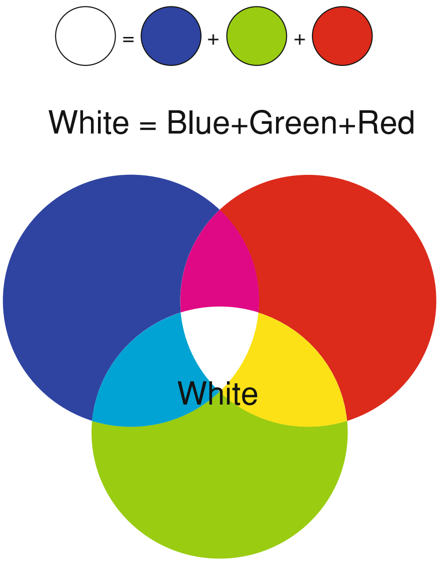


Fig. 4.15 White light emission

applications, white OLED eliminates the need for three colors; hence, it can implement white colors using only two colors.

4.6 OLED Manufacturing Process

The OLED manufacturing process for lighting includes (1) substrate processing, (2) deposition of organic layers using vacuum thermal evaporation or solution process, (3) cathode deposition, (4) cathode encapsulation, and finally (5) module process, including driver. Figure 4.17 shows the block diagram of the conventional OLED manufacturing process. A photolithography instrument for anode patterning and vacuum thermal evaporator with glove box for organic and cathode depositions are displayed in Figs. 4.18 and 4.19.

OLEDs are sensitive to moisture and oxygen and require protection from these in order to maintain a longer lifetime. As such, thin film barriers are one of the prerequisites for OLEDs. Having identified this, it soon became apparent to the Fast2Light consortium (a group of 14 companies, research institutes, and universities from Europe) that measuring the properties of a barrier would be as fundamental and important as the standardization of barrier materials. Fast2Light Consortium is set up with the objective of demonstrating high quality and cost-efficient OLED lighting foils for the future lighting and signage applications [76].

For a large area manufacturing process, fabrication aspects to be considered for the efficient and cost competitive OLED lighting sources are listed in Table 4.2.

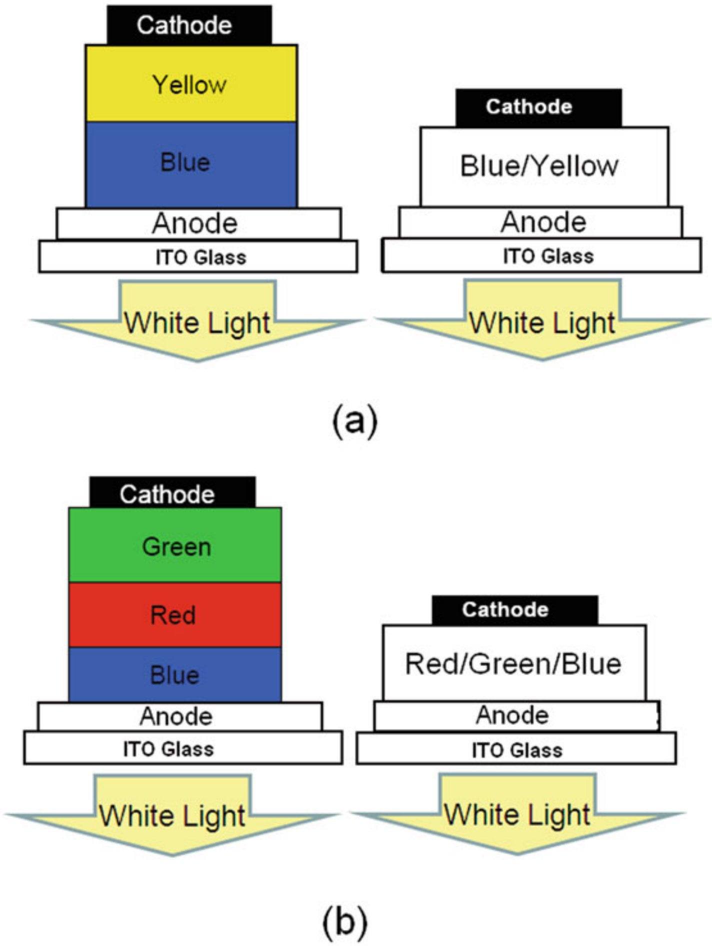


Fig. 4.16 White light emission configurations; **a** two color mixing, and **b** three color mixing

4.7 White OLED Realization Method

WOLED lighting has been developed for use in typical lighting and high-end lighting, and lighting under current development can be classified into two lighting system groups using the deposition process and the solution process. The majority of companies are gearing up to develop white OLEDs employing the monomer deposition process, whilst the OLED lighting market is also likely to open up starting with commercial products based on monomer materials. Although OLED lighting has not yet been commercialized, numerous players have delivered a series of announcements regarding superior property results, and movements for the mass production of OLED lighting have been accelerated in the recent years.

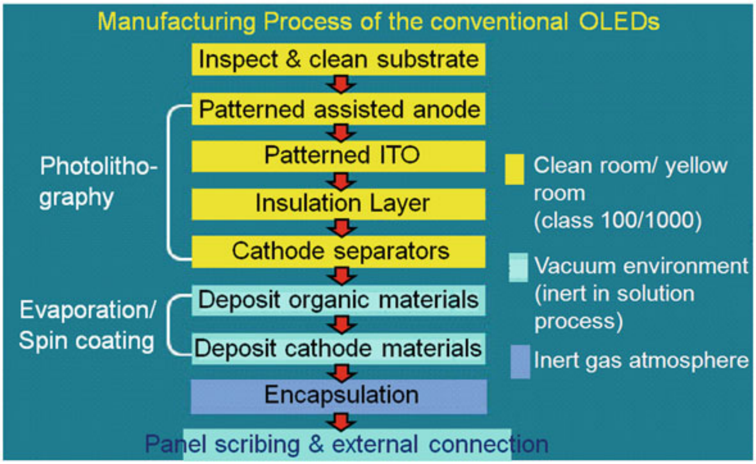


Fig. 4.17 Block diagram of conventional OLED manufacturing process

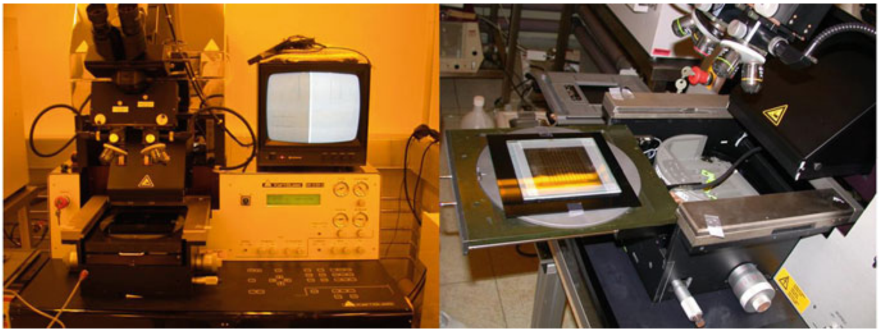


Fig. 4.18 Photolithography instrument for anode patterning

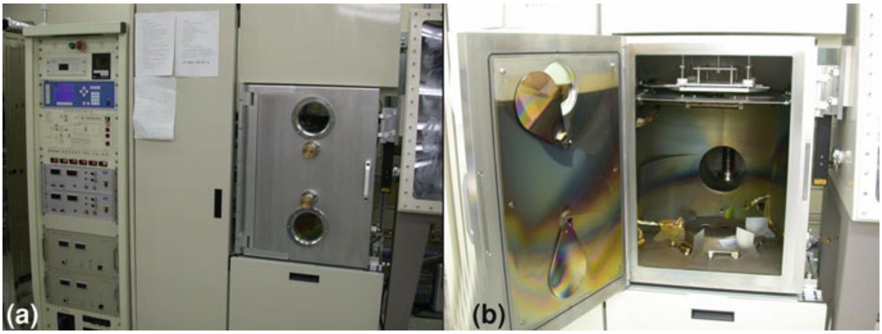


Fig. 4.19 Vacuum thermal evaporator with glove box for organic and cathode deposition (**a**), and interior of the vacuum thermal evaporator (**b**)

Table 4.2 Fabrication aspects for large area lighting

Substrate fabrication	1. Low cost substrate material
	2. Low defect density
	3. Homogeneous current input
	4. Efficient light outcoupling
OLED deposition	1. High efficient/Long lifetime OLED stack
	2. High efficient manufacturing (short tacttime/high material usage)
	3. High manufacturing yield
Encapsulation	1. Low cost large area encapsulation
	2. Long storage lifetime
	3. High yield for encapsulation
Driver Integration	1. High efficient transformation
	2. Simple and low cost mounting

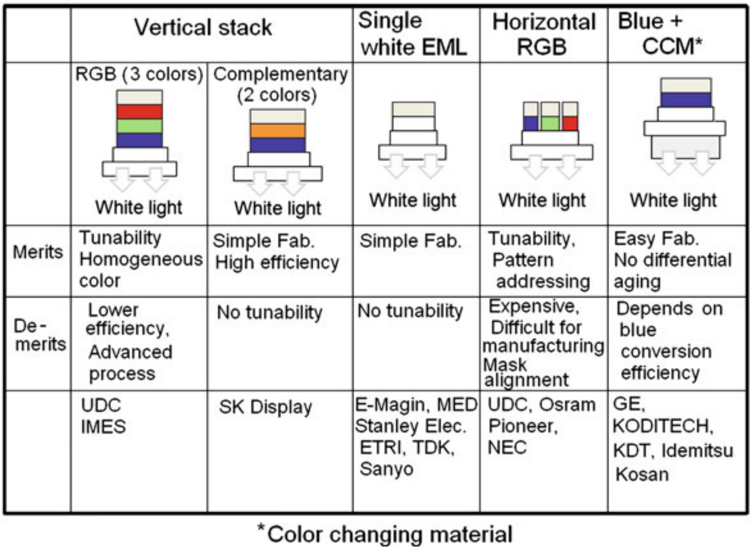


Fig. 4.20 Structures for white OLEDs

Structures for WOLED implementations have been demonstrated in Fig. 4.20. Table 4.3 displays the materials and structures used by various companies to achieve white light emission [77].

Since the introduction of white OLEDs in 1995, a number of breakthrough technology developments for white OLED lighting applications have been achieved, and accordingly, the properties of the elements have improved significantly. The most excellent data known so far is the efficiency of Konica Minolta's 64 lm/W announced in 2006, as shown in Table 4.4 [78–86]. The current efficiency is superior to incandescent lamps but inferior to fluorescent lamps.

Table 4.3 White OLED lighting technology development types by manufacturer

Company	Material	Structure
GE	Polymer	Color conversion
Philips	Polymer	Single layer
Osram	Polymer	Color conversion
Konica	Small molecule	Stacked structure
Japan consortium	Small molecule	Stacked structure Multistack structure
UDC	Small molecule	Stacked structure Patterned RGB
Idemitsu	Small molecule	Stacked structure

(*Source*: SSL Technology Scenery (LED, OLED), Sep. 2007, Display bank)

Table 4.4 Performance of white OLEDs achieved by various companies

Organization	Efficacy at 1,000 cd/m^2 (lm/W)	Lifetime at 1,000 cd/m^2 (h)	Emitter Type R	G	B	Year	Reference
Novaled/Philips	32 88 (CRI)	20,000	P	P	F	2006	78
Konica-Minolta	64	10,000	P	P	P (solution based)	2006	79
The OLLA-project	51	>10,000	P	P	F	2008	80
Idemitsu Kosan	17 lm/W at 10 mA/cm2	30,000	F	F	F	2007	81
OSRAM	46	5,000	P	P	F	2010	82
Novaled	35	100,000	P	P	F	2008	83 (a), (b)
UDC	102	8,000	P	P	P	2008	84
Yamagata Univ. Japan	48	Not disclosed			P	2007	85
Mitsubishi	28 80 (CRI)	8,000				2010	86

P = phosphorescent, *F* = fluorescent

However, the lifetime of 10,000 h, which is needed to create the initial market, has already been achieved, so it will not take very long to commercialize it, and, taking into account the current development speeds, the current levels of fluorescent lamps are predicted to be achieved soon.

Philips and Novaled reached a new record for the power efficiency of a white OLED, obtaining 32 lm/W with Commission Internationale d'Echariage ($CIE_{x,y}$) coordinates of (0.47, 0.45) and a CRI of 88 at a brightness of 1,000 cd/m^2 as shown in Table 4.4. The same device structure thereby simultaneously shows a lifetime of more than 20,000 h which is a major achievement for a future commercialization of the OLED technology for lighting applications.

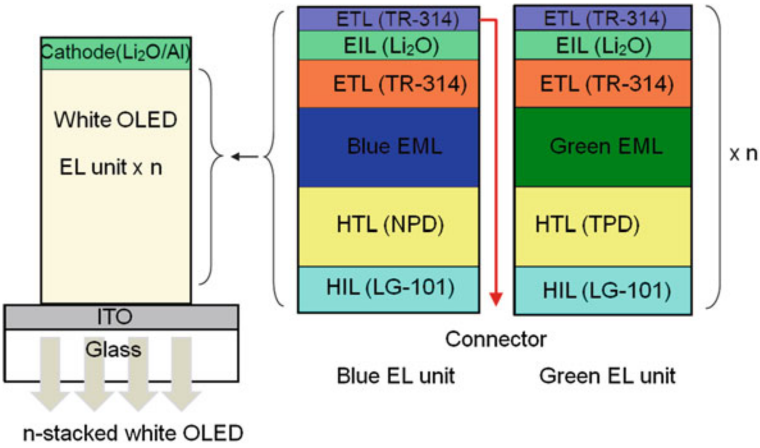


Fig. 4.21 Device structure of stacked white OLEDs

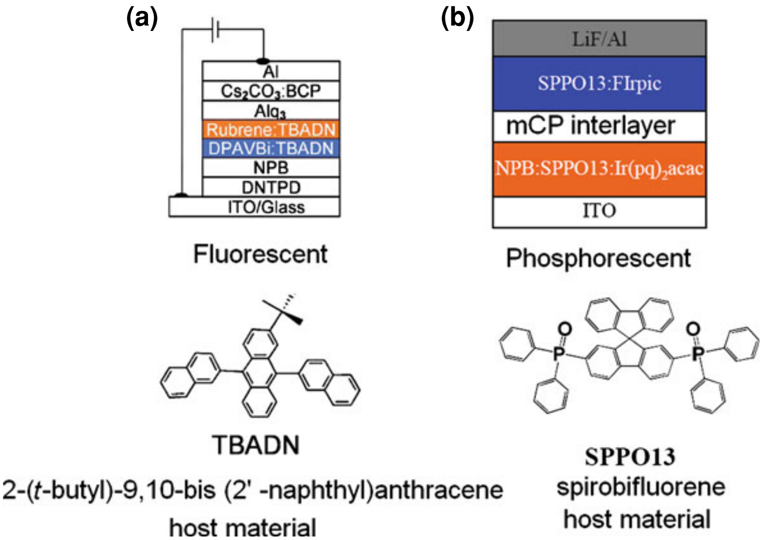


Fig. 4.22 Single layer white OLED **a** Fluorescent [90], and **b** Phosphorescent [92]

Recently, GE and Konica Minolta (KM) announced 56 lm/W flexible white OLED lighting devices [87] with a commercially viable lifetime using ‘solution coating’ rather than ‘vacuum coating’ processes. This allows to make use of the high volume roll-to-roll manufacturing infrastructure that already has been perfected in the printing industry.

4.7.1 Layer Stacking White OLED

Stacked OLEDs use a pixel architecture that stacks the red, green, and blue sub-pixels on top of one another instead of next to one another, leading to substantial increase in gamut and color depth, and greatly reducing the pixel gap as shown in Fig. 4.21 [85, 88, 89]. Currently, other display technologies have the RGB (and RGBW) pixels mapped next to each other decreasing the potential resolution.

4.7.2 Single Layer White OLED

The commercial application of WOLEDs is hindered by their complicated device architecture in particular, the need to insert thin layers of hole blocking materials as well as the poor stability of their blue electro phosphorescent emitters. Therefore, a single white emitting layer may be desirable to produce balanced white light at low dopant concentrations. The device structures of single layer fluorescent and phosphorescent white OLEDs are shown in Fig. 4.22 [85, 90–92].

4.7.3 Color Transformation White OLED

Alternatively, a single, blue-emitting OLED may serve as a pump of R and G fluorescent color-changing media. Less efficiency is lost by using a single blue or ultraviolet OLED to pump organic fluorescent wavelength down-converters, also known as color-changing media (CCM), as illustrated in Fig. 4.23. Each CCM filter consists of a material that efficiently absorbs the blue light and re-emits the energy as either green or red light, depending on the compound used.

4.8 OLED Lighting Technology Issue

The OLED lighting industry saw its first commercial products, albeit extremely expensive ones. While companies have achieved significant strides in OLED performance, high material and manufacturing costs still leave OLEDs with a high price tag. However, OLED lighting seems to have taken the front seat for OLED producers. In the recent years, most producers are now turning to lighting applications. OLED lighting technology issues are illustrated in Fig. 4.24.

OLED lighting seems to present opportunities that are both simpler technically than displays and where entrenched technologies (light bulbs, fluorescent tubes) seemed easier to push aside. OLED lighting is also extremely simple, i. e., a lamp can be one large pixel, whereas displays have thousands of pixels and may need

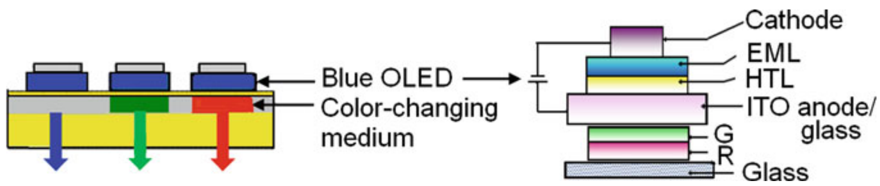
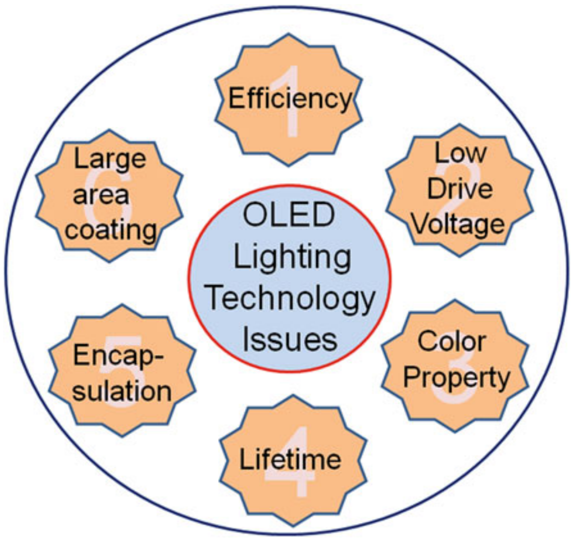


Fig. 4.23 White OLED using single blue with color-changing materials

Fig. 4.24 OLED lighting technology issues



active matrix backplanes. Furthermore, OLED lighting received substantial government funding for R&D in several countries.

The big news in 2009 was the introduction of the first OLED lighting products. Osram introduced the world's first 'functional table light' based on OLED technology although it was only available in small quantities. However, it gave some clarity as to what could be achieved in the OLED market. The 'big three' lighting companies GE, Osram, and Philips appear to be setting the stage for OLED lighting, indicating the level of acceptable performance and introducing lighting panels with that performance for designers to get a feel for.

The challenges for OLED lighting in order to compete with existing light sources were given as:

- High Luminance: Lighting applications need at least 1,000 cd/m^2 brightness
- Long Lifetime: Long operation and shelf lifetime is necessary
- High Efficiency: At least 30 lm/W in white
- Good Homogeneity: Especially on large area applications
- High CRI at high brightness: >80 for direct lighting applications
- Very low costs.

At present, almost all OLEDs employ expensive, rare metals in both the organic layer and the *indium tin oxide* transparent electrode, but the first priority is usually to juggle the rare elements in the organic layer to improve performance and replace the indium with common materials. For example, polythiophene transparent electrodes have been successfully employed. *Drive circuits* and printing technology are being improved with *gravure* looking particularly promising.

4.8.1 Efficiency

Lighting efficiency describes the ratio of luminous flux given off by a lamp to the amount of power consumed; the greater the yield, the lesser the energy lost. Internal and External efficiencies are related to efficiently production and extraction of desirable photons from electron–hole pairs with minimum heat production.

A big step towards energy saving OLED lighting is to have efficiency of more than 60 lm/W. The international standard of light yield of over 60 lm/W for white color requirements is not only met by an OLED, but also, at the same time, meets the international Energy Star SSL Standard with regard to color requirements. Lighting efficiency on this scale had been achieved previously. However, till date, the color values of OLEDs have not been within the acceptable band for color coordinates around the Planck curve, as defined by the Energy Star SSL Standard. The color values of the new OLED are within this band—its light retains the white color at different levels of intensity [93].

If the entire ceiling is emitting, a luminance level of 100 cd/m^2 is necessary (this will give 100 cd/m^2 at desk level if room is large). For a portion of the ceiling (such as in a common office), the needed luminance is near 1,000 cd/m^2. However, the lighting industry will not accept greater than about 850 cd/m^2 for glare reasons and, for 850 cd/m^2, approximately 12% of the ceiling area would be required for lighting. *A luminance level of* 850 cd/m^2 *was decided to be the target for efficiency and stability calculations*.

The short-term efficiency target is >100 lm/W. To achieve this target, a needed efficiency improvement of 2x, 3x, and 4x for G, R, and B, respectively, is estimated.

4.8.2 Low Drive Voltage

The driving voltage is also a critical parameter for the OLED efficiency. However, the pin technology already allows for driving voltages that are relatively close to the thermodynamic limits. Phosphorescent emitters have great potential in fabricating highly efficient white light for SSL application [94], (Nakayama et al. 2007, Proceedings of society for information display, "unpublished, p 1018"). A driving voltage as low as 4.8 V at a practical brightness of 1,000 cd/m^2 with a CIE$_{x,y}$

coordinates of (0.16, 0.35) was reported in a composite blue phosphorescent emitter incorporating a wide-band-gap host [95]. Novaled demonstrated fluorescent white OLED operating voltage at 3.05 V to reach the brightness of 1,000 cd/m^2, and the corresponding power efficiency was 17.5 lm/W [96]. A commercial white OLED lighting system kit with electronic driver is presented by Polymetronics [97]. A very low power consumption of light 5.3 V, 125 mA (663 mW) is reported in this kit.

4.8.3 Color Property

By mixing two, three, or more colors, white emission with the same $CIE_{x,y}$ coordinates can be achieved. Finding the optimum spectra to mix to give the appropriate $CIE_{x,y}$ and color rendition is important. Basic material properties and processes significantly impact color and control CRI. Therefore, materials with sufficient stability and the right emission spectra are desirable to achieve white emission with the required CRI.

4.8.4 Lifetime

Materials-related phenomenon can be tailored to make very high efficiency, low voltage, stable, inexpensive, and reliable devices. Therefore, it is desirable to (1) understand degradation and failure mechanisms to extend practical lifetimes of devices to make them as life cycle cost beneficial as possible and (2) address key materials challenges for OLED use in general illumination applications.

To establish high efficiency, low voltage, stable materials for practical, OLED-based general illumination applications it is necessary to simultaneously ensure that: essentially all electrons and holes injected into the structure form excitons; the excitons recombine radiatively with high probability; the minimum drive voltage is required to establish a given current density in the device; and the material and device are stable under continuous operation. For OLED lighting, a minimum of 10,000 h is needed, with a 20% maximum loss of luminance at 850 cd/m^2 for all colors.

Osram announced the Orbeos panel, its first OLED product on the market. Orbeos can be switched on and off without delay, is continuously dimmable, and unlike LEDs, its heat management is simple. The brightness level is typically 1,000 cd/m^2, with power input of less than 1 W and a lifespan of around 5,000 h under ideal operating conditions. Five thousand hour is an acceptable lifetime for an OLED lighting product.

4.8.5 Cost

Technology development and manufacturing process development decide the cost of OLED luminaire. Therefore, it is necessary to develop the OLED technology that meets the performance specification at acceptable cost. The price of the OLED lighting panel per square meter is still high. The short-term goal is to reduce the price to \$200 or less by 2012 and to \$50 or less by 2020 [98]. The cost target for near-term goals is about \$200/m^2. The development of basic materials to simplify improved encapsulation technology and deposition technology could be some of the options to reduce the manufacturing cost.

4.8.6 Encapsulation

The intrusion of moisture into the lumanire can damage or destroy an OLED's organic material. The organic and cathode metallic films are sensitive to the presence of water vapor and oxygen. As a result, one of the major problems faced by OLED is questionable longevity. The presence of oxygen and water vapor beyond one part per million (ppm) inside the device can deteriorate the performance of OLED. The material undergoes oxidation in the presence of oxygen and water vapor. The metallic film employed for the cathode layer is sensitive for delamination in the oxygen and water vapor environment. The end result is the significant decrease in brightness and formation and spreading of 'black spots' characterized by islands of no light emission. Water vapor transmission rate (WVTR) for the encapsulation of OLEDs in order to reach a minimum lifetime of 10,000 h is 10^{-6} g/(m^2 day). Therefore, an improved OLED sealing process has been developed to reduce moisture intrusion and improve the device lifetime [99–102].

Encapsulation techniques are one of the most expensive parts of white OLED manufacturing, both from a cost and a processing time perspective. OLED encapsulation packaging for lighting applications, should meet the following criteria:

(1) Heat management and dissipation techniques (*not serious*).
(2) Encapsulants to create robust devices.
(3) Down-conversion materials for maximizing high quality lumen output.

Therefore, it is desirable to design devices into practical packages that satisfy the marketing and manufacturing goals. Frantic efforts have been made to develop a new barrier material, designed to significantly prolong the lifetime of OLEDs. The high performance, thin barrier coatings developed by Huntsman are now considered as state-of-the-art and have recently been integrated in the world's first flexible OLED system, on a racing car [103, 104].

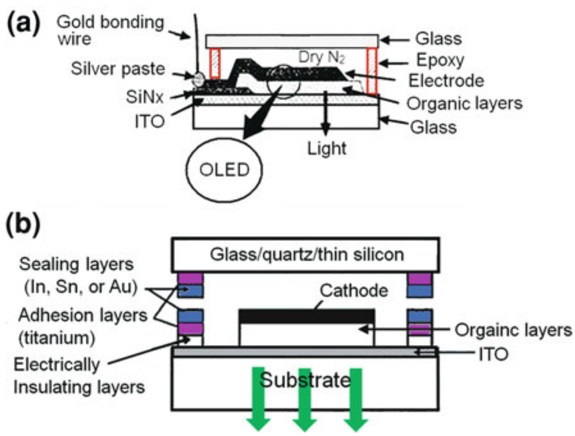


Fig. 4.25 **a** Schematic of substrate encapsulation of OLED device. **b** Schematic of the substrate encapsulation of OLED device

Table 4.5 Thin film hermetic sealing

Buffer layer	Thermal coefficient matching layer	Inorganic layer
Parylenes (polymer with thermal expansion coefficient) Alq_3	SiO_2	Si_3N_4, SiON, SiC

4.8.6.1 Substrate Encapsulation Method

Manufacturers now seal displays in an inert atmosphere or in a vacuum environment. A glass lid is glued on top of the display substrate with a powder inside the display to absorb moisture that diffuses through the glue. These seals are expensive and labor-intensive to assemble.

The simplest way is to use glass as a top cap with a nitrogen-filled chamber. A schematic of the structure is shown in Fig. 4.25a and b [105]. The configuration uses epoxy, a widely used encapsulant in electronic packaging. In addition, a-SiNx is deposited to reduce the permeability of humidity and oxygen from the sides. The sealing process is accomplished by using pressure and a heating element.

4.8.6.2 Thin Film Encapsulation Method

Thin film packing solutions are based on silicon carbide/nitride/oxynitride hermetic coatings (Table 4.5). When these coatings are applied to glass and plastic support OLED lighting devices, they will provide longer life with greater efficiency at lower costs than are currently available. Recently, attempts were made to develop thin film device protection technology to prevent degradation by air-borne moisture [106].

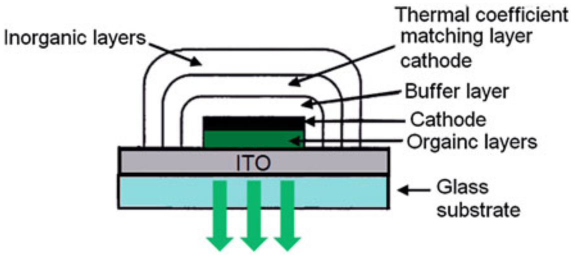


Fig. 4.26 Schematic of the thin film encapsulation

The researchers selected advanced ion assisted deposition, which utilizes reactive ions to deposit a high-density, pinhole-free thin silicon oxynitride (SiON) film on the OLED surface. Schematic of the thin film encapsulation is displayed in Fig. 4.26. Ideally, the film should be as thin as possible, but if it is too thin, a pinhole or other defect could appear and cause a problem. It was shown that a film of 50–200 nm thickness was perfect. During testing, the SiON-encapsulated OLEDs showed no sign of degradation after seven months in an open-air environment, while the OLEDs without the coating degraded completely in less than two weeks under the same conditions. Accelerating aging tests in an environmental chamber that maintained a temperature of 50°C and 50% relative humidity, OLEDs encapsulated with SiON films showed little degradation for at least two weeks. OLEDs without encapsulation, however, decomposed immediately. Outside the plurality of layers, epoxy and a thin metal foil can be added to strengthen its effectiveness against water and oxygen permeation.

4.8.6.3 Packing Encapsulation Method

Packing encapsulation technique is a novel encapsulation method for flexible light emitting diodes (OLEDs) using poly dimethyl siloxane (PDMS). The method, which uses polycarbonate film, silicon dioxide, and PDMS, was found to enhance the lifetime of OLEDs in air. Optical measurements of the preservation of calcium films encapsulated with PDMS showed that the water and oxygen permeation rates of the PDMS encapsulation were reduced from a level of 0.57 g/m^2 d. The PDMS barrier coatings have a good potential for flexible OLEDs [107–111]. The structure to protect permeation of water and oxygen through the flexible substrate is shown in Fig. 4.27. Table 4.6 shows the various polymer and/dielectric and other materials used for hermetic sealing.

For flexible electronics to make the transition from the laboratory to the market, finding a good moisture barrier and encapsulation technology are the key elements. Taking into account the low cost production aspect, candidate technologies must be compatible with roll-to-roll manufacturing processes. Therefore, a roll-to-roll plasma-enhanced chemical vapor deposition (PECVD) deposition tool for barrier encapsulation will be installed alongside the existing roll-to-roll facilities.

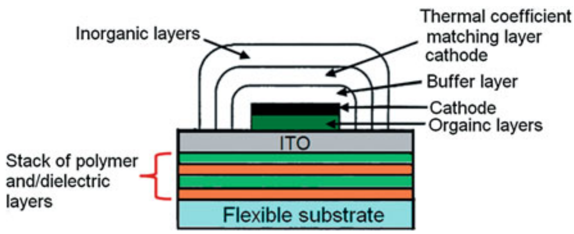


Fig. 4.27 Structure to protect permeation of water and oxygen through the flexible substrate

Table 4.6 Polymer and/dielectric stack Hermetic Sealing

Dielectric layers	Polymers layers	Buffer layer	Thermal coefficient matching layer	Inorganic layer
Silicon monoxide (SiO)	Fluorinated polymers	Parylenes Alq$_3$	SiO_2	Si_3N_4
	Parylenes			
Silicon oxide (SiO_x)	Cyclotenes			
Silicon dioxide (SiO_2)				
Silicon nitride (Si_3N_4)				

4.9 Large Area Coating Technology

4.9.1 Ink-jet Printing Technology

Ink-jet printing technology can reproducibly dispense spheres of fluids with diameters of 25–100 μm (10 pl–0.5 nl) at rates of 0–4,000/s for single droplets on-demand, and up to 1 MHz for continuous droplets. Piezoelectric dispensing technology is adaptable to a wide range of material dispensing applications, such as biomedical reagents, liquid metals, and optical polymers [112–117]. Figure 4.28 shows the schematic of the ink-jet printing. Miniaturization has enabled the electronics/computer age by driving down the cost and increasing the function of electronic and photonic devices [118].

The main advantages of ink-jet printing are (1) no mask, (2) very flexible, (3) almost no waste, (4) fine lines, and (5) suitable for rigid boards and flexible substrate. High precision laboratory ink-jet systems with multiple print heads allow an accurate print of various material layers. Other advantages of ink-jets are:

(a) multi material layers with multiple print heads
(b) very accurate printing technology with low consumption of material (cost saving)
(c) software/graphical user interface for good control over all printing processes and parameters.

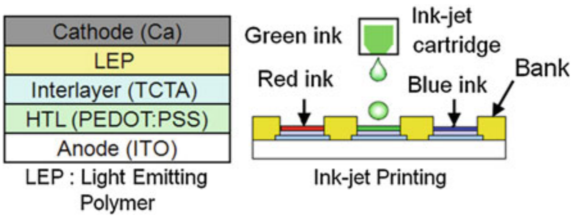


Fig. 4.28 Schematic of the ink-jet printing

The integration of ink-jets in glove boxes allows the user advantages such as:

(a) complete work/process under controlled atmospheres; outside influences, e.g., oxygen can be avoided
(b) for special applications, systems with humidity control are available to allow e.g., a printing process under controlled humidity of 0–60% (without oxygen)
(c) reduction of particles on the substrate; glove boxes typically work as class 100 clean room systems.

In 2009, Seiko Epson unveiled a new *ink-jet printing technology for OLEDs,* suitable for large-sized panels. It is a polymer-based OLED made by printing technology, sealed by a metal plate. They plan to unveil 37 in. (and larger) inkjet-printed OLED TVs in 2012 [119].

4.9.2 Spin Coating Process

In the recent years, the solution process of OLEDs fabrication is becoming attractive due to low cost manufacturing and facile process [120–126]. Recently, Merck reported that in a spin coating process, the gap between solution and evaporation processed phosphorescent green materials has been almost completely bridged. Spin coaters are systems for the production of thin films on flat substrates. The solution is placed on the substrate, either manually or by fluid dispensing systems, which is then rotated at high speed in order to spread the fluid by centrifugal force as displayed in Fig. 4.29. The substrate is fixed by vacuum during the rotation. The spin coaters are integrated in glove boxes to allow the user to dispense materials which are very sensitive to oxygen and moisture. Spin coating is a wet process where a certain amount of solvent is necessary. To avoid the solvent vapors from contaminating the glove box atmosphere, the exhaust of the spin coater is connected to the gas purification system.

4.9.3 Roll-to-Roll Printing

Cost-effective "roll-to-roll" manufacturing is necessary to produce large area OLED lighting. General Electric (GE) has successfully demonstrated a roll-to-roll

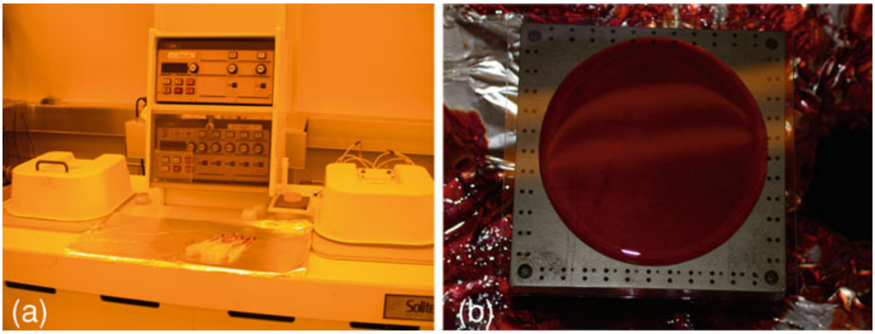


Fig. 4.29 Spin coating instrument (**a**), and ITO-coated glass substrate with solution on the holder of spin coater (**b**)

Table 4.7 Typical efficiency requirements of residential and outdoor WOLEDs luminaire

Applications	Minimum luminaire efficacy (lm/W)	Minimum CRI
Under-cabinet kitchen lighting	23	80
Under-cabinet self-mounted task lighting	29	80
Portable desk task light	29	80
Outdoor wall-mounted porch lights	27	70
Outdoor step lights	23	70
Outdoor pathway lights	23	70

printing (as in newspaper printing style) process for OLEDs. It is a state-of-the-art process for the production of OLEDs that are high performance, energy efficient, and surprisingly inexpensive [127–133]. The applications are endless for printing energy efficient light systems of all sizes.

4.10 OLED Lighting Applications

OLEDs are in general interesting light sources as they are flat sources, give homogeneous light over an area, are potentially very energy efficient, and come with options to have many colors within one device. Glass substrates are usually used and the focus is now on the performance improvement. Table 4.7 shows the efficacy and CRI requirements of WOLEDs luminaires for residential and outdoor applications.

The OLED ceiling lighting fixture is intended to provide general illumination for commercial office spaces. The OLED luminaire is expected to outperform traditional fluorescent lights with regard to energy, making it very attractive in that regard, but is still only marginally cost-effective on the basis of energy savings alone (Fig. 4.30). Both non-energy benefits and energy-related economic incentives will therefore importantly affect the ability to sell this product. The useful light delivered from the typical OLED ceiling lighting fixture is 4,200 lumens and consumes 56 W of power (a luminaire efficacy of 75 LPW) as shown in Fig. 4.30.

Fig. 4.30 Commercial office OLED ceiling lighting fixture

Table 4.8 Requirements of SSL for commercial applications

Market	Brightness (cd/m^2)	Size (cm^2)	Lifetime (h)	Efficiency (lm/W)
Decorative lighting	50–500	10–100	10,000	10–15
Automotive applications	20–2,000	5–50	10,000	10–20
LCD backlighting	2,000–4,000	10–200	10,000	25–50
Emergency lighting	300–500	300	25,000	25–35
Large area illumination	1,000	>1,000	10,000	35–50
General illumination	5,000	5,000	10,000	50–100

Table 4.8 displays the requirements for commercial applications. Commercial lighting purchasers are more sophisticated than residential consumers. They are increasingly sensitive to energy savings and will be taken into account when considering the economics. They are also very concerned about the acceptance of any new lighting technology by the building occupants, and are risk-averse in this respect. There is also the issue of reliability.

4.11 OLED Industry Standards

OLEDs remain a bit of a mystery for most in the lighting industry and they are often assumed to be some type of inorganic LED. An OLED is a diffuse, planar source. While OLED technology has existed for several years, it is only in its second generation of development. Because of its *thermal management issues*, it is a fairly complex technology to create. In order to achieve maximum output and even illumination distribution, panel sizes are still relatively limited in size to only six square inches. Nevertheless, OLEDs do offer the possibility of new lighting strategies. OLEDs offer "a fundamentally different kind of lighting design," where surfaces and objects become the focus rather than space.

A full SSL market is expected to begin after 2012. The distribution trend of LED lighting is also expected to continue. A large number of companies saw this potential of the LED lighting market and sought opportunities to enter the LED lighting industry. However, the understanding of the LED lighting standard and

Table 4.9 Illuminating engineering society (IES) luminaires standard measurement methods–ENERGY STAR

Approved methods for the electrical and photometric testing of SSL devices	IES LM-79-2008—For measurement of initial performance (a) Total flux, (b) Electrical power, (c) Efficacy (lm/W), and (d) Chromaticity.
Approved method for measuring lumen depreciation of LED light sources. Does not cover measurement of luminaires.	IES LM-80-2008—For measurement of lumen depreciation in LEDs (a) Operational failure (LEDs typically do not fail—do not have filament to burn) (b) Useful light output (Lumen maintenance).
Sources–Nonmenclature and definitions	IES-16 Addendum.
Specifications for the Chromaticity of SSL products	ANSIC 78.377-2008 (American National Standards Institute).

Table 4.10 LED lighting standard/certification in development/manufacturing

Sr. No.	Particulars	Standard	Reference
1	Lifetime extrapolation	IESNA TM-21 (use with LM-80)	[134, 135]
2	LED definitions	IESNA RP-16	[134, 136]
3	Color quality scale (new CRI type metric)	CIE TC1-69	[135, 137]
4	Safety	UL 8750	[138, 139]
5	Electric drivers for LED devices, arrays, or systems	NEMA SSL-1	[140, 141]
6	SSL-sockets and interconnects	NEMA LSD-44	[140, 142]
7	Sub-assembly interfaces for luminaires	NEMA LSD-45	[140, 143]
8	Best practices for dimming	NEMA LSD-49	[140, 144]
9	LED application guideline	IESNA	[134]

certification required for a successful LED lighting market entry are in the development stage. Standards are implemented to realize *common specifications for products* by *different makers* to increase the compatibility and exterminate the distribution of low quality products to supply high quality products to consumers. When standards are satisfied, a market is attached and this is called *certification*. In 2015, OLEDs are expected to enter the lighting market. Tables 4.9 and 4.10 show the LED lighting standards and specifications.

Global LED Standards and certifications implemented to realize common specifications for products in different regions are displayed in Fig. 4.31.

4.12 WOLED Lighting Development Trend by Maker

OLEDs are currently a hot topic in the lighting industry [25–27, 145]. With major companies such as Osram, Philips, GE, Lumiotech, Mitsubishi, Novaled displaying prototype products and announcing commercial availability of OLED

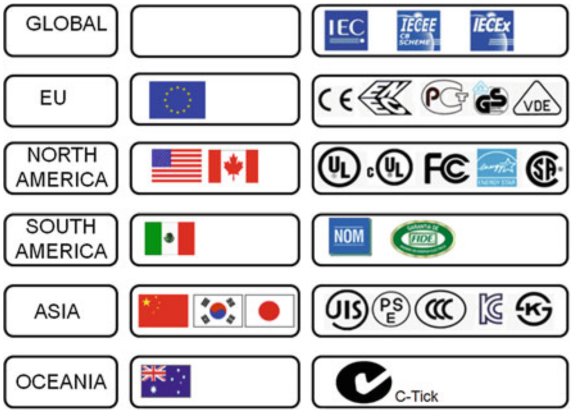


Fig. 4.31 Global major LED lighting certifications (*Source: DisplayBank Report, Jan. 2011*)

panels for prototype lighting applications, it is difficult to ignore the industry buzz: "OLEDs are the future of lighting!" White OLED panels demonstrated by different companies are displayed in Fig. 4.32. At present, inorganic LEDs SSL has become a commercial reality, and it may overshadow fluorescent lamp technology in the near future. However, most experts agree that OLEDs still lag a year or two behind LEDs in terms of light output efficiency.

In addition to the above-mentioned lighting firms, several other companies, including materials suppliers, are likely to influence the first generation of OLED lighting products. Specifically, Merck, Novaled, LG Electronics (through its acquisition of Kodak's OLED business in December 2009), Sumation, Idemitsu Kosan (Japan), UDC, DuPont and Dow Corning will play major roles. Printing industry giants, such as Avery Dennison, Toppan Printing, and Dai Nippon Printing, may also assist with expertise in functional printing technologies.

4.12.1 Philips (Europe)

Philips Lighting has been exploring the potential of OLED technology and the company's entry into the technology. It is currently available in panel formations best suited for artistic explorations, the most dynamic of which is Mirrorwall, an interactive light wall of hundreds of OLED panels, which was introduced at Euroluce 2009. Earlier, Philips started selling its OLED based Lumiblade lighting wafers, but was quiet on the OLED front since that time [146]. Philips started shipping commercial products in 2010.

Philips Panel features:

(a) Size: 11.9 cm diameter $\times$ 3.7 cm $\times$ 2.3 mm
(b) Efficiency (typical): $\sim$15–20 lm/W

Fig. 4.32 White OLEDs for commercial applications demonstrated by some companies

(c) Types of materials: small molecular OLED (as emitter)
(d) Color temperature tunable (3,200 K), and RGB color tunable
(e) Luminance: 3,000 cd/m^2
(f) Lifetime(LT_{50} typical): $\sim$10,000 h @ 1,000 cd/m^2
(g) CRI (typical): 80
(h) Schedule shipping: around Q4'2010

4.12.2 OSRAM (Europe)

Osram Opto Semiconductors, Regensburg, Germany, has been pushing OLED technology, and the company recently launched the Orbeos light panel in Europe [147]. These panels are "market ready" for integration into lighting applications and will be available in the U.S. later this year. OSRAM presented the first OLED Luminaire in November 2010 [148]. The circular ORBEOS OLED has a light density of 1,000 cd/m^2 and over 5,000 h of operating life. Osram is concentrating more effort on research and development of OLEDs for general illumination. The primary focus of the OLED research and development will be on white light, as it is used most frequently for room lighting.

The company aims to achieve a luminous efficiency of 25 lm/W with the right choice of current.

Osram panel features:

(a) Size: 88 mm diameter × 2.1 mm
(b) Efficiency (typical): 23 lm/w
(c) Types of materials: small molecular OLED (as emitter)
(d) Color temperature tunable (2,580–3,320 K), and RGB color tunable
(e) Luminance: 1,000 cd/m^2 @ 186 mA
(f) Lifetime (LT_{70} typical): 8,000 h
(g) CRI (typical): 75

Osram does not expect to have volume OLED lighting products until 2016. It plans to transition into this high volume in 2012 by selling to the design community, where the target customer will value some unique quality of the product, such as transparency.

4.12.3 General Electric (US)

GE Global Research is one of the world's most diversified industrial research laboratory, providing innovative technology for all of GE's businesses. GE has made substantial investments in OLED research that has resulted in world records for OLED lighting device size and efficiency. In 2004, GE researchers were able to demonstrate an OLED device that was fully functional as a 24 × 24 in. panel, which produced 1,200 lumens of light with an efficiency on par with today's incandescent bulb technology. This was the first demonstration that OLED technology could potentially be used for lighting applications.

GE Lighting in collaboration with Konica Minolta (KM) have achieved a major breakthrough that brings the companies closer to making high efficiency OLED lighting devices a reality. They have demonstrated illumination quality white OLEDs using "solution-coatable" materials that are essential for producing OLEDs at a low cost [149]. *The achievement of* 56 lm/W *efficiency demonstrates that flexible, white OLED lighting devices can be made at low cost using "solution-coatable" materials.* The two companies plan to introduce their first flexible OLED lighting product in 2011 [150].

Earlier, GE announced that it would begin volume production of flexible OLED based lighting panels in 2010. In a most recent communiqué in December 2010, they announced a joint development of self-powered OLED lighting devices with Power Paper. The 12-month collaboration will combine power paper's thin film batteries with GE's OLED technology to develop *a first generation of self-powered OLED lighting products and identify next-generation technologies with enhanced capabilities*.

4.12.4 *Fraunhofer (Europe)*

The Fraunhofer IPMS Institute unveiled new *OLED lighting* panels called TABOLA (TABOLA OLED Light Tablets), set to be released in Q1 2011 [151]. These bottom emitting or transparent devices will be available in three sizes (35×75, 75×75, and 150×75 mm^2). The standard color will be white, but they can also make them in other colors. Not much technical information is yet available about this product. The brightness is about 1,000 cd/m^2, and almost no heat is generated. The TABOLA featured a stacked OLED: the grid versions (with the Liana-like grid) will feature double unit stack and the grid-free version will use a triple unit stack.

4.12.5 *NOVALED (Europe)*

Novaled, Dresden, a Germany-based Company, has developed a 15×15 cm^2 OLED device that reaches a power efficiency of 30 lm/W at an initial brightness of 1,000 cd/m^2 [152]. It shows a high quality white light with CIE color coordinates in line with *DoE energy star specifications.* Novaled's technology has achieved a lifetime of 20,000 h, having a white OLED device thickness of less than 2 mm and a very high color rendering index (CRI) of 90.

4.12.6 *Add-Vision (USA)*

Add-Vision (headquartered in Scotts Valley, California, USA) is a pioneer in the development of P-OLEDs technology for use in low-resolution displays and lighting applications.

Add-Vision Inc. (AVI) worked on the project entitled "Materials Degradation Analysis and Development" to Enable Ultra Low Cost, Web-Processed White P-OLED for SSL in 2007, supported by the U.S. Department of Energy (DOE) [153]. Its aim was to produce the high efficiency performance of Light Emitting Polymer (LEP) materials while simultaneously using an ultra low cost manufacturing approach to bring about cost-effective P-OLED solutions. Soon after, Add-Vision, Inc. had successfully demonstrated its first fully printed P-OLED device that exceeded 1,000 h of operating lifetime at peak luminance of 100 cd/m^2 [154].

In recent years, Add-Vision Inc. has been selected by the National Energy Technology Laboratory (NETL) for a three-year research and development project entitled "Low Cost, High Efficiency P-OLEDs based on Stable p-i-n Device Architecture" [155]. Under the collaborative research project, Add-Vision, University of California, Los Angeles (UCLA), and University of California, Santa Cruz (UCSC) will design and synthesize advanced materials to enable a next-generation P-OLED technology, one that is high efficiency, long-lived, and manufacturable using low cost processing assuring adoption into SSL applications.

In June 2009, Bayer signed a licensing agreement with Add-Vision for Flexible P-OLEDs [156]. The printable P-OLED lighting technology is an important component for many applications in the coming years—such as active packaging and labels, gift cards, electronic toys and games, promotional products, or point-of-sale signage.

4.12.7 Universal Display Corporation (USA)

Universal Display Corporation (UDC), founded in 1994, is a world leader in the development of innovative OLED technology for use in flat panel displays, lighting, and organic electronics. Universal Display has one of the largest patent portfolios in the OLED field with licensing rights to over 1,000 issued in a broad array of OLED technologies, materials, and processes.

In recent years, more energy efficient lighting products are in a very high demand. Based on the UDC's PHOLED technology and materials, efficient white OLEDs having the potential to offer power-efficiencies superior to those of today's incandescent bulbs and fluorescent tubes have been developed.

UDC research focuses on the demonstration of an efficient, novel OLED illumination system that exceeds the requirements of an ENERGY STAR product, using large area panels that have the same high efficiency as small area test pixels. It proposes to demonstrate a *non-stacked white phosphorescent OLED* with six organic materials with extremely long lifetime of $LT_{50} > 200{,}000$ h at 1,000 cd/m^2 initial luminance and to design and fabricate a prototype warm white OLED that achieves 75 lm/W with $LT_{70} > 35{,}000$ h at an initial luminance of 1,000 cd/m^2 [157].

4.12.8 Konica Minolta (Japan)

KM Technology Center prototyped a white organic EL panel with 1,000 cd/m^2 luminance and 64 lm/W light emitting efficiency in June 2006 [158]. The company also boasts blue phosphorescent materials, optical design technologies, and a technology to fabricate barrier films that transmit little moisture and oxygen.

Features of KM Panel are [159]:

(a) Size: 15.0 cm diameter × 15.0 cm × 1.5 mm
(b) Efficiency (typical): ~64 lm/W
(c) Types of materials: phosphorescent OLED (as emitter)
(d) Luminance: 1,000 cd/m^2
(e) Lifetime(LT_{50} typical): ~10,000 h @ 1,000 cd/m^2

(f) CRI (typical): NA
(g) Schedule 2011, with large-scale production planned for 2014.

4.12.9 Lumiotec (Japan)

Lumiotec is a joint venture established in May 2008 by four companies, Mitsubishi Heavy Industries, Ltd. (MHI), ROHM Co., Ltd., Toppan Printing Co., Ltd., and Mitsui & Co., Ltd., and Junji Kido as the world's first business enterprise dedicated exclusively to OLED lighting panels. Leveraging the development of a new device structure enabling simultaneous achievement of increased brightness and longer operating life (two features that in the past were considered performance tradeoffs), Lumiotec has prepared for OLED production and established a pilot mass production line at a production facility in Yonezawa [160–162]. The realization of a high-speed, large-scale production system (in line deposition equipment with linear evaporation source for large substrates) has also significantly enhanced material utilization efficiency. The company has started shipping OLED panels for commercial applications [163, 164].

Lumiotec Panel features are:

(a) Size: 14.5 cm diameter × 14.5 cm × 2.3 mm
(b) Efficiency (typical): ~25 lm/W
(c) Types of materials: small molecular OLED (as emitter)
(d) Luminance: 4,000 cd/m^2
(e) Lifetime(LT$_{50}$ typical): ~4,000 h @ 4,000 cd/m^2
(f) CRI (typical): 80
(g) Schedule—Mass Production 2013

4.12.10 Canon/Tokki (Japan)

Tokki, manufacturers of vacuum process equipments and factory automation systems, developed the first OLED mass production system back in 1999, which processed both OLED/electrode material deposition and encapsulation by one system. Tokki's OLED production system has been delivered to most of the small molecule OLED manufacturers in Japan, Korea, and Taiwan [165]. In November 2007, Canon Inc of Japan officially decided to acquire Tokki Corp of Japan [166]. In June 2010, Canon announced that it would make Tokki its wholly owned subsidiary. Canon already has experience in manufacturing solar cells using amorphous Si technology.

4.12.11 Dai Nippon Printing (DNP), Japan

Shueisha, the predecessor of DNP, was founded on October 9, 1876, shortly after the beginning of the "cultural awakening" that accompanied Japan's Meiji Restoration [167]. Started by printing newspapers aimed at spreading Buddhist and Shinto teachings, as well as ordinary daily newspapers, the company changed its name to Dainippon Printing Co., Ltd. following the merger with the Nisshin Printing Co. Ltd. in 1935. In 1944, the Technical Research Laboratory was launched. DNP succeeded in developing a flexible organic EL display in 2001. The prototype flexible OLED poster with a lifetime of 20,000 h and size of 29 in. by 20 in. was displayed at the Eagles' Stadium of Japan's Sendai City in 2008 [168].

4.12.12 Sumitomo (Japan)

The supply of the manufacture of OLED materials is dominated by two Japanese companies, *Idemitsu Kosan* and *Sumitomo Chemical.*

Since its establishment in 1913, Sumitomo Chemical has been researching and producing industrial chemicals and materials. Using polymer materials supplied by Sumitomo, KM was making *mass production* of flexible OLED lighting panels using printing technologies since 2010 [169].

Sumitomo Chemical makes large polymer molecules OLED material that can be sprayed on to a screen by something akin to an ink-jet printer. Sumitomo has not been successful so far in making blue color which can decay too quickly with use on a screen. Furthermore, Sumitomo is focusing on long lifetime blue materials as high as 50,000–60,000 h.

4.12.13 Toppan Printing (Japan)

Toppan Form is a leading company providing product applications by combining various printed electronics technologies. Unlike conventional electronics, printed electronics are not rigid and can be converted into different shapes and sizes [170].

Following the development of printed electronics technologies for several years in cooperation with partners such as Konarka, Add-Vision, and others, the company has determined that it has reached a point where these technologies have matured enough for integration into actual products.

The company has also integrated organic thin film photovoltaic technology with Add-Vision's P-OLED and Toppan Forms' Audio Paper™ technology to create a new breed of Point of Purchase (POP) display applications. P-OLED allows seamless integration due to its thinness, flexibility, and lightweight features.

4.12.14 Kodak (USA)

Eastman Kodak, a leader in the field of OLED technology, sold substantially all the assets associated with its OLED business to a group of LG companies. Kodak has been a pioneer in developing technology associated with OLED displays [171]. Long before in 1970, Kodak scientists developed the world's first viable OLED material.

4.12.15 DuPont (USA)

DuPont Microcircuit Materials has 40 years of experience in the development, manufacture, and sale of specialized ink compositions for a wide variety of electronic applications in the display, photovoltaic, automotive, biomedical, industrial, and telecommunications markets [172]. DuPont, having expertise in OLED displays, is putting its experience in OLED lighting for a more sustainable future.

The DOE awarded a two-year project to develop OLED solution-processing manufacturing techniques [173]. New DuPont solution based Gen3 OLED materials pave the way for lower cost, longer life, solution process OLED displays while meeting or exceeding the performance of current vapor-deposited materials. DuPont is also part of a joint program with GE Global Research, designed to integrate OLED materials with roll-to-roll manufacturing processes [174]. Roll-to-roll manufacturing with DuPont OLED materials can significantly reduce the manufacturing costs for high-efficiency OLED lighting.

4.12.16 Idemitsu Kosan (Japan)

Idemitsu Kosan Co., Ltd. was founded in Moji, Kita-Kyushu in 1911 under the name of Idemitsu Shokai to engage in oil distribution. Idemitsu develops world-class OLED materials that are the combination of sophisticated, precise organic synthesis technologies and accurate performance evaluation methods. The company's expertise lies particularly in the development of new materials, as well as expertise in physical electronics technologies. Idemitsu Kosan is also diversifying into OLED lighting that takes advantage of the properties of OLEDs as light sources [175].

4.12.17 LG Chem (Korea)

LG Chem has announced a plan to commercialize white OLEDs for lighting applications [176]. In 2009, they exhibited a variety of white OLED product concepts at FPD/Green Devices'09 in Yokohama, Japan using Universal PHOLED technology and materials. LG Chem has developed a set of white OLED prototypes (5 × 5 and 10 × 10 cm) that illustrate the beautiful, bright, and uniform light emission of an OLED. LG Chem plans 4 sizes of OLED Lighting panels:

- 50 × 70 mm
- 150 × 20 mm
- 150 × 30 mm
- 150 × 150 mm

The OLEDs developed were cold, full white OLEDs, with 20–25 lm/W efficiency and a color temperature of 5,000–6,800 K. LG Chem is also developing equipment together with Sunic System to mass produce OLED Lighting products.

4.12.18 Samsung Mobile Display (Korea)

Samsung Mobile Display was founded in 2009 and is engaged in the research, development, manufacture, and marketing of display products. It produces AMOLEDs, TFT liquid crystal displays (LCDs), super twisted nematic LCDs, PMOLEDs, and touch screen panels.

Until recently, the South Korea OLED display leader Samsung has not appeared to be addressing the OLED lighting market. However, in recent years, Samsung Mobile Display has begun showing lighting prototypes. They unveiled first OLED modules with a size of 200 × 200 mm^2 and seven organic lighting modules with a size of 150 × 50 mm^2 at the SID-2009 Display Week [177]. These modules have a uniformity of 90% and a luminance of 3,000 cd/m^2.

4.12.19 Visionox (P.R. China)

Visionox, based on the OLED technology developed by the Tsinghua University (China), is a high-tech enterprise integrating R&D, mass production, marketing, and sales. Visionox installed the first OLED Pilot Line in 2002, and marketed the products in small scale in 2003. In October 2008, the mass production line of OLEDs independently designed by Visionox was put into production. Table 4.11 shows the specifications of Visionox lighting products. Today, Visionox business scope covers the design, development, production and sales of OLED products, display products, lighting products (OLED/LED), and others [178].

4.12.20 ModisTech (Korea)

ModisTech is a Korean company focusing on OLED displays and lighting R&D, and also consulting services. ModisTech ventured into the OLED industry in 2001

Table 4.11 Visionox lighting products specifications

Specifications	Olight	V0020-LA-002	V0020-LA-001	Twilight
Module size L × W × T	150 × 48 × 4 mm^3	20 × 20 mm^2	73.5 × 41.5 mm^2	Height 1: 360 mm Height 2: 300 mm
Active area (mm^2)		15.5 × 15.5 mm^2 Thickness: 1.8 mm	60 × 30 mm^2 Thickness: 1.8 mm	Diameter 1: 244–120 mm Diameter 2: 187–70 mm
Brightness (nit)	1,200			
Color temperature (K)		6,500 K	6,500 K	
Drive voltage (V)	5	5–6	5.5–6.5	
Light output (lm)	10			300
Lifetime (h)		10,000	10,000	

and is at present manufacturing flexible OLEDs. This is the only Korean company that focuses on flexible OLED surface lighting. They are seeking and developing more ways to improve and optimize colors white, orange, and red for their plans of commercializing OLEDs for desk lamps, and exterior/interior lighting for cars. ModisTech plans to commercialize 150 × 150 mm^2 flexible OLED indirect lighting [179].

4.12.21 Panasonic (Japan)

Panasonic Electric Works (PEW) is another leader in the development of white OLED lighting. Universal Display has been providing red and green phosphorescent OLED technology and materials to PEW under the New Energy and Industrial Technology Development Organization (NEDO) program in Japan. The company expects that white OLEDs have the opportunity to play an important role in a global "green" solution through such efforts.

4.12.22 AIXTRON (Europe)

AIXTRON is a leading provider of deposition equipment to the semiconductor industry. AIXTRON is participating in a R&D project with its Organic Vapor Phase Deposition (OVPD) technology platform in a consortium together with OSRAM, Philips, BASF, and Applied Materials. The final goal of this project, called OPAL 2008 (Organic Phosphorescent lights for Applications in the Lighting market 2008), is the development of an *OLED production technology capable of achieving the cost target* of a *few Euro cent* per cm^2 for a *high performance white*

OLED device [180]. AIXTRON's contribution to the project will be to improve the production capabilities of the OVPD process by designing equipment for large area deposition of OLED devices. With its unique features, low cost manufacturing, large area deposition, and high flexibility in making novel multilayer devices, the proprietary OVPD technology is considered the most suitable for mass production. These features are seen as the key properties in future production to achieve the efficiency of 50 lm/W at 1,000 cd/m^2 as required for lighting products.

The specialized organic materials required will be developed by BASF. The device architecture for the lighting modules and the adapted OLED processing technology will be developed by OSRAM and Philips.

4.12.23 Mitsubishi

Mitsubishi is focused on a new *high valued lighting market* initially, not *General Lighting*, because OLED lighting is color temperature tunable and RGB color tunable, in addition to being a large-sized thin planar white lighting. The company predicts that it is limited to only the high-valued market for a few years because of high price.

OLED Panel features

(a) Size: 14 × 14 cm
(b) Efficiency (typical): 28 lm/W
(c) Types of materials: small molecular OLED (as emitter)
(d) Types of lighting: Planar thin OLED Lighting, partially using solution OLED
(e) Color temperature tunable (2,700–6,500 K), and RGB color tunable
(f) Lifetime (LT_{70}, typical): 8,000 h
(g) CRI (typical): 80 (R9 = 66)
(h) OLED lighting panels will use printable OLED as under layer (= Hole injection layer)
(i) Schedule Samples 2010, Mass Production 2011

4.12.24 Kaneka

In September 2010, Kaneka (Japan) acquired Tohoku Device Company Ltd. which was founded in 2005 and based in Iwate, Japan, to manufacture OLED lighting panels. It planned to start shipping OLED lighting panels in March 2011 in Japan and in April 2011 in Europe [180, 181]. Kaneka offers OLED square panels in five colors (warm white, red, orange, blue, and green). The panels are dimmable (in the range from 1,000 to 5,000 cd/m^2). The efficiency of the Kaneka panel is around 20 lm/W and offers lifetime around 10,000 h. The company plans to improve the efficiency to about 60 lm/W and 25,000 h lifetime by 2014 [182].

4.13 OLED Lighting Technology Roadmap

OLEDs are now offering more than adequate lifetimes, brightness, and spectrum ranges and are beginning to find opportunities in the lighting business. The commercialization of OLED lighting over the past two years has started to accelerate, with a growing list of companies announcing their intention to enter the market with OLED lighting products. Although traditional lighting companies are active and visible seeking to secure their position with regard to OLED lighting, there are many new entrants that want to challenge these incumbents and influence the future industry.

Looking into the future, the OLED lighting industry is expected to pick up in 2011, with Philips, GE, KM, Lumiotec, and OSRAM entering mass production as displayed in Fig. 4.33. Large investments have been made in OLED lighting in the US, EU, Japan, and Korea. There are about 20 OLED lighting organizations worldwide. Europe is currently leading the participants in OLED lighting in terms of project numbers, government funding, and participating companies.

More than 40 companies, research institutions, and universities are included in this strategic analysis of the industry:

Add-Vision, Agfa, Blackbody, Cambridge Display Technology, Canon, Dai Nippon Printing, Doosan Corp, DuPont Display, Fraunhofer Institute, GE, Global OLED Technology (previously Kodak), Holst Centre, Idemitsu Kosan, Koizumi Lighting Technology, KM, Ledon OLED, LG Group, LG Chem, Lumiotec, Merck, Mitsubishi Chemical, Modistech, Moser Baer, NEC Lighting, Novaled, Organic Lighting, Osram, Panasonic, Petec, Philips, Pioneer, Polyphotonix, RIOE, Samsung Group, Showa Denko, Sumitomo Chemical, TechnoCorp Energy, Toppan Printing, Universal Display Corp, Visionox, VTT, and WAC Lighting.

This increase in technology and product development has led to an explosive growth in the number of OLED lighting patents being filed. A projected roadmap of the applications and technology requirements for OLED Lighting in the next 10 years is displayed in Table 4.12. This increase in International Patent filings coincides with increases in Government funding of OLED lighting projects that has occurred since 2000, most notably in Europe, the United States, Japan, Korea, Taiwan, and China. NanoMarkets expects the market for OLED-based lighting to exceed $1.0 billion by 2014 [183].

4.14 Conclusions

OLED lighting product, although still in the development stage, has advantages still too numerous to mention, not only with flexible, soft, and other features, but also with the paper thin OLED lighting and no maintenance of normal development light. The technical advantage is that the cooling mechanisms in OLED lighting are not needed. In OLED lamps the temperature increases only from 20 to

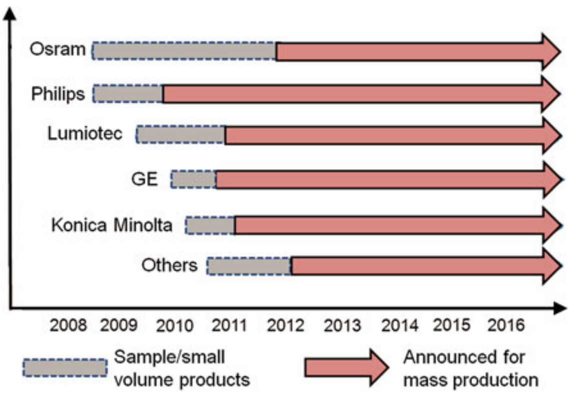


Fig. 4.33 OLED lighting manufacturing participant roadmap

Table 4.12 Roadmap of applications and technology requirements for OLED Lighting

	2010	2010–2015	2015–2020
Applications	Decorative lighting	General lighting (replacement of low-efficient light sources)	General lighting (replacement of high-efficient light sources)
	Small displays in mobile applications	Full color flat display (medium size)	Full color flat display (big size)
			Novel concepts via mergence of light source and display
		Transparent and color variable devices	
		Flexible devices	
Technology	Efficacy (lm/W) (R & D): 64	75–120	>150
	Efficacy (lm/W) (commercial): NA	30–60	>100
	Lamp life (h): 10,000	10,000	50,000
	Lamp price ($/m^2): NA	150–80	30
	Alternatives to ITO	Improved organic materials flexible substrates	
			Integration of (reliable) organic electronic
		Large area processing, novel manufacturing techniques (i.e. roll-to-roll)	

(Source: Fraunhofer Institute for Photonic Microsystems, Dresden, Germany)

30°C, hence the user can avoid the danger of heat, more in line with safety considerations. In conclusion, following are the inhibiting factors of OLED lighting which need immediate attention and benefits as well as impact of the OLED lighting technology.

Inhibiting factors—major improvements required

1. Short operational and shelf life, stability at high brightness levels.
2. Low device efficiency.
3. Device complexity—may affect the cost of manufacturing.
4. Uniformity of large area lighting sources.
5. Nonexistent infrastructure.
6. High electric currents.
7. Customer response (subjective factors).

Impact/Benefits

1. Enormous energy saving for the society.
2. Environmental impact associated with the reduction of the need for electricity (less air pollution, depletion of non-renewable sources of energy, less greenhouse effect).
3. Creation of new lighting (fixture) industry. New methods of power distribution and conduits. New jobs will be created.
4. New architectural designs enabled (lower ceilings, contour lighting, wall/ceiling panel lighting, space saving in airplanes, and tall buildings, etc).
5. Quality of lighting improved.

The requirements of white OLEDs to meet the needs of the lighting industry are (1) 100 lm/W, (2) 3,000–5.000 lm, (3) Lifetime of 50,000 h to L70, and (4) CRI $>$ 80. These requirements may be achieved with improvements in active materials, Electrode technologies, and outcoupling enhancements. Currently, OLED lighting is limited to demonstration programs and decorative/architectural lighting. OLEDs are still in their infancy. However, progress is steady. Three to five years in the future, OLED lighting luminaires are expected to replace fluorescent luminaire, integrate into acoustic ceiling tiles, and compete with inorganic LEDs. For the general lighting market, massive investment and significant technology developments are required. We expect the technology to start being offered to consumers in large volumes in 2016. In a world demanding higher standards for energy efficiency and environmental performance, OLED lighting has the potential to become a major lighting source on both fronts. And because OLED lighting is soft and diffused, it will create some exciting application opportunities for designers and specifiers. The applications are numerous, ranging from ceiling lighting for office and residential applications to interior automotive and aircraft lighting to many specialty lighting applications such as task lighting, signs, and various forms of interior retail lighting.

Due to its unique characteristic of 2D planar light source and new features of transparency, dual-side emitting, and flexibility, OLED light source varies from the traditional light source. It opens an era of brand-new lighting design, brings infinite innovation possibilities and makes new lighting applications (such as lighting wall, lighting glass window, lighting curtain) possible. Light, thin, and all-solid, OLED lighting can be applied to indoor and outdoor lighting, carrying tool (such as car, boat, plane, etc.) lighting and light signal indication as well as providing the standard and background light source for various measurement equipments (e.g., microscope). The long-term objective of OLED lighting development is to enter the widest field of general lighting application in order to provide high-quality lighting for families and public places worldwide such as schools, hospitals, shopping malls, etc.

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Chapter 5
Acceptability of Solar Powered LED Lighting

5.1 Introduction

Rural economic development is a national priority in many developing countries. Consumption of energy is believed to be the hallmark of a modern society. Access to electricity and home lighting are essential for a higher quality of life. However, rural areas frequently lack the safe and uninterrupted electricity supply that is desired for the development of numerous economic activities.

Nearly 1.4 billion people around the world live without access to regular electricity [1]. The social and economic impact of providing clean, safe lighting has been well recognized. A lack of reliable lighting access has manyfold negative impacts such as (1) limiting the productivity of nearly a quarter of the world's population, hindering their ability to carry out basic activities in the dark. Access to proper lighting has significant positive impacts on the productivity and income-generating activity, (2) contributing heavily to global carbon emissions and endangering the environment, and (3) causing chronic illness due to indoor air pollution by using fuel-based lighting and also risk of injury due to the flammable nature of the fuels used [2, 3]. School going children are unable to study, or do their homework if they do not have proper lighting in the evening time. For literacy development programs and nonformal adult education classes in the evening, modern lighting will be useful to provide clean and smoke-free light to enable people to read. However, due to the slow growth of electrification, a substantial portion of the world's population is left far behind those with reliable lighting.

Grid expansion is a vital objective of several developing countries and could be a long-term solution. However, the remoteness, isolation, and low electricity demand of many rural communities make them very unlikely to be reached by the extension of the power grid. Since the grid growth may take decades, many of the benefits of better lighting can and should be captured today through renewable solar light products. Consequently, off-grid generation systems seem to be the most suited to provide electricity services to these isolated rural communities. However, the numerous barriers inhibiting the widespread adoption of solar

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powered lighting systems need to be addressed. Mechanisms to enhance the acceptability of solar powered Light Emitting Diodes (LEDs) lighting to the rural population have been discussed, here.

5.2 Kerosene Fuel Lighting

Until the advent of the electric incandescent light bulb in the late nineteenth century, fuel-based sources such as oil lamps, gas lamps, and candles were used for home lighting. With the commercialization of the electric bulb, most of the urban population has switched to electric lighting where grid electricity is available. However, due to the great disparities in access to electricity and obstacles in the expansion of large-scale electricity generation plants and distribution grids, the rural population still relies on fuel-based sources for home lighting throughout the world. Approximately 1.4 billion people rely on fuel-based lighting for home illumination.

Currently many people in Asia and Africa without electricity use kerosene lanterns as light source. Kerosene fuel is an inefficient source of lighting providing very dim and insufficient light. The output light is only 2–4 lm compared to a 60 W bulb with 900 lm. The light is so faint that children can only see their books if they are almost directly over the flame. They inhale a lot more of the toxic smoke. Besides being a barrier to education and learning, it is unhealthy to do school work with a kerosene lamp.

Furthermore, the government subsidy on kerosene, mostly in developing countries, has undue price advantage against other fuels and has created the ground for diversion for adulteration of other petroleum fuels, usually diesel and gasoline. Diesel and gasoline are major transport fuels. Use of adulterated fuels causes serious environment-related problems. Kerosene subsidy is not benefiting the rural poor and has also failed to shift the fuel consumption patterns away from biomass in the rural areas.

5.2.1 Impact on Health

The World Bank (WB) estimates that 780 million women and children are inhaling particulate laden kerosene fumes. Fuel-based lighting is inefficient, expensive, dangerous and unhealthy. Due to poor ventilation, fuel-based lighting poses serious and debiliating health hazards, such as respiratory and eye problems, particularly in developing nations.

Burning kerosene lamps indoors produces pollutants such as:

- Carbon Dioxide (CO_2) which causes global warming.
- Carbon Monoxide (CO) replaces the oxygen indoors and can be fatal.

- Nitrogen Oxides and Sulfur Oxides (NO_x, SO_x) cause lung and eye infections, respiratory problems, and cancer. They also contribute to acid rain and ozone depletion.
- Volatile Organic Compounds (VOCs) cause eye, nose and throat infections, kidney and liver afflictions, and are carcinogenic substances that are released into the atmosphere.

5.2.2 Kerosene Fire Danger

Many families cannot afford a proper bottle and wick and rely on a fragile glass bottle and a piece of rope for a wick. Fuel-based lighting has more probabilities of causing fires. According to the World Health Organization, there are over 300,000 deaths each year from fire-related burns worldwide [4]. Over 95% of fatal fire-related burns occur in low and middle income countries. Southeast Asia alone accounts for just over one-half of the total number of fire-related deaths worldwide and females in this region have the highest fire-related burn mortality rates globally.

5.2.3 Impact on the Environment

It is estimated that in 2005 about 77 billion liters of kerosene (paraffin) and gasoline/diesel per year was used by fuel-based lighting.

$$\begin{aligned}
\text{Emission baseline } (\mathrm{CO_2/year}) &= \text{kerosene baseline} \\
&\quad (\text{i.e. kerosene consumption (liter/year)} \\
&\quad \times \text{ Emission Coefficient Efficiency of kerosene} \\
&\quad (\mathrm{kg\ CO_2/liter}) \\
&= (77{,}000 \text{ million L/year}) \times (2.63 \text{ kg } \mathrm{CO_2/L}) \\
&= 202{,}510 \text{ million kg } \mathrm{CO_2} \text{ per year} \\
\text{or } &= 202.5 \text{ million metric tons } \mathrm{CO_2/year}
\end{aligned}$$

Currently, fuel-based lighting in the developing world is a source of 244 million tons of CO_2 emissions to the atmosphere each year, or 58% of the CO_2 emissions from residential electric lighting. *Also, subsidized kerosene for domestic lighting sometimes finds its way into vehicles with additional environmental consequences.*

Rising CO_2 and other greenhouse gas concentrations in the atmosphere, resulting largely from fossil-energy combustions, are contributing to global warming and to climate change [5]. Climate-destabilizing CO_2 emissions continue to rise, drawing concern for the long-term sustainability of the global energy system. In 2030, energy-related CO_2 emissions would be 52% higher than at present; this needs to change in order to get the planet onto a sustainable energy path.

To address the greenhouse gases (GHGs) emission problem, judicious and intelligent use of energy resources are recommended. The best option is to use *more efficient and energy saving devices and appliances.*

New types of light sources and technologies are desired to convert energy directly into visible light at room temperature without any emission of greenhouse gases. In this context, solar powered compact fluorescent lamps (CFL) and white LEDs *provide* the solution with *less power consumption* and *almost no environment contamination*. The single most efficient way to reduce greenhouse gases associated with the lighting energy used is to replace kerosene lamps with solar powered CFL and white LED lighting systems in developing countries.

5.2.4 Impact on Income Generating Activity

Access to electricity and poverty are closely linked; countries that have the lowest levels of electrification also have the highest levels of poverty. Without adequate electricity and lighting, adults are unable to continue income generating activities after daylight hours which help to lessen the burden of poverty. Access to proper lighting (of high enough illumination to enable reading and other household and business-related activities) has a significant positive impact on productivity broadly and income generating activity specifically [2]. Through provision of solar lights, individuals can (1) run their businesses without dependence on fuel-based products for lighting, and (2) operate small cottage industries to increase their income by using light to extend their productive hours after nightfall. Furthermore, solar lanterns contribute to longer working hours for occupational groups such as traditional handicraft artisans, textile workers, and livestock herders. The quality of illumination also boosts sales since customers pay more attention to the display and engage in purchase-oriented behaviors more often.

5.3 Solar Powered Lighting

5.3.1 Solar Powered Compact Fluorescent Lamp Lighting

Solar powered lighting systems are acquiring the center stage in Rural Lighting owing to cost competitiveness and clean lighting without any GHGs emission compared to fossil fuel based lighting. For the past few years, an alternative to fuel-based lighting has been the relatively efficient CFL lamps powered by solar

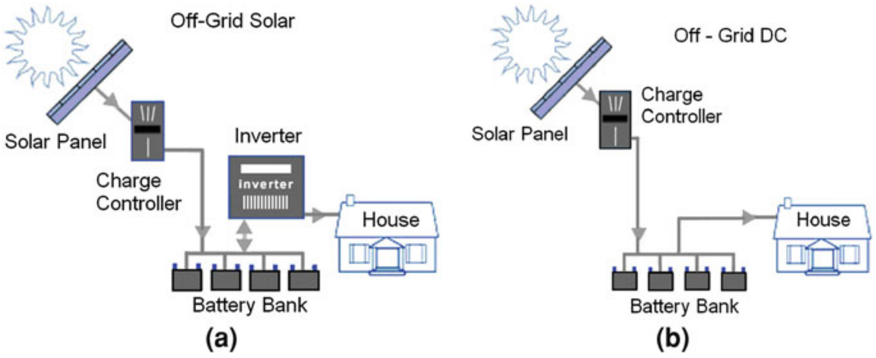

Fig. 5.1 **a** Off-Grid AC solar power systems to provide power for normal AC appliances. **b** Off-Grid DC solar power systems to provide power for only DC appliances

photovoltaic panels (Fig. 5.1a, b). The essential components of a solar home system are:

1. Solar panel array to convert sunlight (photons) into electrical power.
2. Charge controller to charge a battery (increase its voltage).
3. Solar batteries for power storage (for off-grid systems).
4. High-quality cables for connection panels and Battery Junction Box.
5. Sine wave inverter to convert battery direct current (DC) into alternating current (AC) output (10 ~ 15 V DC input, 220 V AC output, 50 Hz) suitable to be connected to standard household appliances (optional).

Figure 5.2 shows the CFLs powered by solar photovoltaic panels for rural lighting. The important features of CFL lamps are:

- Preheating, high electronic efficiency, Polarity Protection.
- Saves up to 80% of energy compared to an incandescent bulb.
- Rated Voltage: 12 V (10.5–15 V) or 24 V (18–28 V).
- Rated Wattage: 3, 5, 7, 9, 11 and 13 W (+5–10%).
- Color Temperature: 2,700, 4,200, 6,400 K, Red, Green, Blue.
- Operation Temperature: −10 ~ 50°C.
- Low temperature and low voltage start.
- Average lumens 150 ~ 715 lm.
- Compact and robust product design.
- Life Time: 6,000 h.

Unfortunately, all fluorescent lamps including CFL contain small amounts of elemental mercury (5–50 mg). Mercury is toxic by ingestion, inhalation, and skin absorption with acute and chronic exposure effects, to the central nervous system including kidney damage. Fluorescent lamps often contain over three times the concentration of mercury allowable for landfill disposal. Through improper

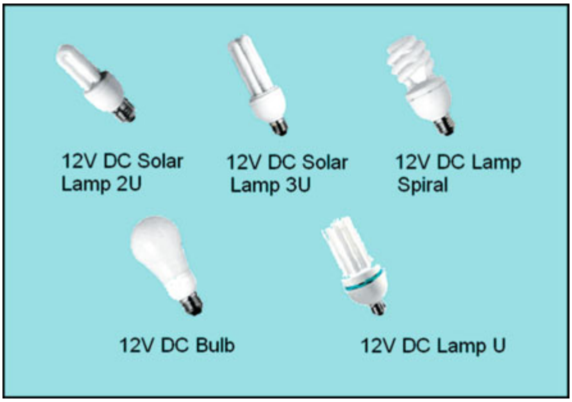

Fig. 5.2 12 V DC fluorescent CFL light bulb designed for photovoltaic PV system use

disposal methods, mercury may travel from the soil to various water sources. Lakes have been found to be polluted with mercury, rendering fish unsafe to eat. As mercury moves up the food chain, it becomes more concentrated and poisonous to the human nervous system.

The United Nations Environmental Program (UNEP) noted that mercury is a globally dispersed pollutant that is accumulating, and has called to minimize the further release of mercury.

Disposal of Spent CFL Lamps

Disposal of burned fluorescent lamps is a major concern that needs to be addressed. The European Commission Regulation—August 2005, Waste Electronics and Electrical Equipment Directive bans lighting containing mercury from landfills. In 2006, the EU set a target recovery rate of 80% of the mercury used.

In the USA, regulations of mercury containing luminaires vary considerably between states. Some states have banned incineration of lamps, and others have banned lamps from landfills. In California, all fluorescent lamps must be recycled. Some states have established a collection scheme whereby householders can deposit spent lamps at some retail stores.

Some Asian countries have lamp endorsement labels that impose maximum mercury content. Japan, Taiwan, and South Korea have implemented take-back programs. Australia has a recycling program for all spent lamps. Many developing countries have no regulations for disposal of burned CFL and fluorescent lamps.

Inspite of these regulations, how many people in developed and developing countries understand that they must be recycled. How many people just toss them in the trash like an incandescent lamp? How many of the CFLs are actually being recycled?

5.3.2 Solar Powered LED Lighting

CFL is considered as outdated technology and people are looking for new, smarter, energy efficient options. LED light bulbs are the most ideal replacement bulbs that can achieve natural light results (without UV rays and no flickering) and are truly environment friendly.

LED lighting technologies use Light Emitting Diodes. A diode is the simplest semiconductor device. Broadly speaking, a semiconductor is a material with a varying ability to conduct electrical current. As current passes through the LED, the materials that make up the junction react, and white light is emitted.

LEDs are considered to be the future low power consumption lighting sources to the urban on-grid population, while solar powered LEDs provide clean lighting to rural off-grid communities [6]. *Furthermore, no GHGs emissions and mercury and lead contents are the most imperative features of solar powered LEDs lighting* [7]. Research has shown that LED-based lighting improves the quality of illumination, compared to traditional lighting [8]. Replacing fuel-based lighting with white LEDs can also contribute to the overall development of the underprivileged and underdeveloped communities by helping to improve the health, education, and life expectancy of the people as well as income generation.

The adoption of solar powered LED Lighting minimizes the use of kerosene fuel-based lighting. Replacing kerosene with LED lights offers several benefits: reduced air pollution, improved studying conditions for children, saved lives from kerosene risk, reduced spending by poor families on kerosene, reduced health risks [9, 10].

LED bulbs offer significant advantages over traditional kerosene by: emitting a brighter light, requiring less maintenance, improved studying conditions for children, saved lives from kerosene risk, and lasting longer. One of the greatest benefits, however, would be the elimination of fumes and smoke which would both improve the health of families and reduce greenhouse gas emissions.

LEDs have already been commercialized and LED products are available in the market for end use although they do not have cost-competitive advantage with regard to other light sources as shown in Fig. 5.3. The price of LED lamps is too high; 5–6 times that of normal energy-saving lamps, and even 10 times higher than incandescent lamps. Such high prices cannot be afforded by ordinary families. However, technological advancements, policy mandates, decreasing LED prices, and rising electrical prices are prompting a shift in the lighting industry from incandescent and fluorescent bulbs to solid-state lights like LEDs.

According to “Moore’s Law” of the LED industry, LED’s light output will be doubled every 18–24 months, while prices will decline by half. Based on prediction analysis, by 2012, the price of LED lighting will drop drastically increasing the use of energy saving LED lamps in home lighting application. Indeed, the cost of 7.2 W cool white LED strip $10 USD in 2010 is reduced to $6 USD in 2011.

Fig. 5.3 LED lamp sources for lighting

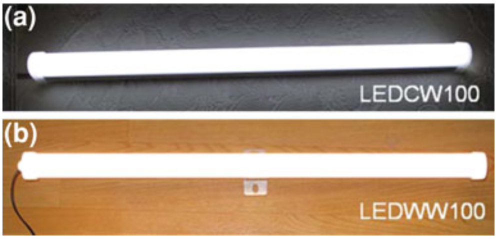

Fig. 5.4 Linear LED lights. **a** Cool white. **b** Warm white

Important Features of LEDs for Solar Powered Lighting Systems

- Power consumption 3–10 W
- Luminous flux − 780 lux
- Operating voltage LED—12 or 24 VDC
- Operating temperature −30 ~ +60°C
- LED lifetime—80,000 h
- Power factor 0.911

LED light sources are also available in linear form. Figure 5.4 shows 12 V (7.2 W) cool and warm white LEDs. Linear LED lights give sufficient illumination, pleasant, and widely accepted for solar lighting. The specifications of these linear LED lights are illustrated in Table 5.1.

Comparative illumination of LED and normal fluorescent lamp and applications of LEDs are displayed in Figs. 5.5 and 5.6, respectively..

Table 5.1 Specifications of linear LED lights

LED device	LED quantity	V DC (V)	Dim. L×W×H (mm)	Wt (gm)	Forward current (mA)	Power (W)	Total lumen flux (lm)	Color/ temp. (K)	CRI index	Applications
LED CW100	30	12	530 × 25 × 18	250	600	7.2	880	White 6,500	70	Indoor lighting illumination decoration linear lighting
LED WW100	30	12	530 × 25 × 18	250	600	7.2	880	Warm white 4,500	70	Indoor lighting illumination decoration linear lighting

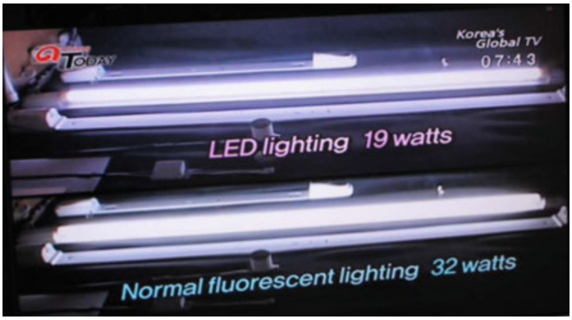

Fig. 5.5 LED lighting and normal fluorescent lighting illumination

Fig. 5.6 Applications of LED light sources

5.4 Economics of LED Lighting

In remote areas, the high cost of kerosene can consume much of a family's income. One lamp consumes 0.04–0.06 L/h, and the daily usage of three to four hours burn time. One liter of kerosene per week times $1.00 USD = $52.00 USD per year (see Table 5.2). The amount of light from the lamp is only about 0.2% of what the people in industrialized countries have for the same price. Furthermore, these lamps use kerosene, which has to be imported and is expensive or often unavailable in rural areas.

Kerosene lighting is far more expensive than electric lighting. The cost of useful light energy ($/lumen hour of light) for kerosene is 325 times higher than inefficient incandescent bulbs, and 1,625 times higher than compact fluorescent light bulbs [11].

Table 5.2 Economics of various lighting technologies in off-grid applications

Lamp type	Kerosene	Incandescent	Compact fluorescent	White LED
Efficiency (lumens/watt) rated life (hours) durability	0.018	5–18	30–79	25–50
	Supply of kerosene fragile and dangerous 0.04–0.06 L/h ∼ 80	1,000	6,500–5,000	50,000
		Very fragile	Very fragile	Durable
		5 W	4 W	1 W
		98	62	82
Power consumption color rendering index (CRI) $ after 50,000 h use	1,251	175	75	20

Table 5.3 Case-study—Solar-based LED lighting for semi-nomadic populations of rural Tibet

Current lighting systems	Solar home system or diesel fuel lamps
Solar home systems (CFL)	1. Donated or subsidized by the central or local governments or outside organizations (like USDOE, WB, etc.)
	2. Villagers pay fee between no fee and $ 150/-for their systems, depending on the amount of subsidy.
	3. Solar panel—10 or 20 W solar panel to operate 2 CFL bulbs. Sometimes radio, tape player, or television
	CFL costs: 2–3 $, replacement time varies from 2 months to 2 years.
Diesel lamps	1. Small Jars of fuel with a thick wick inside. As a supplemental source to solar powered lighting.
	2. 100 ml of fuel gives light for 3 h per day. One to five liters for one month, US$ 6 ∼ 30 per year.
	3. Light output–very low.

5.5 Case Study for Solar LED Lighting in Tibet

Despite the high rates of electrification in China, 25–30 million people remain without access to electricity. Fuel-based lighting has shown to be significantly more costly than solar powered CFLs and solar powered LEDs alternatives. Thus, there is a need to explore off-grid technologies for lighting in China. In this case study, they examined the lighting pattern in the off-grid population in rural regions of the province of Tibet (see Table 5.3) [11].

5.5.1 Findings of the Project

1. The success of solar powered CFL is dominated by the solar panel and battery components and scale with the power output needed.
2. The retail costs of these systems to the end user are often prohibitive. As a result, the potential for these systems has remained highly dependent on subsidy.

3. The local market for solar home systems in Tibet is largely driven by subsidies from the federal government.
4. A consumer market for solar home systems exists in the city of Lhasa, but its sales volume did not appear comparable to the subsidized market.
5. Limitations associated with the current system (1) there is no strong drive for innovation, (2) the end users of the products have little influence on the product design and improvement, and (3) the products are provided free, or at low cost, there may be little incentive for the end users to invest in maintenance of the product.
6. A significant percentage of the solar home systems encountered during the study were non-operational, either due to minor maintenance issues that could not be replaced by local villagers or due to defective products that could not be returned.

5.5.2 Reactions to Solar Powered LED Lighting Systems

Solar powered LED lighting is shown to be cost-competitive compared to fuel-based and solar powered CFL lightings. Other benefits of LEDs are (1) ruggedness, (2) significantly longer service life compared to competing electric light sources. Despite the potential benefits of LEDs, market forces are likely to spur innovation in solar LED lighting options for the off-grid populations of Tibet. Villagers were asked to compare the solar powered LED lighting with the traditional CFL bulbs and diesel lamps.

1. The strong directionality of LED light was a major complaint.
2. Villagers welcomed greater luminance LED lightings.
3. Villagers placed a high value on the daily operating time and power consumption.

5.6 Barrier to Consumer Acceptability of Solar Powered Lighting

UNEP and several agencies of different governments are aggressively encouraging the use of solar lighting systems in their countries particularly in the rural communities to reduce the GHG emission and global warming. However, a plethora of factors are inhibiting the rapid development of solar home systems. It is therefore necessary to identify the barriers to penetration of solar lighting system and address concerns of consumers to boost the solar lighting market.

Table 5.4 Barriers to adoption of solar PV technology in Mwanza, Tanzania

Barrier	Degree of importance	Methodology to redress issues
Limited awareness of, and experience with PV technology and 12 VDC appliances. Energy is a low priority area among users.	Major barrier	Increase the understanding of solar PV technology to the large community via TV/radio programs, personal networks
Inadequate business knowledge and capacity for distribution	Major barrier	Build business knowledge and capacity for Distribution of solar PV systems
Limited technical knowledge of proper sizing, installation, operation, and maintenance	Major barrier	Training, promotion, and trade fair
High cost of solar systems, initial capital investment, and operation and maintenance	Major barrier	Link installation of PV systems with poverty alleviation projects
Low purchasing power of the rural people	Major barrier	Subsidize promotion of solar technology
Lack of established dealer network	Secondary barrier	Build a network of dealer
Inadequate policy implementation	Secondary barrier	Formulate/revise policies to support solar PV
Difficult access to finance for end users	Secondary barrier	Subsidize promotion of solar technology

5.6.1 Case Study of Tanzania-Barriers to Solar PV Technology Transfer in Mwanza, Tanzania

Barriers to adoption and use of solar based lighting in Mwanza, Tanzania are shown in Table 5.4 [12].

5.6.2 Solar Home System in Botswana: A Case Study

In Botswana, more than 70% of the country's population lives in rural areas. They depend mainly on traditional agriculture and pastoralism for their livelihood. Lack of access to on-grid electricity forced them to use fuel-based lighting systems.

To address the issue of energy poverty among rural communities, the Botswana Government initiated several programs for rural electrification [13]:

1. Promotion of solar energy by the Botswana Government,
2. Integration of grid and non-grid technologies,
3. Identification of an appropriate institutional framework for rural electricity using renewable energy,
4. Development of strategies for removing the barriers to widespread use of renewable energies,

5. Promotion of women and children's welfare through the provision of photovoltaic power generation.

The Government installed a pilot project on the photovoltaic solar system in three villages. In this model, the service Company provides electricity to the households in a community for a monthly fee. A system for regular monitoring of revenue collected from participants is required.

Some major impediments causing low use of solar home systems by rural communities are:

1. Low-income status of most rural inhabitants which is a major factor/ impediment,
2. Fee for-service model is an unsuitable model used by the authority—Major factor,
3. Migration of house owners from village status to lands, or cattle posts—Secondary Factor.

5.6.3 Case Study of Morocco

The project is to provide 101,500 rural households in all regions of Morocco with photovoltaic kits (75.7 W_P (watt peak)) along with the basic installation for domestic electricity use (bulbs, plugs) during the period 2004–2008 to enable them to meet their basic energy needs.

Barriers to achieve final goal are listed as [14]

1. Investment Barrier: The main barrier to large-scale adoption (in rural areas where it is most appropriate) is the economic factor.
2. Technical Barrier: The performance uncertainty, the low market share of the solar photovoltaic technology, the low ability of local technicians to deal with maintenance problems, and after-sales services contribute to reduce the reliability of the solar PV systems.
3. Other Barriers: Limited information about the end users, lack of organization capacity, and financial resources are also barriers to the adoption of the solar PV systems on a large scale in rural areas.
4. Therefore, without strong financial support and owing to the aforementioned barriers, the diesel generator system will remain the common option, leading to higher emission.

5.6.4 Case Study of Egypt and Zimbabwe

Although renewable energy technologies have made progress in Egypt, it has been limited to technology development, demonstrations, and very little commercialization. Effective market penetration of renewable energy technology has been

Table 5.5 Case study of Zimbabwe

Barrier	Causes for barrier	Degree of barrier
Economic and financial	Cost of installation and after-sales services are very high. Estimated to be about 30% of the total costs of PV systems.	Major barrier-I
	High capital cost and lack of financing mechanism	
Awareness/information	Awareness of the applications of solar photovoltaic systems is very low.	Major barrier-IV
Technical barrier	Lack of access to technology, inadequate maintenance facilities, bad quality product	Major barrier-II
	Lack of skilled manpower and training facilities.	
Market barrier	Small-size market.	Major barrier-III
	Limited involvement of private sector.	
Social barrier	Lack of social acceptance and local participation	Major barrier-V
Institutional	Unfavorable energy sector policies and unwieldy regulatory mechanisms.	Secondary barrier

below expectations [15]. In spite of these barriers, solar PV systems still have opportunities and potentials for contribution to rural development programs.

Only 20% of Zimbabwean households have access to on-grid electricity. A majority of the community could not afford to utilize the electricity due to lack of access to financial and technical resources [15]. Alternative energy sources were recognized as a viable solution for the energy needs of the poor (Table 5.5).

5.6.5 Case Study of India

In India, 46% of the population, mostly the rural community, has no access to electricity. Fuel-based lighting, Kerosene lamps, are used for illumination, contributing to global warming and also causing serious health problems. In this context, solar photovoltaic systems offer a good alternative for electrification in the rural and remote parts of India [16, 17]. However, several issues need to be addressed to improve the acceptability of solar photovoltaic systems by the rural population.

1. Absence of government subsidy programs. Solar photovoltaic home systems are too expensive and unaffordable by rural inhabitants.
2. No awareness of solar photovoltaic systems and their benefits.
3. Lack of marketing network in rural parts.
4. Reliability of solar photovoltaic system.
5. Non provision of after-sales service. No service back-up network.

Recently, Solar Electric Company Pvt. Ltd, Bangalore, India, has developed a business model through innovative rural financing schemes for creating a maintenance network in villages. However, reliability of the system, particularly service after the sale and network in case of any technical faults, is debatable. To increase the acceptability and market share of any new technology, the reliability of the systems is the single most imperative factor.

5.6.6 Case Study of Vientiane, Lao PDR

1. Solar home systems and portable solar lamps are rented at prices lower than the expenditure on kerosene for lighting, so that families can save money by switching to solar PV [18].
2. Uses a carefully selected and trained network of franchises to install and maintain the solar PV equipment, and each franchise trains technicians in the villages to perform the day-to-day maintenance.
3. Rents equipment to the Village Energy Committee (VEC), which is selected by the whole community, and the VEC leases it to individual households.
4. Community is responsible for setting prices, collecting rents, and performing basic maintenance.
5. Larger village systems provide power to community services such as health systems and water pumping.
6. This business model ensures high-quality solar PV lighting and good customer service at a price people can afford.

5.6.7 USAID Project in the Philippines

In Philippines, USAID is developing off-grid renewable energy systems in 160 remote rural communities in the Autonomous Region in Muslim dominated Mindanao, through alliance with Mindanao off-grid Renewable Energy [19].

The program addresses specific barriers to widespread adoption of rural energy technologies. The barriers include:

1. Lack of awareness of the costs and benefits of renewable energy technologies.
2. Prevalent policy bias towards fossil fuels.
3. Lack of adequate financing and ability to pay, and limited institutional policy.
4. Lack of sectoral specialists in understanding how Renewable Energy Technologies can be applied in their sectors, including health, education, agriculture, and information and communication technologies.

USAID addresses these barriers by overcoming technical, financial, policy, and institutional challenges.

Through solar powered battery charging stations and individual batteries, residents are now saving 70% each month of what they used to spend on kerosene for

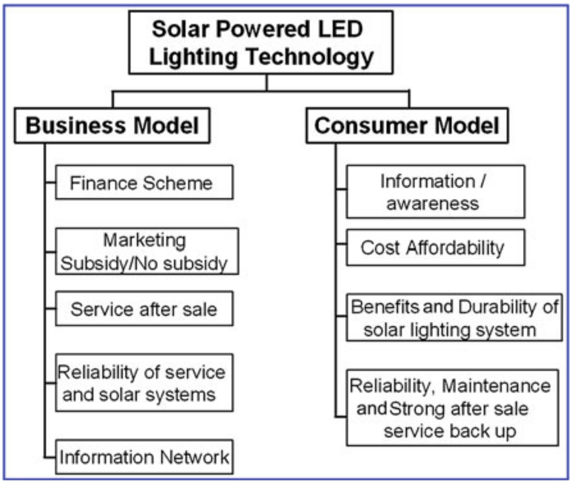

Fig. 5.7 Model to enhance the use of solar powered LED lighting technology

light. Residents have increased opportunities for productive activities such as mat weaving, sewing, and extended daylight hours for study time and household work.

5.7 Acceptability of Solar Powered LED Lighting

Solar powered LED lighting technologies have a niche in rural areas that are off-grid and in most parts that have no availability of electricity. Therefore, focus should be on providing clean energy for *certain productive uses* across non-energy sectors and not solely for the *sake of installing units*. The success of any new technology depends on the viable business model and widespread adoption by consumers. Acceptable business and rural consumer friendly models are desirable to enhance the market share of solar powered LED technology. Figure 5.7 shows the proposed model to enhance the market share of solar powered LED lighting technology.

5.7.1 Business Model

Finance Scheme

- Financing Institutions need to be educated about the nature, and future potential of renewable energy technologies—particularly local and regional commercial banks.
- Increased knowledge about these technologies can stimulate investment, lending, and business.

- Rural financing scheme through the village body with adequate safeguards for repayments through peer pressures. A loan will be made available from the bank directly to the Village Committee, thus avoiding time and middle persons. However, such loan schemes should ensure that the consumer would be able to buy the solar system as per his requirements and choice.

Marketing—Subsidy/No subsidy

- With the Government subsidy, the solar system up-front cost can be made affordable and end users mostly in rural areas have to pay a small amount initially and the remaining balance payment may be divided into several installments. Government subsidy schemes may be implemented either through NGOs, private business establishments, village organizations, or other government organizations in rural areas.
- In the absence of a Government subsidy program, private business owners and NGOs may develop an innovative consumer finance scheme through rural credit institutions or through village body with loans from commercial banks. The village organization/body sells solar systems along with installation, maintenance, and also repayment of loan.
- However, in both financing schemes, the fear is that end users may be compelled to buy certain substandard, outdated solar system units. Consumers must be given an opportunity to buy a modern solar system model as per his needs, thus ensuring enough scope for future technology innovation.
- Rent solar photovoltaic systems to Village Committee at prices lower than expenditure on kerosene for lighting. Success of the scheme depends on the Village Committee and participation of local communities, as the Village Committee is responsible for the installation, maintenance, and collection of energy bills.

Service after sale

- Trouble-free light source with minimum maintenance expenditure.
- Trained local technicians for doorstep installation and maintenance.
- Quick after-sales service and regular check up.
- Local infrastructure for repair and maintenance, to provide quick and effective services in case of any technical failure of the system.
- Solar Battery bank and availability of other components locally.

Reliability of service and solar systems

- Success of the clean light to rural community scheme and solar powered LED lighting technology depend on the reliability of the system.
- Solar powered LED lighting technology must give confidence to end users that they will get electricity supply without any failure.
- Efficient service from local technicians is very important. Some incentives (or commission) from the manufacturers/local dealers may motivate technicians to provide the service immediately.

Information Network/Training Network

- Increase understanding of solar PV technology to the large community via TV/radio programs, personal networks.
- Community technology demonstrations. At least one demo-project at a public meeting place/religious place/village chief house.
- Disseminate information about the solar systems through Religious/community services.
- Network system that can give information about the minor repair and maintenance of the solar system.
- Network between dealers and local technicians to understand the difficulties faced by end users.

5.7.2 Consumer Model

Information/awareness

- Awareness dissemination about the new lighting technology in rural communities.
- Community awareness program to help people understand how they can help themselves to maintain and use the system.
- Awareness program about the viability and reliability of solar powered LED lighting technology.

Cost Affordability

- If energy hub is used to provide the electricity to entire village, some credit system should be made available to help poor communities who have limited ability to pay.
- Micro-credit system with extremely low interest as up-front cost of solar system is required for rural population who are beyond the paying capacity.
- They may be allowed to make payment even on daily basis. The amount may be of the order of the daily consumption of kerosene fuel.

Benefits and Durability of solar lighting system

- Economical, compared to kerosene fuel-based lighting and solar powered CFL lighting. Health Benefits, free from fumes and pollutant gases.
- Improved Quality of life.
- Increased opportunities for productive activities for income generation to support family by setting up small-scale business at home.
- Income generation activities in health, education, agriculture, and information/communication sectors.
- Significant increase in monthly saving.

Reliability, Maintenance and Strong after-sale service back up

- Reliability of the solar system to provide uninterrupted electricity is the most important factor for end users.
- Durability of lighting system.
- Dealers/technicians must ensure end users that they will get electricity throughout the day.
- High quality lighting and good service at a reasonable cost that people can afford.

Other Benefits

- Opportunities to develop new DC-driven appliances and other solar power-driven equipments in health, education, agriculture, and information/communication sectors to boost rural economic development.

5.7.3 Energy Hub

Recently, OSRAM has setup an Energy Hub in April 2008 in Mbita which supplies up to 10 KW of electricity. This is enough to recharge around 350 lamps per day. In addition to the lamps, the energy hub also charges batteries that can be connected to electrical devices such as radios. When the lamps and batteries run out of power, they can be exchanged for recharged devices under the deposit system that has been set up. In this way the equipment can be regularly maintained and controlled, which gives the system a further advantage over other solutions: proper maintenance ensures long life, and also creates new jobs.

5.8 Financing Solar LED System

Most inhabitants who lack access to grid electricity are categorized as low income. Low-income consumers often do not have the initial investment needed to purchase new lighting products due to high up-front costs of LED solar home systems (SHS). A recent report shows that approximately 90% of households lack access to formal financial services [20], a primary means of acquisition. Financial institutions (FIs) are often hesitant to lend to consumers due to the risk factor of non-receipt of loans. Moreover, available financing is often security based. In fact, access to finance is the biggest hurdle to scaling-up the solar lighting market. A lack of financing options, including limited access to long-term growth capital as well as short-term working capital are also significant barriers to market growth. Figure 5.8 shows the various financial institutions which could be helpful to provide solutions to finance LED SHSs. Rural Banks, Commercial Banks, National Banks, Cooperative Banks, Rural Farmer Cooperatives, and NGOs are

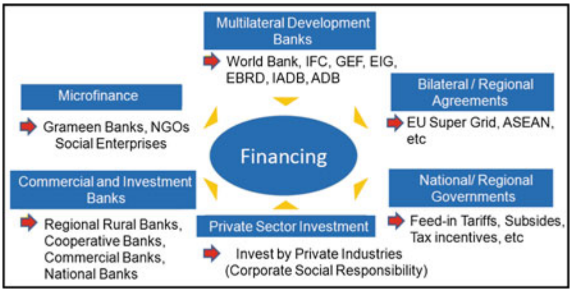

Fig. 5.8 Financial institutions for providing credit to LED SHS

imperative to develop financial solutions to obtain the necessary credit to customers for purchase of solar lighting. If the targeted population segment does not have access to formal financial services, informal finance mechanisms should be made available to ensure the financial transactions.

5.8.1 Best Practices of Financing in Africa

The IEA (2010) estimates that about 589 million people in Africa live without access to electricity [21]. Africa's non-electrified population is expected to grow from 110 million households to 120 million households by 2015 [2]. African grid expansion is failing to keep pace with population growth. Solar technologies provide the alternative to sustainable development and life-changing improvements. However, the high up-front cost of LED SHS continues to be an issue for the poorest African consumers. Access to finance, therefore, is a key factor for the adoption of solar lighting technology.

1. Desertec Consortium is investing in solar business in North Africa.
2. China is funding a study to evaluate Kenya's potential for solar water heaters and solar PV.
3. The Global Environment Fund (GEF) is providing millions of dollars as financial capital to help spur development in Africa, financing through Multilateral and Bilateral agencies.
4. Government incentives: South Africa—\$0.269/kWh feed-in tariff; Morocco-plans to double the share of renewable energy sources to 19%.

5.8.2 Best Practices of Financing in Asia

In Asia, about 799 million people live without access to electricity. Approximately 85% of those people live in rural areas [22]. The rural banking system plays a significant role to finance sustainable energy systems for poor rural households.

People can take a microfinance loan from a bank or microfinance institute, non-governmental organization (NGO) or social enterprise in return for payments spread over an agreed period and buy the solar system directly [23, 24]. In addition, credit facilities to customers are also provided by Commercial Banks, National Banks, Cooperative Banks, etc. But not everyone has access to banking or microfinance. Although such financing is designed to help poor people, the terms can still be impossible to meet for the very poor. Innovative finance mechanism based on local practices may be desirable.

5.8.3 Credit Guarantee System

Potential customers require some sort of collateral which the poorest people do not have and need a good track record to qualify for a solar loan. Sometimes customers also need to make a part of the down payment. Bank insists on the evidence that the customer has a minimum regular income before the loan can proceed. They have difficulty in gaining access to financial institutions due to insufficient credit. The Local Credit Center (non-profit organization) formed with the stakeholder of local people and contributions from the Government and Private Institutions, can issue a letter of credit guarantee for the loan to the Bank. In case of financial crisis, the Credit Center pays the Bank instalment.

5.9 Conclusions

It is believed that LEDs operated using solar energy offer the solution to provide clean and affordable light to 1.4 billion people around the world, mostly in Asia and Africa, who are living without electricity and currently use kerosene lanterns as a light source. Replacing kerosene with LED lights offers an array of benefits: reduced air pollution, improved study conditions for children, and reduced spending by poor families on kerosene. Quality of Life is also improved. Use of solar powered white LEDs significantly reduces power consumption, no environment contamination by mercury or lead, and increases monthly savings by up to 70%. The greenhouse gases associated with kerosene-based lighting will be completely minimized with solar powered white LED lighting systems in developing countries.

Putting reliable solar power systems into the hands of poor and remote villagers has not been an easy task. However, the lighting project should not fail. Careful planning and a number of best practices to address the sustainable development of the market and the acceptance of LED SHS technologies are vital for the success of solar lighting projects.

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Appendix 1: Suppliers of Organic Materials

Suppliers of organic materials used in OLED lighting devices fabrication

Light emitting hosts and dopants	Injectors/Transporters
• Cambridge display technology—Polymers • DuPont—Solution based phosphorescent small Molecule • Idemitsu Kosan—Fluorescent and phosphorescent small molecule • Merck—Polymers, small molecule • Universal display—Phosphorescent small molecule • Dow chemical—Fluorescent and phosphorescent small molecule • Sunfine chem—Fluorescent and phosphorescent small molecule • LG Chemical—Fluorescent small molecule • Sumitomo chemicals (Japan)—Polymers	• DS himetal dow chemical • H.C. starck group • LG chemical • Cheil Industries Inc. • Toray • Merck • Nippon steel chemical Co., Ltd. • Nissan chemical industries • Novaled—P/N doping • Plextronics • BASF

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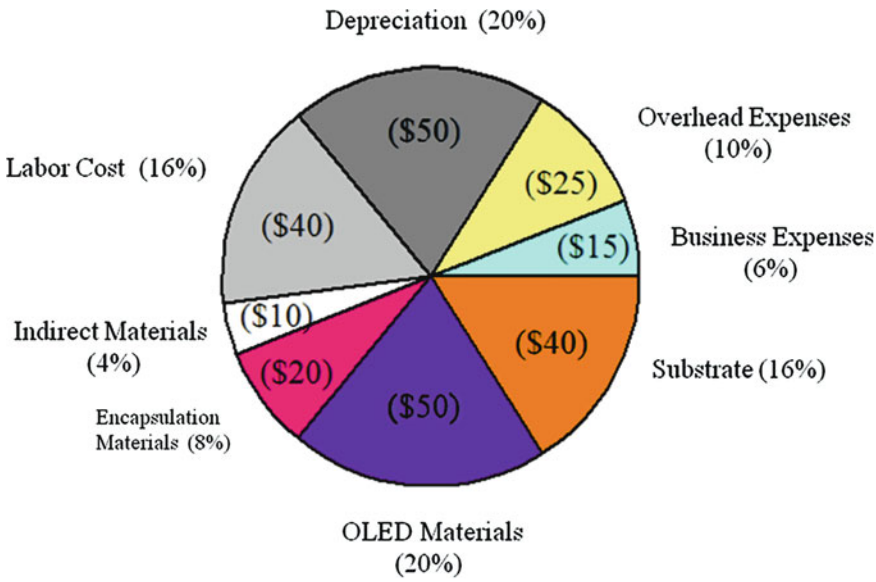
Appendix 2: Costs of Commercial OLED Lighting Panels

Manufacturing cost breakdown per square meter is presented for year 2012–2013 for mass production. Total cost of panel is \$250.00/m^2.



Source: G. Rajeswaran, Moser Baer estimate for 2012–2013

The price of the OLED lighting panel is still very high. Consequently, some companies are focusing on a high valued lighting market. They predict that OLED white light products may be limited to only the high-valued market for a few years because of high price. For general lighting, it is necessary to reduce the cost

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substantially. The cost reduction strategy of the OLED lighting panel in 2020 will be:

(i) OLED materials: <\$10/m^2
(ii) Glass, light extraction, TCO, encapsulation, other: <\$30/m^2
(iii) Labor: <\$5/m^2
(iv) Equipment (entire line): <\$20/m^2.

The total cost per square meter will be about \$65 or less by 2020.

Appendix 3: LED SHS for a Typical House in Rural Region

Electrical appliances usage:

- Four 7.2 W–12 VDC Linear LED lamps used for 5 h per day.
- Two 6 W–12 VDC fan used for 10 h per day.
- Other DC appliances 10 W for 2 h per day.

A. Power Consumption Demands

$$\begin{aligned}\text{Total appliances use} &= (7.2\,\mathrm{W} \times 5\,\mathrm{h}) + (6\,\mathrm{W} \times 10\,\mathrm{h}) + (10\,\mathrm{W} \times 2\,\mathrm{h}) \\ &= 116\,\mathrm{Wh/day}\end{aligned}$$

$$\begin{aligned}\text{Total PV panels energy needed} &= 116\ \mathrm{Wh/day} \times 1.3(\text{the energy lost in the system}) \\ &= 150\,\mathrm{Wh/day}\end{aligned}$$

B. Size of the PV Panel

Sun energy is available for 4 h a day.

Total Wp of PV panel $= 150/4 = 37.5\,\mathrm{Wp}$

Actual requirement $= 40\,\mathrm{Wp}$ *one module*

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C. Battery Sizing

The battery should be large enough to store sufficient energy to operate the appliances at night and cloudy days.

$$\text{Total appliances use} = (7.2\,\text{W} \times 5\,\text{h}) + (6\,\text{W} \times 10\,\text{h}) + (10\,\text{W} \times 2\,\text{h}) = 116\,\text{W h}$$

Divide the total watt-hours per day used by 0.85 for battery loss = 116/0.85
= 136.47 W h

Divide this number by 0.5 for depth of discharge = 136.47/0.5
= 272.94 W h

Nominal battery voltage = 12 V

Days of autonomy = 2 days

Battery capacity = (272.94 W h/12 V) × 2 = 45.49 A h

Total ampere-hours required = 45 A h (or better 75 A h) deep cycle battery to have a longer lifespan.

So the battery should be rated 12 V 50 A h *for* 2 *days autonomy*.

D. Solar Charge Controller Sizing

According to standard practice, the sizing of solar charge controller is to take the short circuit current (I_{SC}) of the PV array, and multiply it by 1.3 PV module specifications

Pm = 40 Wp

Panel voltage = 12 V

Solar charge controller rating = 40 Wp/12 V = 3.33 A

So the solar charge controller should be rated 5 A 12 V *or greater*.

10 ft × 10 ft Kitchen illuminated by 7.2 W warm cool solar powered LED light

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