**PUDUCHERRY COUNCIL OF SCIENCE AND TECHNOLOGY**

**GOVERNMENT OF PUDUCHERRY**

**Puducherry – 605005**

**FINAL REPORT**

**OF**

**GIA SPONSORED RESEACH PROJECT**

**TITLED**

# "DECENTRALIZED RENEWABLE ENERGY POWER SOLUTIONS FOR UNION TERRITORY OF PUDUCHERRY"

**SUBMITTED BY**


**Dr. P. AJAY-D-VIMALRAJ**

**Assistant Professor**

**DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING**

**PONDICHERRY ENGINEERING COLLEGE**

**Puducherry – 605014**


**AUGUST 2017**

# ABSTRACT

Renewable energy resources were becoming inevitable in the field of power generation systems and have got many advantages over conventional energy resources. Apart from being eco-friendly, these renewable energy resources like sunlight, wind, water bodies are great gifts of nature, which makes them non-deflectable. Though available in huge amount, energy produced from a single renewable energy resource, such as sunlight or wind, may fluctuate with the time and hour of the day or month, depending on the climatic conditions. In this case, energy produced from hybrid energy system consisting of different renewable energy resources, may prove to be more reliable, with two or more energy resources coming into play at the same time.

In energy costs, wind photovoltaic hybrid system (WPVHS) utilization is becoming more popular, with prices of turbines and PV panels decreasing. Moreover hydro power is also a very reliable source of power generation. However, to compensate for the drawbacks, raised by variation in climatic conditions, back-up power is often essential. Thereby, these issues were taken care of by using a hybrid system of Wind- PV-Hydro, along with back-up sources of battery bank and conventional grid continuity supported by a Bi- directional inverter and charge controller. Optimization also becomes necessary, so as to develop an efficient and an economical hybrid system.

In the phase I simulation analysis the optimum configuration of hybrid system to the kalapet region of Puducherry is suggested. A sample energy requirement for a village load is estimated and it is met by a suitable model of hybrid renewable electric power generation based on renewable energy resources availability in the kalapet region of Puducherry, The proposed approach deals with the detailed procedure for designing and developing an hybrid electric power generation system consisting of photovoltaic modules, wind turbine for electrification of loads accompanied with battery for backup and the simulation analysis were performed using performance based optimization algorithm Hybrid Optimum Model for Electric Renewable (HOMER) environment in order to achieve the best optimum configuration of hybrid power generation system.

The aim of the phase II research analysis is to build a roof top PV system which provides enhanced efficiency and good safety level to the PV installers. By increasing the efficiency of the system, solar power can be utilized in a better manner to electrify the buildings. There are two major types of inverter topologies (a) with transformer (b) without transformer. Since the transformerless topologies are compact and more efficient as compared to the other topology, an enhanced PWM strategy is proposed for transformerless topology. The demerit of the transformerless arrangement is the absence of galvanic isolation, which in turn is responsible for the generation of leakage current. The leakage current in the system causes some serious issues like safety issues and reduced efficiency. In this project the performance of the proposed technique is verified by implementing the proposed carrier overlapping technique in a 0.5 kW solar photovoltaic based cascaded multi level inverter system. The hardware results exhibits that the leakage current has been reduced to considerable range. The developed inverter also produces more fundamental output voltage with lesser harmonics.

# ACKNOWLEDGEMENT

I would like to express my deepest gratitude to **Dr.P.Dananjayan**, Principal, Pondicherry Engineering College, Puducherry, for his proficient and enthusiastic guidance, advice and encouragement, which were the constant source of inspiration for the development and completion of this research project work.

I wish my deepest and profound gratitude to **Shri. M.Dwarakanath,** Member Secretary**,** Puducherry Council For Science and Technology, Government of Puducherry, Puducherry for the grant-in-aid and moral support during the course of this research project work.

I am greatly debted to **Dr. Alamelu Nachiappan**, Head of the Department, Department of Electrical and Electronics Engineering, Pondicherry Engineering College for her incredible support and for permitting me to utilize the facilities for the completion of this research project work.

I also express my sincere gratitude to **Dr. M. Sudhakaran**, Co-Investigator of this research project and Professor, Department of Electrical and Electronics Engineering for his valuable guidance, motivations and constant encouragement throughout the period of this research project work.

I would like to convey my sincere thanks to the faculty members, technical staffs, and research scholars and under graduate students of Department of Electrical and Electronics Engineering, Pondicherry Engineering College for their immense support and valuable suggestions for framing and completion of this research project work.

As always, I thank and praise God for being there constantly as my guide for the successful completion of this research project work.



**Dr. P. Ajay-D-Vimal Raj,**

Assistant Professor,

EEE Department/ PEC

Puducherry-14

# TABLE OF CONTENTS

## LIST OF TABLES

# LIST OF FIGURES

# NOMENCLATURES

| | |
|---|---|
| PV | Photo Voltaic |
| PWM | Pulse Width Modulation |
| SCSPWM | Single-Carrier Sinusoidal Pulse Width Modulation |
| SHPWM | Sub-Harmonic Pulse Width Modulation |
| PD | Phase Disposition |
| APOD | Alternative Phase Opposition Disposition |
| POD | Phase Opposition Disposition |
| PSC | Phase Shifted Carriers |
| CPV | Carrier Polarity Variation |
| VFCB | Variable Frequency Carrier Bands |
| THD | Total Harmonic Distortion |
| PF | Power factor |
| HERIC | Highly Efficient and Reliable Inverter Concept |
| AM | Amplitude Modulation |
| FM | Frequency Modulation |
| RES | Renewable Energy Sources |
| HREPG | Hybrid Renewable Electric Power Generation |

# CHAPTER 1
# DESIGN AND SIMULATION OF HYBRID POWER SYSTEM

## 1.1 INTRODUCTION

In recent years grid interface of renewable energy sources has been paid much attention due to increased concern for depletion of fossil fuels in near future. Solar photovoltaic (PV) power is a renewable source of energy and has been proved to be environmental friendly, low maintenance and with input solar energy available at no cost. India being blessed with abundant amount of sunshine and has high potential of solar energy.

In the present world, every country is giving important place on energy security and sustainable development; hence role of renewable energy has become ever more significant. With the expectation of promoting electricity generation based on non-conventional renewable energy, the Government of Puducherry has taken many initiatives to promote power generation through non-conventional energy sources.

India is a country of over a billion people. As of $31^{st}$ August 2010 there were 89,808 villages or 15.1 % of the total which were still un-electrified. Over 40% of the country's population currently have limited energy access .India as a country still depends heavily on imports of oil and natural gas when it comes to meeting the daily energy needs. Using these sources of energy is an economic burden to the government and at the same time they heavily contribute to the pollution. To realize the dream of becoming a superpower by 2020 India needs to be self-sufficient in its energy needs. Even though non-renewable sources of energy such as oil and gas are cheaper to work with than renewable sources, Renewable sources have an advantage in terms is most likely solution to the energy crisis of the future generation because of the attractive aspects of its availability all over the world, low maintenance and eco friendly in nature. Since India lies at the tropic of cancer we get abundant sunshine to make full use of solar energy. Solar energy has become an attractive source of renewable energy because of reduction in the cost of manufacturing of solar panel these days. With about 300 clear sunny days in a year, India's theoretical solar power reception, just on its land area is about 5000 trillion kWh/year [1]. The daily average solar energy incident over India varies from 4 to 7 kWh/m$^2$ with about 2,300–3,200 sunshine hours per year, depending upon location. This is far more than current total energy consumption. For example, even assuming 10 % conversion efficiency for PV modules, it will still be thousand times greater than the likely electricity demand in India. As of August 2010 India fulfills around 10.9% of the total requirement with renewable sources of energy while solar accounts for a total of 1% of the renewable energy generation.

From the solar sources it is expected to generate 20GW by 2022, by deploying 20 million solar lighting systems and to achieve 20 million sq. meters solar thermal collector area (get the latest from http://www.mnre.gov.in/). However a point to note is that India is currently ranked number one with United States in terms of total solar power generation capacity. Experts are recommending that India should adopt a policy to create solar energy as a backbone of its economy by 2050. To summarize we can see that some steps have been taken to tap the potential of solar energy but still more effort needs to be put in. We need more private investments so that the initial costs of the panels come down. We need the government to fund research projects to develop solar panel with high-efficiency. Also common man needs to be made aware about the merits so that he is convinced to use solar energy in his day-to-day life.

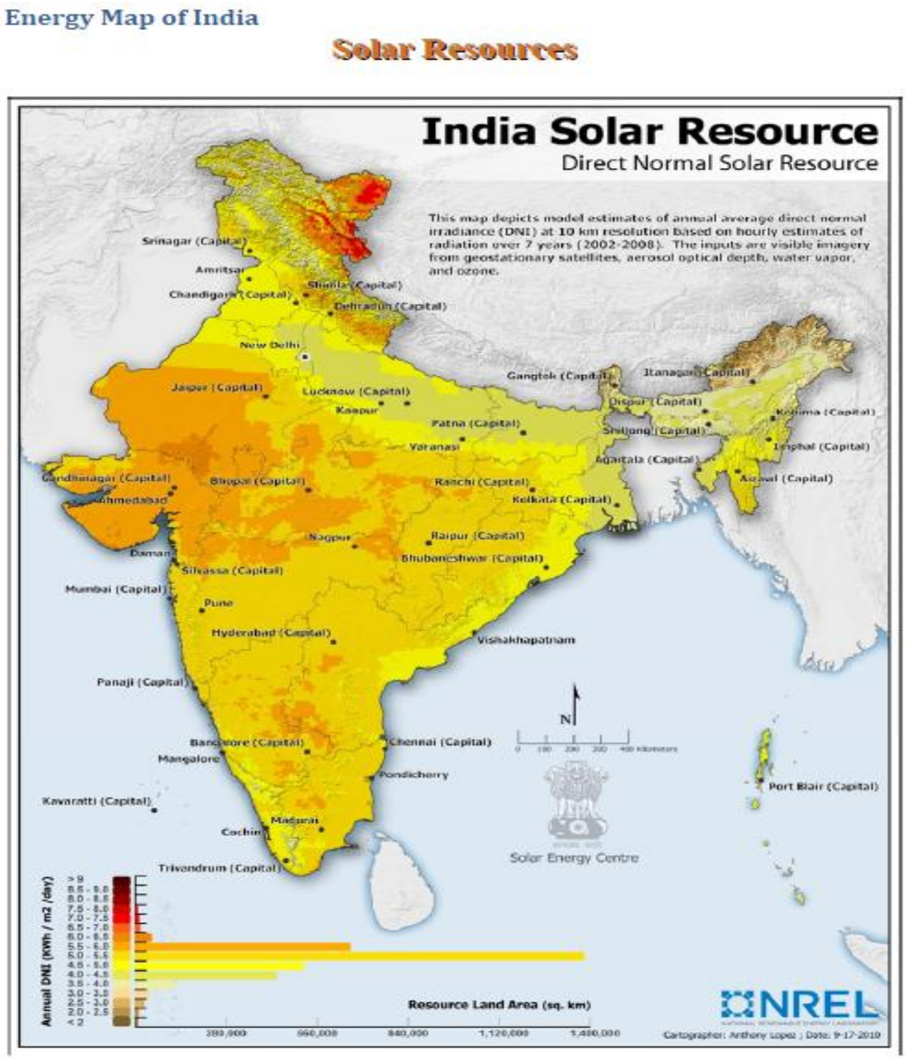



Figure.1.1 Solar energy resources available in India[2]

Among the available renewable energy resources like solar, wind, tidal, geothermal etc, Nowadays grid connected photovoltaic systems are greatly recognized for their contribution to clean power generation and abundant availability. A primary goal of these systems is to increase energy injected into the grid at maximum power point of the module by reducing the switching frequency and by providing high reliability.

Electricity generation from renewable energy sources, especially from solar PV is believed to be the need of the hour choice. Government of India targets both for deployment of solar power stations as well as ‘Make in India’, both these missions shows that they are complimentary to each other and not in conflict.

India is plagued by an acute shortage of power. Erratic power supply and frequent power outages have serious financial implications for Industry. Reports from industry association suggest that 26 per cent of firms have disruptions in power supply for more than 21 hours a week, while another 68 per cent face up to 10 hours of power cut every week. As a result, large industries rely on expensive and unsustainable diesel-based back up to cover this short fall.

Existing thermal plants operate at plant load factor as low as 60 per cent due to fuel shortages. Furthermore, cost of input for thermal power plants is on the rise as quality of Indian coal is low, thus requiring washing or blending with imported coal.

The higher cost of imported coal clearly indicates that the price of thermal power will continue to go up and its supply constrained by fuel shortages and geo-political occurrences. Matching demand with peaks in production of solar power from captive systems could result in cost of electricity declining notably for consumers.

In India industries pay an average power tariff of Rs.6.3/ kWh. Commercial consumers pay even higher tariffs, Rs7.7/ kWh on average. In contrast, rooftop solar supplies power at Rs.5-8/ kWh, without any subsidy, depending upon the size of the system and the cost of finance.In Puducherry industries pay an average power tariff of Rs.5.5/ kWh. Commercial consumers pay even higher tariffs, Rs.5.1/ kWh on average. In contrast, rooftop solar supplies power at Rs.2.8/ kWh.

As per the announcement of the Solar Energy Regulations by the Joint Electricity Regulatory Commission (JERC) for Goa and Union Territories in December 2014. Decentralised solar power solutions, despite relatively more expensive than grid based thermal power, provide electricity at rates lower than diesel based systems. The adoption of decentralised solar power solutions, especially in rural and urban Puducherry, can help this sector to develop momentum by overcoming the challenges of intermittent power supply from the grid

Union territory of Puducherry faces a number of challenges in meeting the long term energy needs of the community while supporting the State’s growing economy. Renewable energy will play a key role in meeting these needs, as the Central and State Government has to incorporate in its mission a strategy that serves to derive the maximum benefits of an improved performance and enhanced reliability.

Demand side management options for energy sustainability of Union Territory of Puducherry regions may be fulfilled by recommending separate Hybrid Renewable Electric Power Generators (HREPG) for all the regions based on renewable energy resources availability on that particular geographical area.

The proposed work includes the state-of-the- art methods and procedures for designing and developing a hybrid electric power generation system for union territory of Puducherry regions. This work takes into account the theoretical investigations and practical considerations based on resource availability, feasibility of the system performance and best optimum configuration to achieve developed energy demand.

### 1.1.1 DESCRIPTION OF THE BACKGROUND

The Union Territory of Puducherry consists of four enclaves which are widely scattered in the three southern states viz Puducherry and Karaikal enclaves in Tamil Nadu, Mahe enclave in Kerala and Yanam enclave in Andhra Pardesh. Puducherry which is the headquarters of the Union Territory located 160 Kms down south of Chennai while Karaikal is located further down south at about 160 Kms from Puducherry. Mahe is located horizontally opposite to Puducherry on the Western coast at about 647 Kms from Puducherry and 58 Kms from Kozhikode, 24 Kms from Kannur in Kerala State. Yanam is located up to north of Puducherry on the eastern coast at about 870 Kms from Puducherry, and 24 Kms from Kakinada

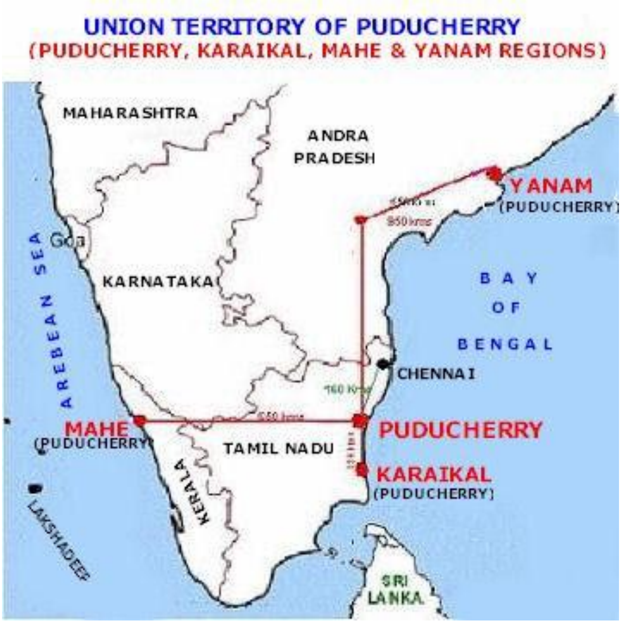



Figure 1.2 Map locations of U.T. of Puducherry

The Total power demand of the Union Territory including that of the four regions of Puducherry, Karaikal, Mahe and Yanam is 349.97 MW during peak period. There is no power generation in the Union Territory except that a 32.0 MW Gas based Power Plant operated by the Pondicherry Power Corporation Limited. The demand is normally being met from the power allocation from Central Generating Stations (CGS), drawal of power from neighbouring state Electricity Boards and the Gas Power Plant of Pondicherry Power Corporation Limited.

### 1.1.2 RESEARCH PROJECT OBJECTIVES:

The main objectives of the research project are:

- To analyze about the U.T. of Puducherry region's peak electric potential demand, existing power supply scenario and availability of renewable energy resources.
- It is proposed to quickly realize the recent developments in the field of power generation systems by computer based simulation package.
- To build a suitable renewable energy generators with a view to identify the equipment's specification, technology, models and quantity to be connected in order to maximize the power generation capacity based on resources availability.
- To develop an optimum algorithm for renewable energy configuration problem in order to minimize the net present cost using HOMER simulation environment.
- To solve and simulate the hybrid power generation system for each and every hour of the year based on selected site's forecasting resource availability.
- To build a cascaded topology based multi level inverter with novel modulation strategy and to reduce the leakage current for single phase transformerless PV based inverter system.

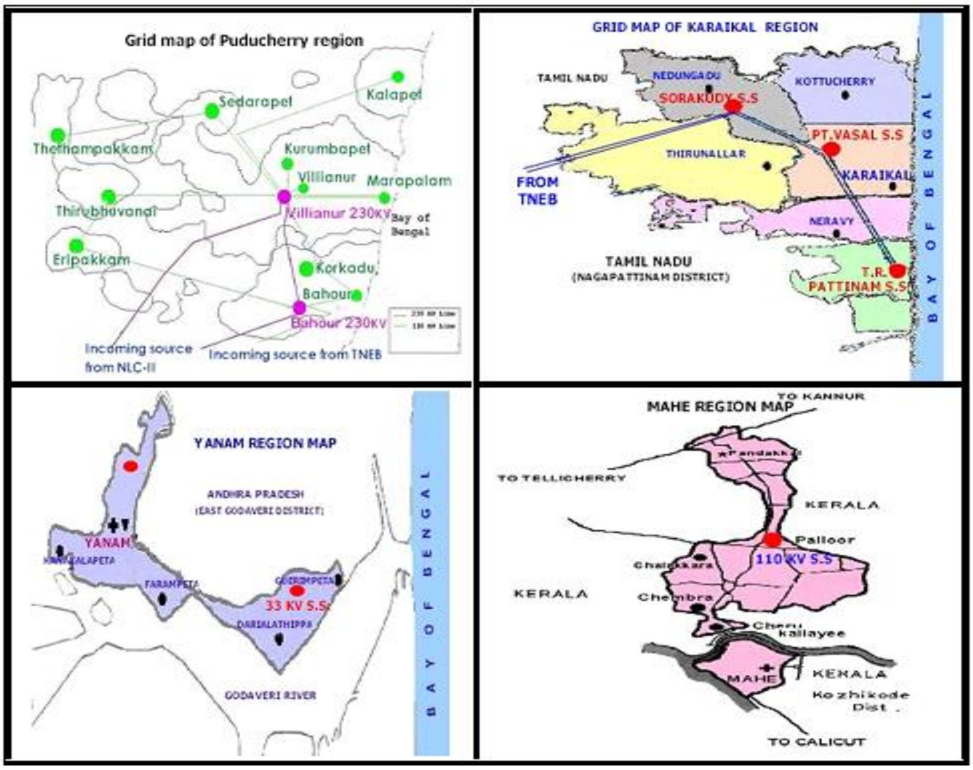



Figure1.3 Location maps for U.T. of Puducherry Regions

Ensuring energy security, energy resources used in the country in the future need to be diversified. Also in order to ensure the continuity of supply, energy mix need to be rationalized considering important factors, such as economic cost, environmental impact, reliability of supplies and convenience to consumers. The hybrid renewable power generation is a system aimed at the production and utilization of the electrical energy stemming from more than one source, provided that at least one of them is renewable.

### 1.1.3 ENERGY SCENARIO – INDIA

There has been an exception economic growth in Indian economy, over the last decade. Today, India is the ninth largest economy in the world, given to its Gross Domestic Product (GDP) growth of 8.7 % in the last 5 years (7.5% over the last 10 years). The GDP growth of India came as the 5$^{th}$ highest in the world, in the year 2010.

India’s vast variation of energy resources, has a combination of all resources available including the renewable resources. In near future, it is predicted that the pre-dominance of coal over other energy resources will prevail. It is made out from the fact that 54% of the total installed electricity generation capacity is coal based and 67% of the capacity has been added in the past 5 year slot 2007-2012 is again coal-based. Moreover till now, around 70% of the total electricity generated is from coal based power plants.

### 1.1.4 ORIGIN OF THE PHASE I RESEARCH PROPOSAL

This phase I research analysis proposes the detailed procedures for designing and developing an hybrid renewable electric power generation system consisting of photovoltaic modules, wind turbine for electrification of village loads accompanied with battery for backup and simulation is performed using performance based optimization algorithm (HOMER) to achieve the best optimum configuration for the considered sample village load. Hybrid Optimization Model for Electric Renewables (HOMER) software is used to analyze the resource data's of U.T. of Puducherry. HOMER is a micro-power optimization model for both off-grid and grid connected power systems in a variety of applications. Wind-solar hybrid system has numerous advantages. One of the advantages is reliability, when solar and wind power production resources were used together, reliability is improved and the system energy service is enhanced. One of the significant feature is in the absence of one type of energy resource, another resource would be available to carry out the service. Other merits are the stability and lower maintenance requirements, thus reducing the downtime during repairs or routine maintenance. In addition to these, indigenous and free, renewable energy resources contribute to the reduction of pollution emissions leading to green environment.

### 1.1.5 METHODOLOGY

The following methodology is adopted in the phase I work for developing an hybrid system for a sample load in the U.T. region of Puducherry.

**Task # 1: Characteristics of energy resources**

Initially, literature review was done to get better understanding about the energy situation and the resources of availability of energy sector in Puducherry. Analysis of energy situation in U.T. of Puducherry is performed and identification of different regional locations with wind and solar potential resources were identified.

**Task # 2: Analysis of wind and solar data available in different identified locations.**

Solar resources and wind resources are imported directly by HOMER from the NASA Surface Meteorology and Solar Energy database by entering the GPS co-ordinates .

**Task # 3: Design and analyze a wind-solar hybrid system for the selected location using the HOMER software tool.**

The detailed procedures for designing and developing hybrid electric power generation system consisting of photovoltaic modules, wind turbine for electrification of sample village load accompanied with battery for backup and simulation is performed using performance based optimization algorithm (HOMER) in order to achieve the best optimum configuration for the considered load demand.

### 1.1.6 PUDUCHERRY REGION ENERGY ANALYSIS

In order to design and simulate an hybrid electric model with effective renewable power generation through PV array and wind turbines along with battery backup support for peak load management, the perfect value of load profiles were the essential components. The developed load demand was observed in all the hours of the annual days based on equipment rating with quantity of operating hours. The load profile calculation mainly provides the key range of average demand per day and peak load per day. The determination of maximum demand for the selected place for hybrid renewable power generation system in the various regions of Puducherry serves as the basic input parameter for simulation analysis. The region wise recorded maximum demands for Puducherry is shown in Table 1.1.

Table 1.1 : Puducherry Region Wise Maximum Demand (in MVA)

(Source: Puducherry State Electricity Department)

| S. No | Name of the UT Region | Selected place for Hybrid Renewable Energy System | Type of Major Consumers | Maximum Demand Recorded (MVA) | Minimum Demand Recorded (MVA) |
|---|---|---|---|---|---|
| 1 | Puducherry | Kalapet (2*10=20MVA) | Commercial Domestic | 12 | 7.7 |
| 2 | | Bahour (3*16=48MVA) | Agricultural Domestic | 38 | 25.1 |
| 3 | | Villiyanur (3*10=30MVA) | Industrial, Commercial, Domestic | 21.8 | 17.5 |
| 4 | | Sedarapet (2*16=32MVA) | Industrial Estate | 31.8 | 26.2 |
| 5 | | Eripakkam (3*16=48MVA) | Industrial, Agricultural, Domestic | 39.4 | 28.1 |
| 6 | Karaikal | Sorakudy (3*16=48MVA) | Industrial Commercial | 32.15 | 25.5 |
| 7 | | TR Pattinam (2*10=20MVA) | commercial Domestic | 31.9 | 15.8 |
| 8 | | Pillaitheruvasal (2*10=20MVA) | Industrial Commercial | 15.8 | 10.8 |
| 9 | Yanam | Thariyalathippa (3*10=30MVA) | Industrial Domestic Commercial | 23 | 9 |
| 10 | Mahe | Palloor (2*10=20MVA) | Industrial Domestic Commercial | 6.37 | 5.2 |

## 1.2 LITERATURE SURVEY ON HYBRID RENEWABLE ENERGY SYSTEM

They are reviewed in a systematic way in the following sections.

### 1.2.1 PV –DG – BATTERY

Hybrid optimization model for electric renewable has been effectively used by P. Lilienthal [8] for designing an optimization model which can analyze small power technologies individually in addition to it the hybrid systems were also identified providing the most cost effective solution to the energy requirements.

Baharudin et al. [5] have effectively used hybrid optimization model for optimizing and designing an electric renewable based PV power system in the region of desalination process of sea water located at Kuala Perlis. The optimized design consists of site selection, load selection, system sizing and cost effectiveness. The feasibility and reliability of this design have been verified along with the experimental setup for the desalination system.

The use of an hybrid optimization model for designing and modeling of a domestic based power system of a particular family with household usage in Boulder, Colorado has presented in [6]. In addition to it a PV grid has been used for power generation with a battery bank for backup power.

Lim et al. [7] have forecasted solar irradiance and load demands in supervisory control and developed an off-grid hybrid energy system. The models were developed for foreseeing and predicting the solar resource and load demand. These models were also used to control an off-grid PV-variable speed diesel generators hybrid energy system.

### 1.2.2 WIND – DG – BATTERY

Although wind energy sometimes failed to produce the required power output given to the meteorological variations of the area, under consideration, Rehman [8] has incorporated diesel generator as the back power, using a diesel plant for a village in north eastern part of Saudi Arabia. Hybrid optimization model for electric renewable have also been used for modeling and designing of the system.

Khadem [9] has investigated the utility of wind home system in a coastal region of Bangladesh using Hybrid optimization model for electric renewable software. By which, the possibility of using wind power as a renewable energy technology were found to be optimum in the selected region. With a variation of wind speed around 4 m/s the investigations stated that considering environmental influence, power consumption and remote accessibility using wind based home system is the most suitable system for the coastal region.

### 1.2.3 PV – HYDRO – DG – BATTERY

Hybrid optimization model for electric renewable have been effectively used by Beluco et al. [10] for designing a hybrid system with solar energy, hydro power and diesel generator. They have evaluated the power generation during peak sunlight hours. The optimization models consisted of two variations – one with PV module, diesel generators and micro hydro power plants and another with PV modules and hydro power plants.

### 1.2.4 WIND – PV – FUEL CELL

Alam et al. [11] have used hybrid optimization model using electric renewable software and proposed a hybrid power generation system for application in remote areas. This hybrid system have a combination of PV panels, wind turbine and fuel cell. In addition to it hydrogen supply for fuel cell an electrolyzer and a reformer were also taken into consideration. The developed combination of renewable technology have been found to be successful by meeting the load requirement for standalone applications at remote locations.

### 1.2.5 WIND – PV – DG – FUEL CELL – BATTERY

Badawe et al. [12] have made effective use of an hybrid optimization model for electric renewable and presented a study for optimization and comparision between renewable technology and conventional power generation techniques to a telecommunication site in Mulligan, Labrador, in Canada. Renewable technology have reduced environmental pollution and also lowered the overall cost of power production. They have also formulated a cost effective solution and reduced the operational time of the diesel generator and reduced the emission level.

### 1.2.6 PV – BIOMASS - BATTERY

Barsoum et al. [13] have developed MATLAB based Simulink and Hybrid optimization model for electric renewable for designing, modeling and cost simulation of standalone solar and biomass energy in Sarawak. The formulated model produced an optimized, reliable, feasible and autonomous system and met the power requirements of the area under consideration and along with that cost effectiveness were also ensured.

Mitra et al. [16] have introduced an hybrid optimization model for electric renewable in the Islands of Indian Sundarbans thereby supply electricity to remote villages through renewable energy technology were electrified. They also revealed that around 20 islands with more than 100000 households inhabiting in 131 villages in India, needed electricity as a very basic need of their daily living. Their strategy have found that the wind potential in the selected region is found to be very low and hence the renewable technologies used were biomass and solar panels.

### 1.2.7 MICRO-POWER

Lambert et al. [14] have used an hybrid optimization model for electric renewable for micropower system for the sake of comparison of power generation technology across a wide range of applications. A system generated electricity and heat for meeting a certain amount of load. They evaluated the power system's physical behavior and optimized the total life cycle cost using hybrid optimization model for electric renewable.

Hafez et al. [15] have successfully used hybrid optimization model for electric renewable as the most favorable and ideal planning, designing and modeling of a renewable energy based supply system for microgrids. In their elaborate analysis four different types of designs are developed viz. a diesel-only, a fully renewable-based, a diesel-renewable mixed and an external grid-connected microgrid configurations were deployed. The economic issues were also considered in the design.

## 1.3 RENEWABLE RESOURCE ANALYSIS

The solar and wind energy resources are used for hybrid system. Analyzing the resources of the particular geographical area is necessary for the development of Hybrid Renewable Energy System (HRES).

### 1.3.1 SOLAR RESOURCES

Solar resources were imported directly by HOMER software package from the NASA surface meteorology and solar energy database by entering the GPS co-ordinates. Selected site of Pondicherry Engineering College , Puducherry located in between the latitude of 12.5' N and the longitude of 79.59' E. Based on this geographical location , the past 10 year historical solar irradiation and clearness index value are considered to forecast the future solar irradiation's. The annual solar radiation of Pondicherry Engineering College region is 5.37 kWh/m$^2$/d. And also the monthly solar irradiation seems to be constant than the wind speed [3].The month wise solar irradiation and clearness index were shown in Table 1.2 and in Figure 1.4.

Table:1.2 Monthly Solar radiation for Kalapet Region

| **Month** | **Clearness Index** | **Daily Radiation** (kWh/m2/d) |
|---|---|---|
| January | 0.598 | 5.156 |

| | | |
|---|---|---|
| February | 0.659 | 6.172 |
| March | 0.63 | 6.389 |
| April | 0.646 | 6.809 |
| May | 0.583 | 6.152 |
| June | 0.505 | 5.267 |
| July | 0.496 | 5.182 |
| August | 0.494 | 5.177 |
| September | 0.527 | 5.386 |
| October | 0.515 | 4.917 |
| November | 0.546 | 4.784 |
| December | 0.573 | 4.781 |

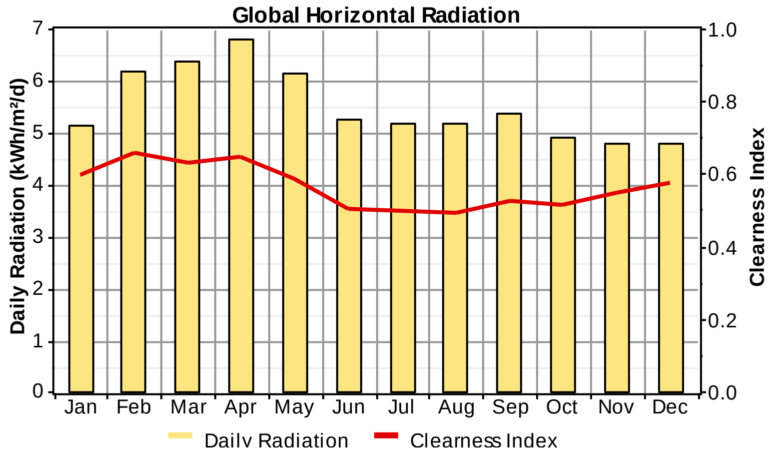



Figure 1.4 . Solar radiation chart for Kalapet region of U.T. of Puducherry

### 1.3.2 WIND RESOURCES

The wind resources potentials are predetermined from NASA surface meteorology and solar energy data base. The wind speed and direction and its direction measured 5 meters above the surface of the earth were considered for the analysis. The database provides the monthly wind speed means for the respective month over a time span of 10 year period .The average of monthly wind speed was evaluated as the numerical average of 3 hour values for the given month. Observed wind speed in the Pondicherry Engineering College region is between 2.5m/s and 5m/s average per month [3]. Monthly wise wind potential available for the selected site is provided in Table 1.3 and in Figure 1.5.

Table 1.3 Wind Speed at Kalapet Region

| **Month** | **Wind Speed (m/s)** |
|---|---|
| January | 2.5 |
| February | 3.2 |
| March | 3.4 |

| | |
|---|---|
| April | 3.5 |
| May | 4 |
| June | 4 |
| July | 4 |
| August | 5 |
| September | 4 |
| October | 4 |
| November | 4 |
| December | 3.2 |

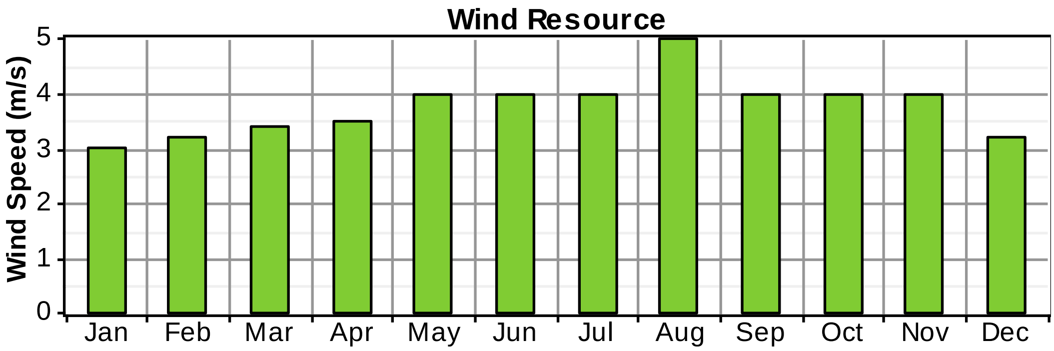



Figure 1.5 Wind Speed chart for Kalapet region of U.T. of Puducherry

The annual wind speed average may perhaps be a good factor for the fitting and installation of a wind turbine in a given location and generally values ranging above 5 m/s for few months and below 4 m/s for rest of the months were considered adequate for providing satisfactory results. The load calculations were done, the resources for this selected geographical area were analyzed and their characteristics were also plotted using the software tool. These data's have been used for simulation analysis.

## 1.4 COMPONENTS OF HYBRID ENERGY SYSTEM

A broader overview of the hybrid energy system and its various aspects were presented through the literature review section by various researchers. The principal components of the hybrid energy system are discussed as follows:.

A hybrid renewable energy system is one in which two or more different renewable energy sources for example - solar-thermal, solar-photovoltaic, wind, biomass, etc. are integrated to supply electricity or heat or both to the same load demand. The hybrid system consisting of Photovoltaic (PV) modules and wind turbines is the most promising combination [2].

In order to provide an optimum design, it is very essential for PV/wind/Grid hybrid system, by ensuring battery bank usage at the most optimum conditions possible, thereby prolonging the battery life and reducing cost of energy production. In recent days, computer simulation techniques were employed to design the optimum system configurations and to analyze the performance aspects and also energy production costs for different configurations of wind and PV power based hybrid generating systems.

For the predicted demand the power supplied by the hybrid system depends on the weather conditions. Thereby, a backup system consisting of a battery bank is always kept ready in case of deficit of power generated from the hybrid system.

Apart from these, other requirements like transmission and distribution of power generated from the hybrid system, protection from discharging of battery beyond limits, or overvoltage protection, have to be fulfilled. Hence a charge controller and a bidirectional inverter are used for the supporting system of the hybrid system to fulfill the above mentioned purposes. The structural view of project proposal simulation phase is highlighted in Figure 1.6

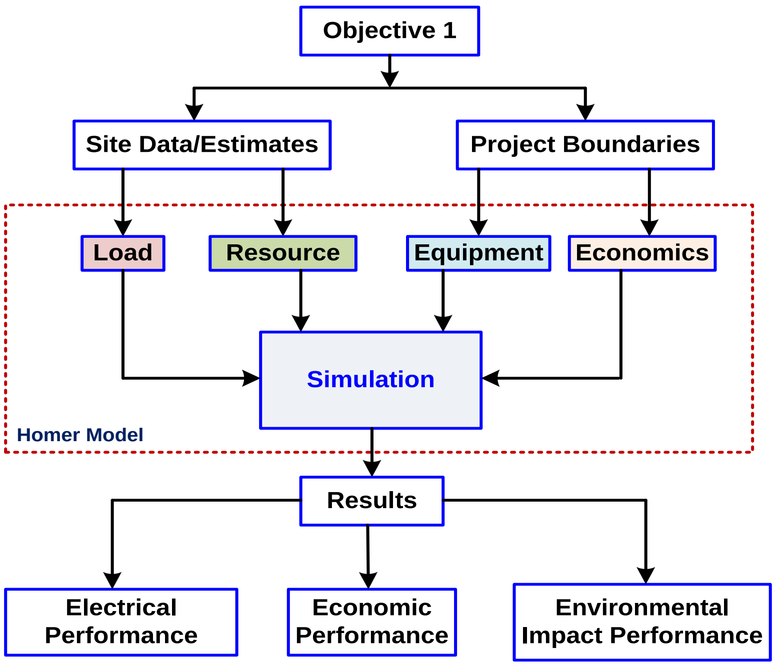



Figure1.6.Structure of project proposal simulation phase

## 1.5 PROPOSED HYBRID MODEL STRUCTURE

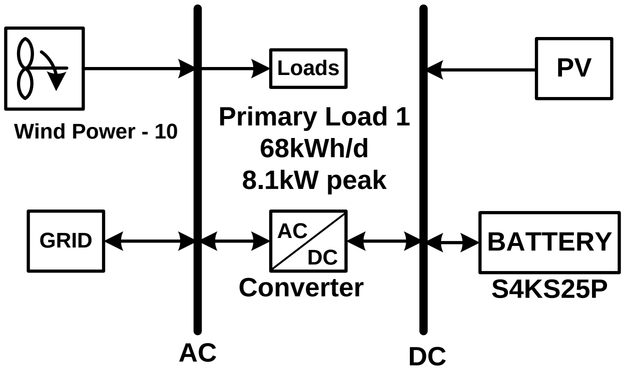



Figure1.7 Hybrid renewable energy model

The categorized optimization results list, gives the best suitable configuration of hybrid system , based on sizing of solar PV and wind turbine, operation constraints regarding load following or cycle charging, least to higher net present value of the project, life time of the project and its cash flow. From the categorized result the most optimum configuration of hybrid power system for selected geographical area is obtained. The financial and performance optimization analysis conducted using the parameters of net present cost and cost of electricity is also analyzed The proposed hybrid model is built using wind power turbine, solar PV system, battery bank and with a AC/Dc converter toplogy supported with the grid system for a connected sample village load of 68kWh/ d and peak load of 8.1 kW is represented in Figure 1.7

## 1.6 SIMULATION ANALYSIS

The simulation results for the proposed model structure is tabulated as follows based on the availability of wind power turbine, solar PV system, battery bank and with a AC/Dc converter toplogy supported with the grid system.

| PV (kW) | XLS | CP12240D | Conv. (kW) | Grid (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. |
|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 4 | 0.5 | 1000 | $ 336,000 | -12,453 | $ 176,803 | 0.778 | 0.83 |
| | 1 | 4 | 0.5 | 1000 | $ 315,000 | -10,250 | $ 183,974 | 0.810 | 0.82 |
| 2.0 | 1 | 4 | 0.5 | 1000 | $ 399,000 | -15,506 | $ 200,775 | 0.884 | 0.85 |
| 0.5 | 1 | 8 | 0.5 | 1000 | $ 348,000 | -10,143 | $ 218,333 | 0.961 | 0.83 |
| | 1 | 8 | 0.5 | 1000 | $ 327,000 | -7,940 | $ 225,504 | 0.992 | 0.82 |
| 2.0 | 1 | 8 | 0.5 | 1000 | $ 411,000 | -13,196 | $ 242,305 | 1.066 | 0.85 |
| 0.5 | 1 | 12 | 0.5 | 1000 | $ 360,000 | -7,833 | $ 259,863 | 1.144 | 0.83 |
| | 1 | 12 | 0.5 | 1000 | $ 339,000 | -5,630 | $ 267,034 | 1.175 | 0.82 |
| 4.0 | 1 | 4 | 0.5 | 1000 | $ 483,000 | -15,980 | $ 278,723 | 1.227 | 0.87 |
| 2.0 | 1 | 12 | 0.5 | 1000 | $ 423,000 | -10,886 | $ 283,835 | 1.249 | 0.85 |
| 10.0 | 1 | 4 | 20.0 | 1000 | $ 852,000 | -43,525 | $ 295,602 | 1.301 | 0.96 |
| 0.5 | 1 | 16 | 0.5 | 1000 | $ 372,000 | -5,523 | $ 301,393 | 1.326 | 0.83 |
| | 1 | 16 | 0.5 | 1000 | $ 351,000 | -3,320 | $ 308,564 | 1.358 | 0.82 |
| 4.0 | 1 | 8 | 0.5 | 1000 | $ 495,000 | -13,670 | $ 320,253 | 1.409 | 0.87 |
| 8.0 | 1 | 4 | 20.0 | 1000 | $ 768,000 | -34,710 | $ 324,284 | 1.427 | 0.94 |
| 2.0 | 1 | 16 | 0.5 | 1000 | $ 435,000 | -8,576 | $ 325,365 | 1.432 | 0.85 |
| 10.0 | 1 | 8 | 20.0 | 1000 | $ 864,000 | -41,215 | $ 337,132 | 1.484 | 0.96 |
| 6.0 | 1 | 4 | 20.0 | 1000 | $ 684,000 | -25,896 | $ 352,966 | 1.553 | 0.93 |
| 4.0 | 1 | 12 | 0.5 | 1000 | $ 507,000 | -11,360 | $ 361,783 | 1.592 | 0.87 |
| 6.0 | 1 | 4 | 0.5 | 1000 | $ 567,000 | -15,928 | $ 363,390 | 1.599 | 0.88 |
| 8.0 | 1 | 8 | 20.0 | 1000 | $ 780,000 | -32,400 | $ 365,814 | 1.610 | 0.94 |
| 10.0 | 1 | 12 | 20.0 | 1000 | $ 876,000 | -38,905 | $ 378,662 | 1.666 | 0.96 |
| 4.0 | 1 | 4 | 20.0 | 1000 | $ 600,000 | -17,081 | $ 381,648 | 1.680 | 0.90 |
| 6.0 | 1 | 8 | 20.0 | 1000 | $ 696,000 | -23,586 | $ 394,496 | 1.736 | 0.93 |
| 4.0 | 1 | 16 | 0.5 | 1000 | $ 519,000 | -9,050 | $ 403,313 | 1.775 | 0.87 |
| 6.0 | 1 | 8 | 0.5 | 1000 | $ 579,000 | -13,618 | $ 404,920 | 1.782 | 0.88 |
| 8.0 | 1 | 12 | 20.0 | 1000 | $ 792,000 | -30,090 | $ 407,344 | 1.793 | 0.94 |

Figure1.8 Optimum result configuration with different cases

Fig.1.8 highlights the simulated results of different case studies of operational performance and component sizing of a suitable configuration of hybrid renewable energy system which can be suggested to a renewable energy source investor based on their requirements. The main scrutiny factors such as net present cost, renewable factor and components constraints can be chosen for evaluating the optimum configuration of the system.

| PV (kW) | XLS | CP12240D | Conv. (kW) | Grid (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. |
|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 4 | 0.5 | 1000 | $ 336,000 | -12,453 | $ 176,803 | 0.778 | 0.83 |
| | 1 | 4 | 0.5 | 1000 | $ 315,000 | -10,250 | $ 183,974 | 0.810 | 0.82 |
| 0.5 | | 4 | 0.5 | 1000 | $ 36,000 | 62,598 | $ 836,207 | 3.680 | 0.04 |
| | | 4 | 0.5 | 1000 | $ 15,000 | 64,801 | $ 843,377 | 3.712 | 0.00 |

Figure1.9 Category wise best configuration based on NPC values

From the Fig.1.9 the category wise best configuration result is obtained for knowing the quicker selection of suitable system for the predicted estimated electric power requirement in the selected site of Kalapet region of U.T. of Puducherry, the row 1 configuration of the proposed system is highly recommended due to its high renewable factor and less Net Present Cost.

Table 1.4. System Architecture

| | |
|---|---|
| PV Array | 0.5 Kw |
| Wind turbine | 1 BWC Excel-S |

| | |
|---|---|
| Grid | 1,000 kW |
| Battery | CP12240D |
| Inverter | 0.5 kW |
| Rectifier | 0.5 kW |

The detailed specification and system architecture of renewable energy system components and its performance analysis and economic analysis for kalapet region of Puducherry is provided in Table 1.4 and Table 1.5.

Table 1.5 .Solar PV Performance

| **Quantity** | **Value** | **Units** |
|---|---|---|
| Rated capacity | 0.5 | kW |
| Mean output | 0.08 | kW |
| Mean output | 2 | kWh/d |
| Capacity factor | 16.7 | % |
| Total production | 731 | kWh/yr |
| Minimum output | 0 | kW |
| Maximum output | 0.52 | kW |
| PV penetration | 4.11 | % |
| Hours of operation | 4,376 | hr/yr |
| Levelized cost | 2.38 | Rs/kWh |

From the selected solar panel specification taken for the analysis it is observed that total solar power generation from the panel is 731 Kwh/yr .The maximum possible power based on solar resource availability in the kalapet region of Puducherry is 520 watt. It is also realized that the one unit cost from solar investment is Rs 2.38 per unit.  Figure 1.10 highlights D- map of kalpet reion of Puducherry for the solar power generation for 8760 hours.

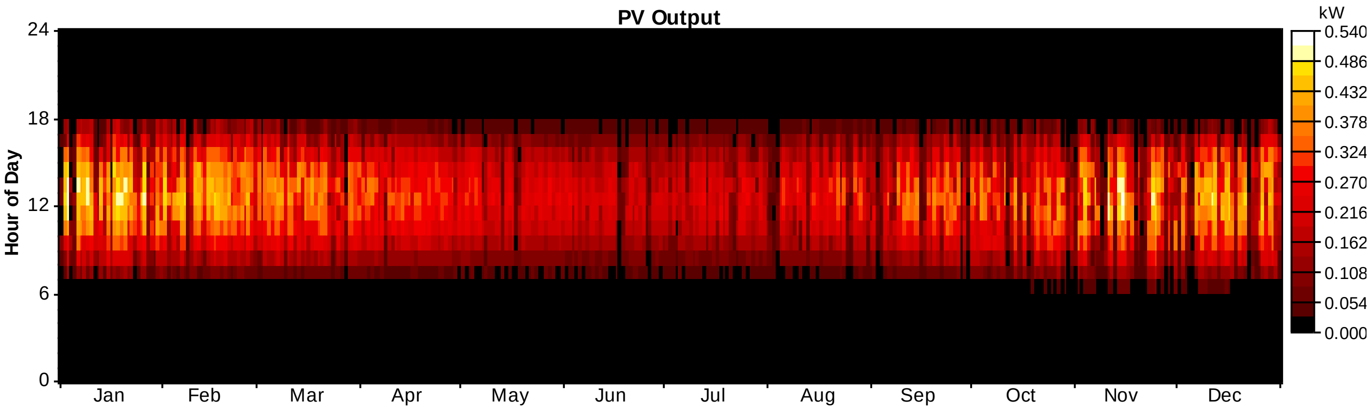



Figure1.10 Solar power D-Map for kalapet region of Puducherry

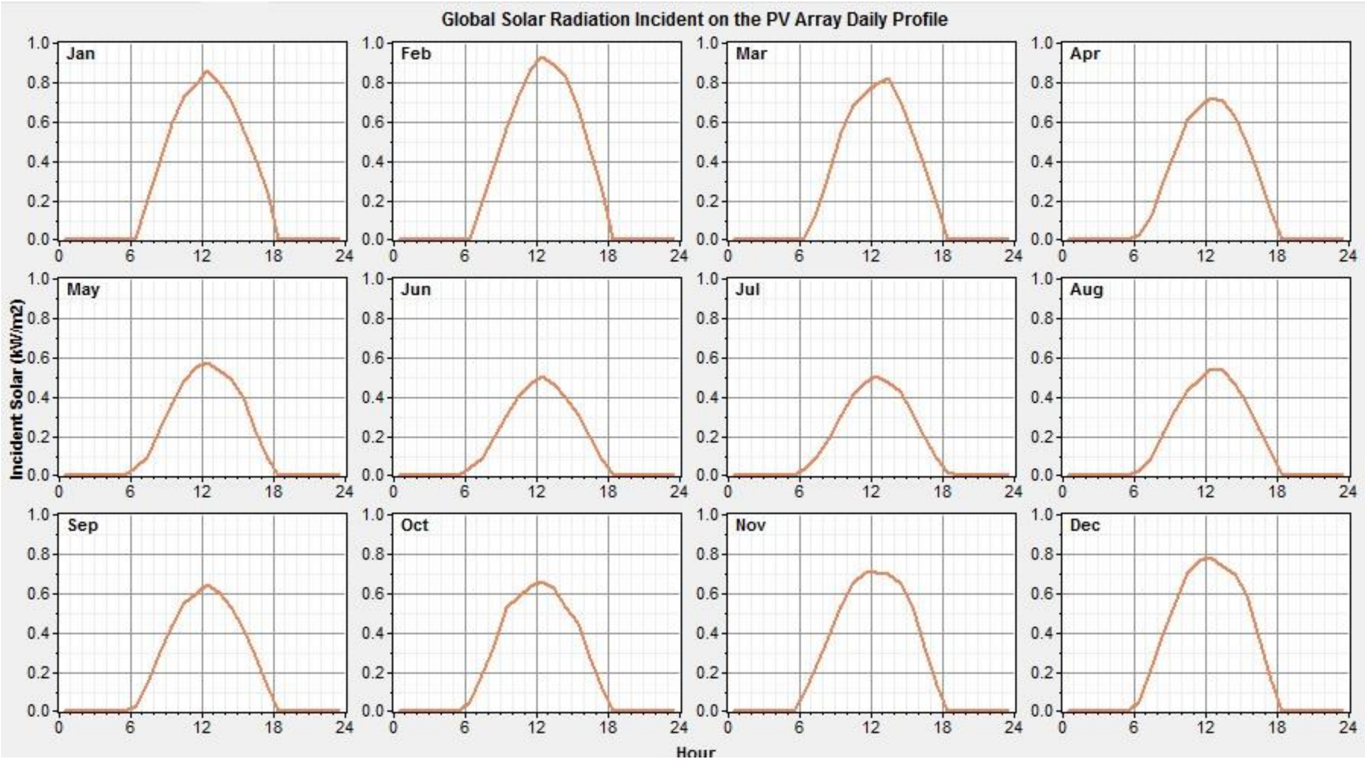



Figure1.11Monthly wise solar power generation levels

Table 1.6. Wind Turbine performance

| Quantity | Value | Units |
|---|---|---|
| Total rated capacity | 10 | kW |
| Mean output | 2.86 | kW |
| Capacity factor | 28.6 | % |
| Total production | 25,059 | kWh/yr |
| Maximum output | 9 | kW |
| Wind penetration | 141 | % |
| Hours of operation | 8,756 | hr/yr |

Wind turbine specification is listed in Table 1.6 and D map for wind power generation at the kalapet region of U.T. Puducherry is shown in Figure 1.12.

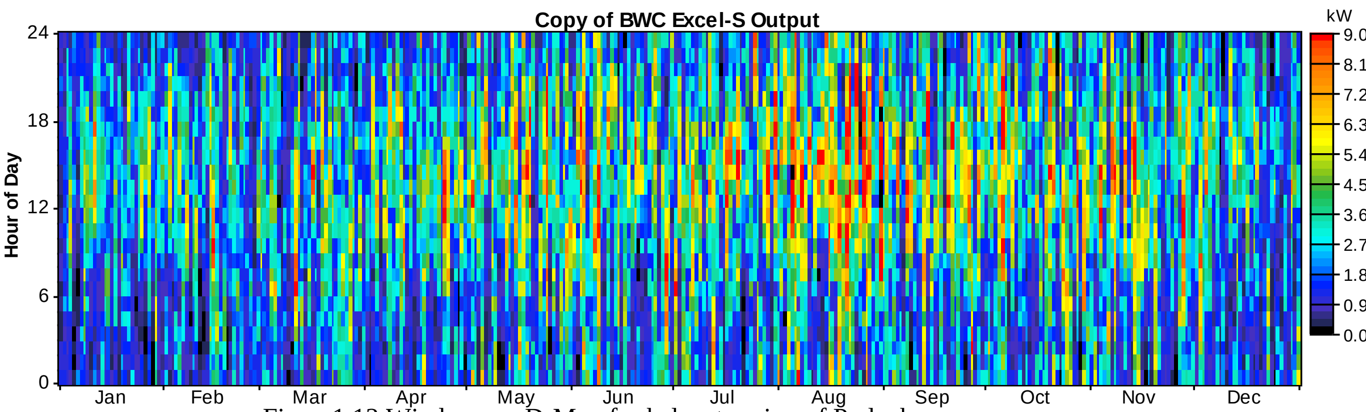



Figure1.12 Wind power D-Map for kalapet region of Puducherry

From the optimization and performance resuls of solar-wind based hybrid power system the levelized cost of wind power is Rs 1.44 Kwh.the maximum power generation possiblity in the month of July and August of the year.

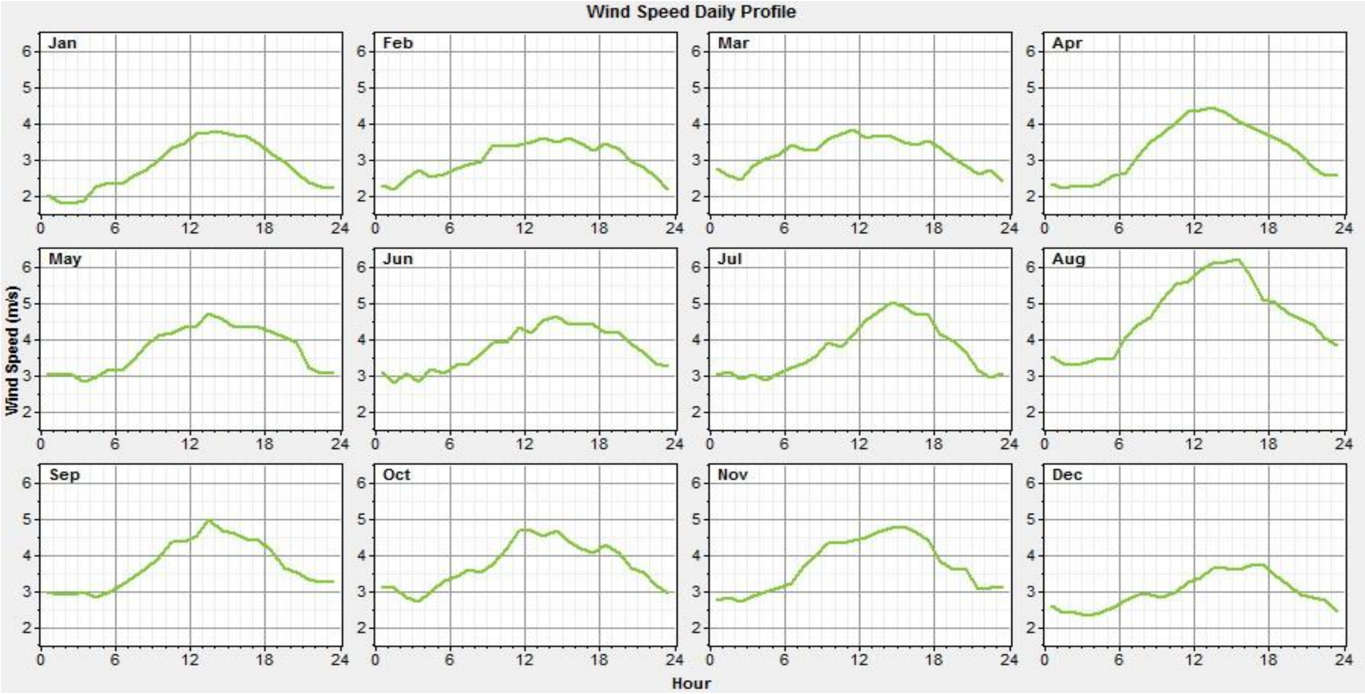



Figure1.13 Month wise wind power prediction at the Kalapet region of Puducherry

Table 1.7. battery performance

| Quantity | Value | |
|---|---|---|
| String size | 1 | |
| Strings in parallel | 4 | |
| Batteries | 4 | |
| Bus voltage (V) | 12 | |
| Nominal capacity | 1.15 | kWh |
| Usable nominal capacity | 0.691 | kWh |
| Autonomy | 0.341 | Hr |
| Lifetime throughput | 412 | kWh |
| Battery wear cost | 32.533 | Rs/kWh |
| Average energy cost | 0 | Rs/kWh |
| Energy in | 0 | kWh/yr |
| Energy out | 0 | kWh/yr |
| Storage depletion | 0 | kWh/yr |
| Losses | 0 | kWh/yr |
| Annual throughput | 0 | kWh/yr |
| Expected life | 5 | Yr |

The total better performance and its operating hours is shown in the Table 1.7 and found that lifetime throughout is 412 Kwh. The output from the battery contribution is found to be very less due to grid connectivity for the proposed system.

Table 1.8. Inverter performance

| Quantity | Inverter | Rectifier | Units |
|---|---|---|---|
| Capacity | 0.5 | 0.5 | kW |
| Mean output | 0.08 | 0 | kW |
| Minimum output | 0 | 0 | kW |
| Maximum output | 0.47 | 0 | kW |
| Capacity factor | 15 | 0 | % |
| Hours of operation | 4,371 | 0 | hrs/yr |
| Energy in | 731 | 0 | kWh/yr |
| Energy out | 658 | 0 | kWh/yr |
| Losses | 73 | 0 | kWh/yr |

The performance of converter/inverter section for the proposed hybrid system shown in Table 1.8. From the table it is revealed that as inverting operation is to fulfill for the developed energy demand by total hour of inverter operation is 4371 hours in a year and the total converter losses is estimated as 73 units per year.

Table 1.9. Grid Performance

| Month | Energy Purchased (kWh) | Energy Sold (kWh) | Net Purchases (kWh) | Peak Demand (kW) | Energy Charge (Rs) | Demand Charge (Rs) |
|---|---|---|---|---|---|---|
| Jan | 749 | 535 | 215 | 9 | 751 | 0 |
| Feb | 601 | 597 | 4 | 10 | 14 | 0 |
| Mar | 774 | 747 | 27 | 11 | 93 | 0 |
| Apr | 622 | 728 | -106 | 11 | -370 | 0 |
| May | 561 | 1,117 | -556 | 11 | -1,944 | 0 |
| Jun | 281 | 1,278 | -997 | 8 | -3,490 | 0 |
| Jul | 259 | 1,339 | -1,079 | 6 | -3,778 | 0 |
| Aug | 196 | 1,905 | -1,709 | 8 | -5,983 | 0 |
| Sep | 272 | 1,290 | -1,018 | 9 | -3,564 | 0 |
| Oct | 255 | 1,366 | -1,110 | 6 | -3,887 | 0 |
| Nov | 222 | 1,337 | -1,115 | 6 | -3,903 | 0 |
| Dec | 395 | 891 | -496 | 8 | -1,738 | 0 |
| **Annual** | **5,187** | **13,129** | **-7,942** | **11** | **-27,797** | **0** |

Table 1.9 shows the total power contribution from conventional grid to the proposed hybrid system. The month wise total energy purchased from grid is 5187 units per year. And also the total energy sold to grid system per year is 13129 units. Due to this grid connected hybrid power system provisions the total earning from electricity department is Rs 27,797 per year.

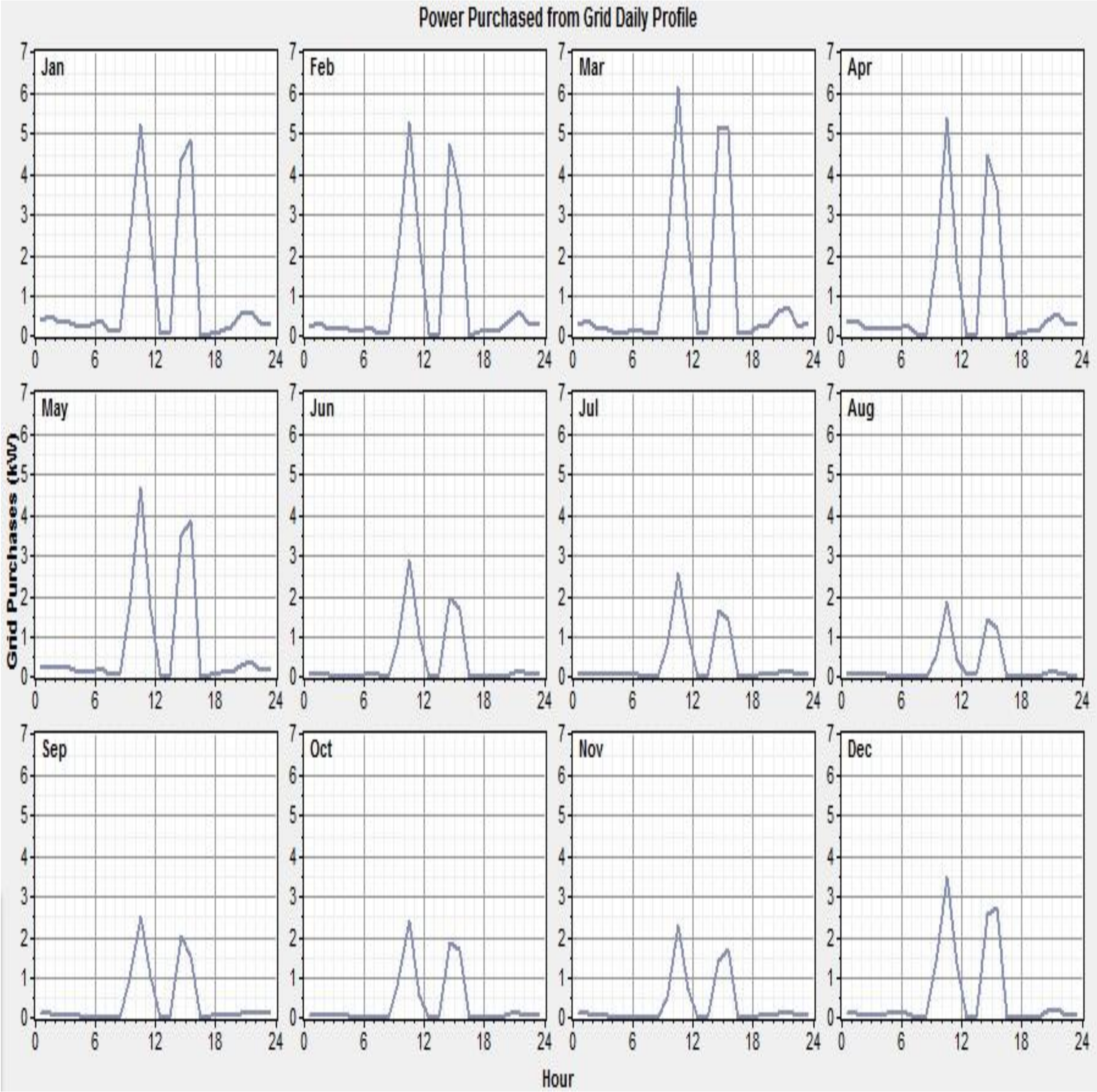



Figure1.14 Monthly wise power purchase from conventional grid

Table 1.10. Pollution level

| **Pollutant** | **Emissions (kg/yr)** |
|---|---|
| Carbon dioxide | 5,019 |
| Carbon monoxide | 0 |
| Unburned hydrocarbons | 0 |
| Particulate matter | 0 |
| Sulfur dioxide | 21.8 |
| Nitrogen oxides | 10.6 |

The level of pollution and the various components of pollutant for the equivalent use of conventional electricity forthe proposed model in the kalapet region of Puducherry is predicted and tabulated in Table 1.10.

Table 1.11.Prediction of  Electrical Power Production and Consumption

| **Power Resources** | | **KWh/Yr** | **in %** |
|---|---|---|---|
| Total Power Production | PV array | 731 | 2% |
| | Wind turbine | 25,059 | 81% |
| | Grid purchases | 5,187 | 17% |
| **Total** | | **30,978** | **100%** |
| Total Power Consumption | AC primary load | 17,775 | 58% |
| | Grid sales | 13,129 | 42% |
| **Total** | | **30,905** | **100%** |
| other Analysis parameters | Excess electricity | 0.00250 | kWh/yr |
| | Unmet load | 0.0000666 | kWh/yr |
| | Capacity shortage | 0.00 | kWh/yr |
| | **Renewable fraction** | **0.833** | |

Table 1.11 exhibits the total electricity generated for the proposed system is 30978 units per year. Out of this PV generation is 731(2 %) units. wind power is 25059(81%) units remaining 17% obtained from the conventional grid.  The total power consumption for the developed load is 58% remaining 42 % is synchronized to the existing conventional grid . The proposed system possesses a higher magnitude of renewable fraction around 0.833. The system also balances an unmet load of 0.0000666 and excess electricity of 0.00250 units per year. This performance prediction analysis is duly designed with a PV wind based hybrid renewable system to the Kalapet region of Puducherry with the available renewable energy resources.

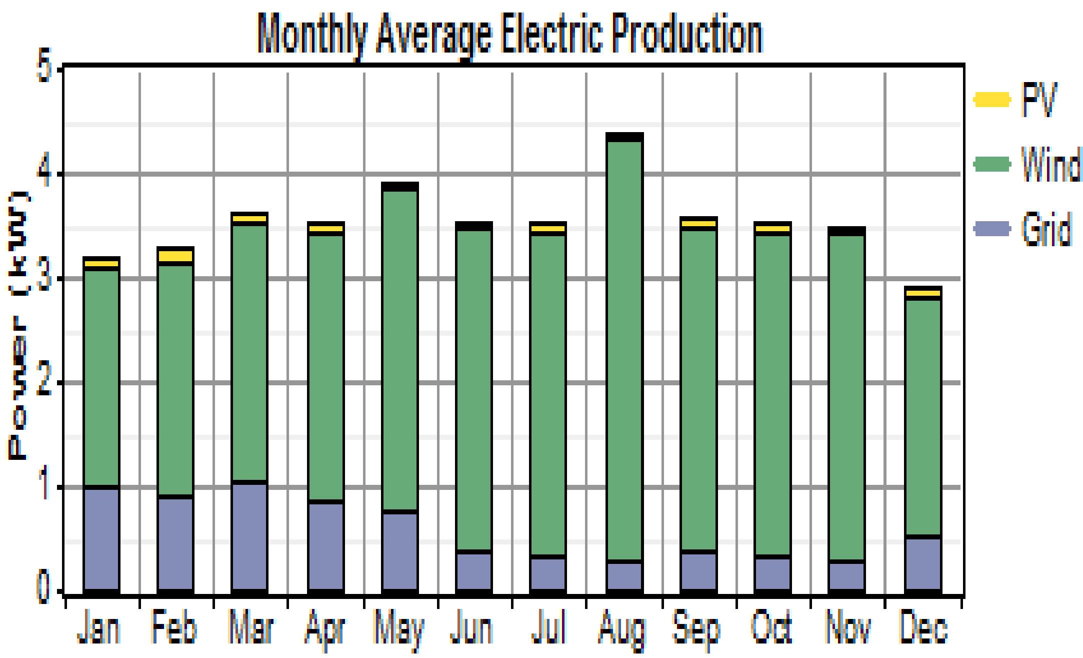



Figure1.15 Resource wise power generation for proposed Hybrid system

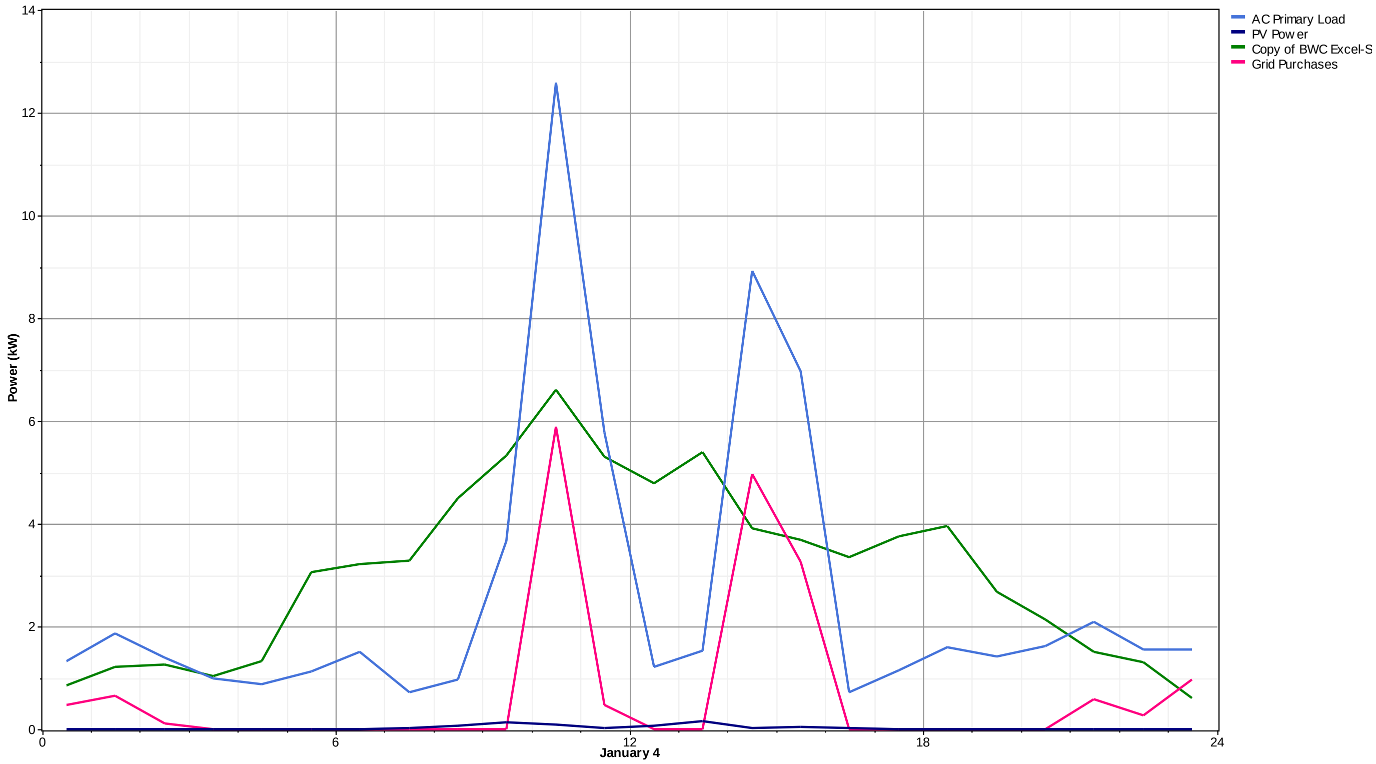


Figure1.16 Power Balance Curve

Fig1.16 exhibits that the proposed hybrid system has the capability to fulfill developed load demand, at any instant of hours in day.

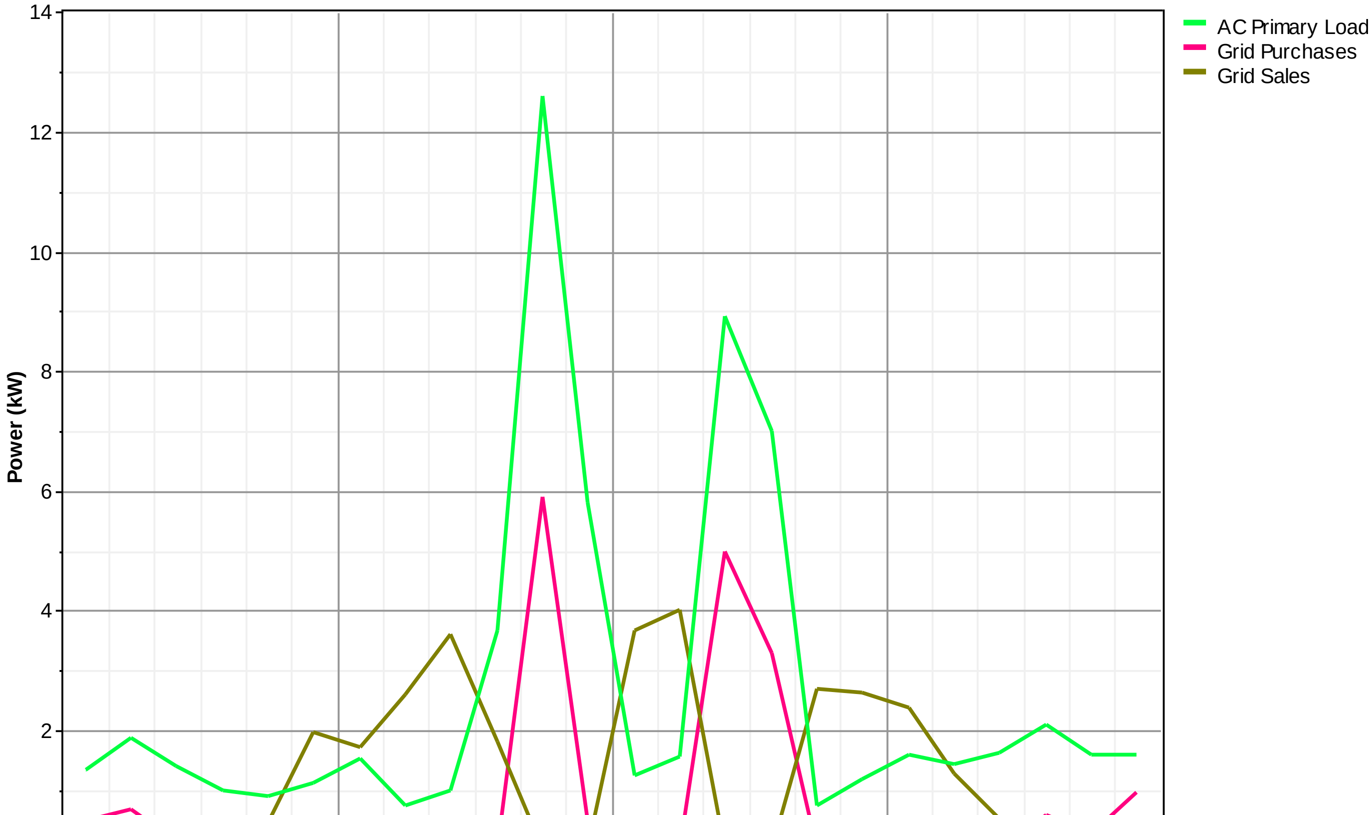


Figure1.17 Power Consumption Curve with Grid Integration

Fig.1.17 exhibits the simulated wave forms expressing the load interaction with the conventional grid power. When renewable energy system fails to meet out the power demand, the grid in turn will be support the power supply and the excess power generation can also be sold back to the grid system. At the end of the year net metering based energy utilization can be calculated. In the simulated graph at the 12o clock on January 4 power can be sold to grid as 2 units. The developed load demand on that period is approximately 3.8 units. Hence, At that time total power generation capability is 5.8 units from renewable resource. Thereby we can predict all the factors of power generation in every instant of time.

Table 1.12. Net Present Costs

| **Component** | **Capital** (Rs.) | **Replacement** (Rs.) | **O&M** (Rs.) | **Salvage** (Rs.) | **Total** (Rs.) |
|---|---|---|---|---|---|
| PV | 21,000 | 0 | 1,278 | 0 | 22,278 |
| Copy of BWC Excel-S | 300,000 | 41,727 | 127,834 | -7,767 | 461,794 |
| Grid | 0 | 0 | -355,338 | 0 | -355,338 |
| Vision CP12240D | 12,000 | 24,417 | 5,113 | 0 | 41,530 |
| Converter | 3,000 | 2,611 | 1,278 | -349 | 6,539 |
| System | 336,000 | 68,754 | -219,835 | -8,116 | 176,803 |

In Table 1.12 tabulates the total net present cost for the proposed hybrid model to the kalapet region of Puducherry. In general the net present cost (NPC) considers the investment and its interest values for investment of life time of project. It also considers the depreciation values of equipment performance. For the proposed system the net present cost is around Rs. 1, 76,803/-. The component wise NPC is Rs 22,278 for PV sector,Rs. 4,61,794 for wind powers, for battery Rs. 41,530/- ,for converter Rs. 6,539/-. By means of interaction with the grid. The proposed system shall obtain an earning of Rs. 3,55,338/- through O&M activity of grid.

Table 1.13. Annualized Costs

| **Component** | **Capital** (Rs./yr) | **Replacement** (Rs./yr) | **O&M** (Rs./yr) | **Salvage** (Rs./yr) | **Total** (Rs./yr) |
|---|---|---|---|---|---|
| PV | 1,643 | 0 | 100 | 0 | 1,743 |
| Copy of BWC Excel-S | 23,468 | 3,264 | 10,000 | -608 | 36,125 |
| Grid | 0 | 0 | -27,797 | 0 | -27,797 |
| Vision CP12240D | 939 | 1,910 | 400 | 0 | 3,249 |
| Converter | 235 | 204 | 100 | -27 | 512 |
| System | 26,284 | 5,378 | -17,197 | -635 | 13,831 |

If the investor in the kalapet region of Puducherry is interested to install a hybrid renewable system, which consisting of solar (500 watts) wind turbine (10KW) with battery and grid continuity. From the Table 1.13 it is revealed that an amount of Rs 13,831 is to be invested for the proposed system every year up to the life of project for meeting out the developed sample village load demand by possessing an average 68 Kwhr /day.

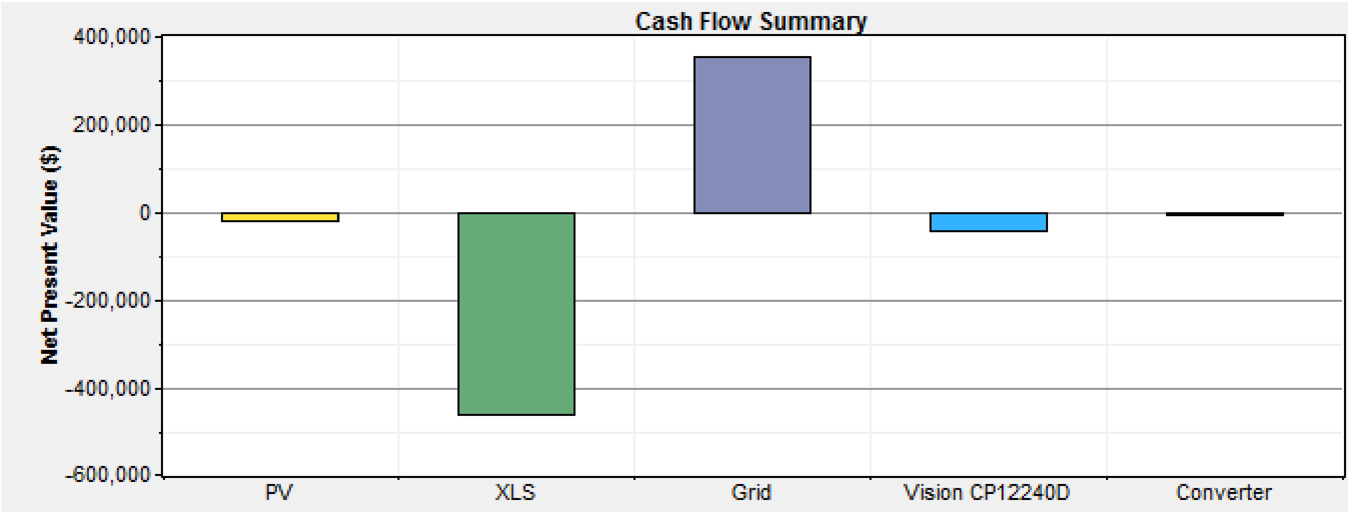



Figure1.18. Cash flow in the proposed structure

Component wise net present cost is shown in the figure 1.18. The type of cost investment can also be obtained from above figure. Negative direction indicates the investments made in the project and the positive direction exhibits the return money flow from the grid system for the sold power.

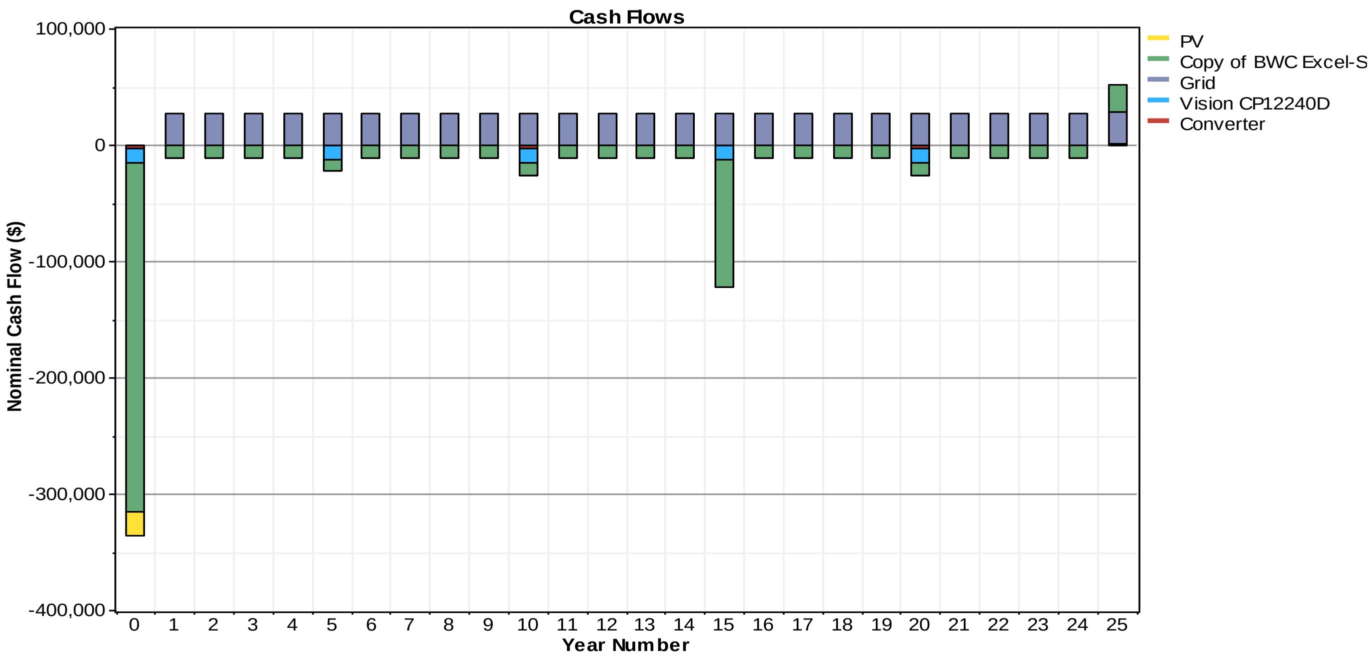



Figure1.19.year wise cash flow in the proposed structure

Year wise cash flow is exhibited in Fig.1.19 towards the life time of the project. The proposed system is designed for 25 years. During the initial period an initial capital cost for investment is found to be higher. Subsequently, in the further years replacement and operational cost occurring in the project is found to be reduced. The negative direction states the project investments and positive directions indicates the year wise returns from the project.

## 1.7 SUMMARY

In the Phase I research analysis , a solar wind based hybrid system is recommended to the kalapet region of Puducherry .The system is found to be the optimum configuration for selected site location in terms of sizing of components, cost of economics, and operating performance to meet out sample load consisting of residential ,commercial, industrial and deferrable load patens . This recommendation can be raised based on the simulation proof of optimization and performance analysis of the selected hybrid model .

# CHAPTER 2

# DEVELOPMENT OF 0.5 KW PV BASED TRANSFORMERLESS INVERTER SYSTEM

## 2.1 INTRODUCTION

The total installed capacity of power stations in India stood at 315,426.32 Megawatt (MW) as of February 28, 2017. The Ministry of Power has set a target of 1,229.4 billion units (BU) of electricity to be generated in the financial year 2017-18, which is 50 BU's higher than the target for 2016-17. The annual growth rate in renewable energy generation has been estimated to be 27 per cent and 18 per cent for conventional energy. The Government has added 8.5 GW of conventional generation capacity during the April 2016-January 2017 period. Under the 12th Five Year Plan, the Government has added 93.5 GW of power generation capacity, thereby surpassing its target of 88.5 GW during the period.

Government of India is giving a strong push to renewable energy in line with its commitment to cut carbon emission 35% and increase the use of renewable energy sources to generate at least 40%ofits power needs by 2030.In line with the Paris Climate Agreement, Ministry of New and Renewable Energy, Government of India Announced the renewable energy target of installing 175GW capacity by 2022.India has already installed 6GW of utility scale solar capacity and 740MW of rooftop capacity. 25GW of projects are under different stages of development. It added 3019 MW of solar power in 2015 which has been an increase of 142% as compared to 2014.With expected new capacity addition of 5.4 GW in 2016; India will become the fourth largest solar Market globally this year, overtaking the UK, Germany and France. A rapid reduction in costs and increased demand for solar installation has found tremendous growth over the past 12 months in India. As on 31$^{st}$ March 2016, total installed power capacity from renewable energy sources (excluding Hydro Power) was 43.7 GW. This accounts for ~14% of the total installed power.

In recent year's renewable energy sources has been paid much attention due to increased concern for depletion of fossil fuels in near future. Solar photovoltaic (PV) power is a renewable source of energy and has been proved to be environmental friendly, low maintenance and with input solar energy available at no cost. India being blessed with abundant amount of sunshine and has high potential of solar energy. The electrical power available from solar PV module is low in voltage (15-30 V) and low power (50-300 W). Above all this power output is DC in nature. Moreover the output power from the PV module does depend upon the connected load at a particular cell temperature and solar insolation level. Most low voltage grids are AC and mostly the loads also require AC power with at least 230 V AC supply. The common technique to extract AC power from solar PV is to use an inverter for obtaining power from the PV modules.

The transformerless photovoltaic (PV) inverters have the advantages of small size, light weight and low cost, thus attract more and more attention in both academic and industrial fields. However, the leakage current exists due to lack of galvanic isolation [20]. The leakage current may result in the electromagnetic inferences, current harmonic distortion and potential safety concerns Many interesting solutions have been presented in literature and patents. They can be classified into two groups. One is single-phase solution, and the other is three-phase one. For the former, the versatile topologies have been presented in [21]-[24]. The basic idea is to achieve the unipolar pulse pattern and constant common-mode voltage by adding the auxiliary switches. However, these single-phase topologies are mainly for the low-power application, e.g. below 4.6kVA, as specified in VDE-AR-N_4105. Moreover, connecting the single-phase topologies into three-phase utility will lead to the unbalance problems [25-26]. The other proposed solutions for minimizing the leakage current by maintaining the constant CMV during all the switching states. However, the given solution requires extra circuitry elements for the achievement of constant CMV. Another method to minimize the leakage current is based on isolating the PV array and grid during the zero state or turn-off state in the switching cycle [27-28]. The inverter topology proposed [29-31] by minimizes the leakage current by isolating the PV array and grid during turn-off state of the switching cycle. Such solutions have worked well for three-level inverter configurations. However, when the configuration is extended for more than three levels, there is again a chance for leakage current to flow in the intermediate states other than zero state. Thus, a study and analysis is required for the minimization of leakage current at the terminal voltage of Multi-Level Inverter (MLI). The leakage current in the PV system is minimized without addition of any extra circuitry elements. The proposed PWM technique is also compared with the conventional modulation scheme for five-level CMLI. The objective of this phase II analysis is to build a transformer-less modular inverter system for solar array.

## 2.2 METHODOLOGY

The following methodology is adopted in the phase II analysis for developing a 0.5 kW PV based transformerless Inverter system

**Task # 1: Multilevel inverter topologies with different PWM Techniques**

Step1:

In the first step, the literature reviews of different multi level inverter topologies suitable for solar PV array were analyzed. Computer simulations were carried out for different PWM techniques are simulated and its performance were analyzed.

Step 2:

In this step a comparison between various PWM techniques namely PD, POD and Hybrid technique is done. A novel Carrier Overlapping (COP) technique suitable for inverter system in solar array is developed. This technique is implemented in PV system based inverter topology.

Step 3:

Finally, Implementation of the simulation model of proposed COP based 5 level inverter and the results exhibits the maximum benefits capability and the simulation studies are validated.

**Task # 2: Prototype model of 0.5 kW PV based Transformerless Inverter System**

Step 1:

In this step, various components used for building the multilevel inverter system and their ratings are identified.

Step 2:

Here a suitable digital controller platform, named Field Programmable Gate Array (FPGA) is chosen and studies carried out for the implementation of the proposed COP technique in the inverter system.

Step 3:

In this task we mounted 0.5 kW photovoltaic modules on the roof top of EEE Department of Pondicherry Engineering College, Puducherry. The orientation of the panel is adjusted with respect to the maximum solar insolation level.

Step 4:

Finally the prototype is built for the modular structure of solar array based inverter system for standalone applications. Its performance is verified through experiment on comparing with its simulation results.

## 2.3 MULTILEVEL INVERTER

### 2.3.1 NEED FOR MULTILEVEL INVERTER

Numerous industrial applications have begun to require higher power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly. As a result, a multilevel power converter structure has been introduced as an alternative in high power and medium voltage situations. A multilevel converter not only achieves high power ratings, but also enables the use of renewable energy sources. Renewable energy sources such as photovoltaic, wind, and fuel cells can be easily interfaced to a multilevel converter system for a high power application.

### 2.3.2 CONCEPT OF MULTILEVEL CONVERTER

The concept of multilevel converters has been introduced since 1975. The term multilevel began with the three-level converter. Subsequently, several multilevel converter topologies have been developed. However, the elementary concept of a multilevel converter to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple dc voltage sources. The commutation of the power switches aggregate these multiple dc sources in order to achieve high voltage at the output; however, the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected.

A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM). The attractive features of a multilevel converter can be briefly summarized as follows.

**Staircase waveform quality:** Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the dv/dt stresses; therefore electromagnetic compatibility (EMC) problems can be reduced.

**Common-mode (CM) voltage:** Multilevel converters produce smaller CM voltage; therefore, the stress in the bearings of a motor connected to a multilevel motor drive can be reduced. Furthermore, CM voltage can be eliminated by using advanced modulation strategies such as that proposed in [24].

**Input current:** Multilevel converters can draw input current with low distortion.

**Switching frequency:** Multilevel converters can operate at both fundamental switching frequency and high switching frequency PWM. It should be noted that lower switching frequency usually means lower switching loss and higher efficiency.

Unfortunately, multilevel converters do have some disadvantages. One particular disadvantage is the greater number of power semiconductor switches needed. Although lower voltage rated switches can be utilized in a multilevel converter, each switch requires a related gate drive circuit. This may cause the overall system to be more expensive and complex.

Plentiful multilevel converter topologies have been proposed during the last two decades. Contemporary research has engaged novel converter topologies and unique modulation schemes. Moreover, three different major multilevel converter structures have been reported in the literature: cascaded H-bridges converter with separate dc sources, diode clamped (neutral clamped), and flying capacitors (capacitor clamped).

Moreover, abundant modulation techniques and control paradigms have been developed for multilevel converters such as sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE-PWM), space vector modulation (SVM), and others.

## 2.4 CASCADED H-BRIDGE

A single-phase structure of an m-level cascaded inverter is illustrated in Figure 2.1. Each separate dc source (SDCS) is connected to a single-phase full-bridge or H-bridge inverter. Each inverter level can generate three different voltage outputs, +Vdc, 0, and –Vdc by connecting the dc source to the ac output by different combinations of the four switches. To get the desired 5 level output, we have to construct two H-bridges with independent symmetrical voltage sources. We can generate 5 different levels, +Vdc, +Vdc/2, 0, -Vdc/2, -Vdc. We make use of eight switches to achieve this 5 level output. The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of output phase voltage levels m in a cascade inverter is defined by $m = 2s+1$, where s is the number of separate dc sources.

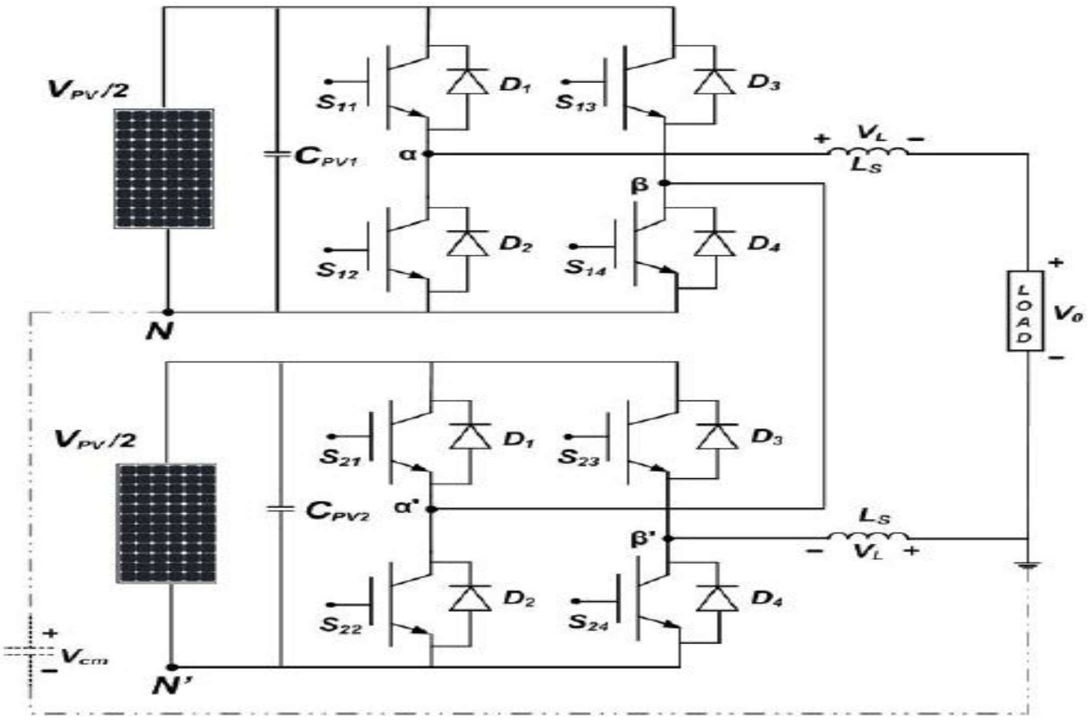



Figure 2.1: Cascaded H-Bridge Topology

### 2.5 PROPOSED CARRIER OVERLAPPINGPING TECHNIQUE:

This proposed carrier Overlapping technique is executed in the multilevel cascaded H-bridge inverter. This PWM technique uses only two triangular carriers which are being compared with the fundamental sine wave. This technique implies more switching states due to the Overlapping carriers; this makes the m more efficient than other techniques. The carriers in this technique are Overlapping with each other in their magnitude axis. The representation of carriers with the full sine wave is shown in the figure below. Due to more switching instances this technique gives a better output voltage and a reduced common mode voltage.

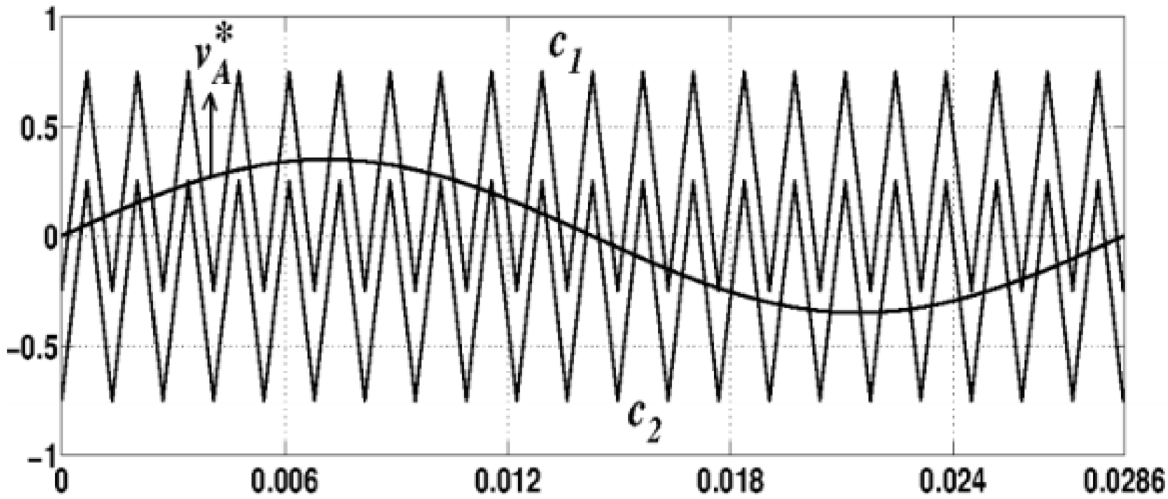



Figure 2.2: Carrier Generation with the Sinusoidal Waveform

## 2.6 SIMULATION RESULTS AND DISCUSSION

Comparison of Hybrid [24] and Proposed Carrier Overlapping technique for the following parameter:

Switching Frequency Vs Leakage Current

Switching Frequency Vs Output RMS Voltage

Switching Frequency Vs Output Current

Table 2.1: Switching Frequency Vs Leakage Current

| **Switching Frequency (kHz)** | **Leakage Current (mA)** | |
|---|---|---|
| | **Existing Hybrid Technique [24]** | **Proposed Carrier Overlapping Technique** |
| 5 | 0.3908 | **0.381** |
| 6 | 0.3879 | **0.3612** |
| 7 | 0.3867 | **0.3613** |
| 8 | 0.3829 | **0.3533** |
| 9 | 0.3946 | **0.3553** |
| 10 | 0.4184 | **0.3483** |
| 11 | 0.3911 | **0.2542** |
| 12 | 0.3868 | **0.3453** |
| 13 | 0.3841 | **0.346** |

| | | |
|---|---|---|
| 14 | 0.3839 | **0.3459** |
| 15 | 0.3834 | **0.3583** |

Table 2.1 shows value of leakage current at various switching frequency starting from 5KHz to 15KHz. The magnitude of leakage current is measured through simulation for both hybrid and carrier overlapping technique. Comparison of leakage current between hybrid and cop technique is given in table. It is inferred that cop technique has lesser magnitude than proven hybrid technique. More over leakage current is very minimum at 11 KHz switching frequency.

Table 2.2: Switching Frequency Vs Output Voltage

| **Switching Frequency (kHz)** | **Output Voltage (V)** | | | |
|---|---|---|---|---|
| | **Phase Disposition** | **Phase Opposite Disposition** | **Existing Hybrid Technique [24]** | **Proposed Carrier Overlapping Technique** |
| 5 | 44.08 | 45.57 | 51.03 | **56.94** |
| 6 | 44.04 | 45.44 | 50.89 | **55.44** |
| 7 | 43.72 | 45.01 | 50.92 | **55.36** |
| 8 | 44.49 | 45.30 | 51.07 | **54.83** |
| 9 | 43.03 | 45.04 | 51.66 | **54.93** |
| 10 | 44.74 | 45.28 | 46.7 | **59.06** |

| | | | | |
|---|---|---|---|---|
| 11 | 44.47 | 44.52 | 51.76 | **54.36** |
| 12 | 43.28 | 45.20 | 51.75 | **54.38** |
| 13 | 44.51 | 45.79 | 51.61 | **54.53** |
| 14 | 43.64 | 45.93 | 51.07 | **54.5** |
| 15 | 44.10 | 45.98 | 51.51 | **55.25** |

A five level cascaded MLI is simulated in MATLAB with various modulation technique like PD, POD, Hybrid and COP. Comparative results of output voltage are shown in table 2.2. Among all these techniques proposed PWM produce more fundamental voltage nearly 20% greater than other existing technique at various frequencies. Table 2.2 shows when switching frequency is 10KHz COP technique produc emore fundamental voltage nearly 59.06 volts. Whereas for the same frequency PD, POD, Hybrid gives 44.74V, 45.V and 45.7V respectively. From simulated results it is inferred that COP technique is well suited for cascaded multilevel inverter topologies.

Table 2.3: Switching Frequency Vs Output Current

| **Switching frequency (Khz)** | **Output Current (A)** | |
|---|---|---|
| | **Existing Hybrid Technique [24]** | **Proposed Carrier Overlapping Technique** |
| 5 | 1.018 | **1.129** |
| 6 | 1.021 | **1.109** |
| 7 | 1.018 | **1.107** |

| | | |
|---|---|---|
| 8 | 1.021 | **1.097** |
| 9 | 1.033 | **1.099** |
| 10 | 0.934 | **1.181** |
| 11 | 1.035 | **1.087** |
| 12 | 1.035 | **1.088** |
| 13 | 1.032 | **1.091** |
| 14 | 1.021 | **1.091** |
| 15 | 1.03 | **1.105** |

Table 4.3 gives comparison of output current between Hybrid and carrier overlapping technique at various switching frequencies.

## 2.7 SIMULATION WAVEFORMS:

### 2.7.1 WITHOUT FILTER CIRCUIT, WITH 50 Ohm LOAD

(i) Proposed Carrier Overlapping Technique (COP):

(a) Output Voltage Waveform

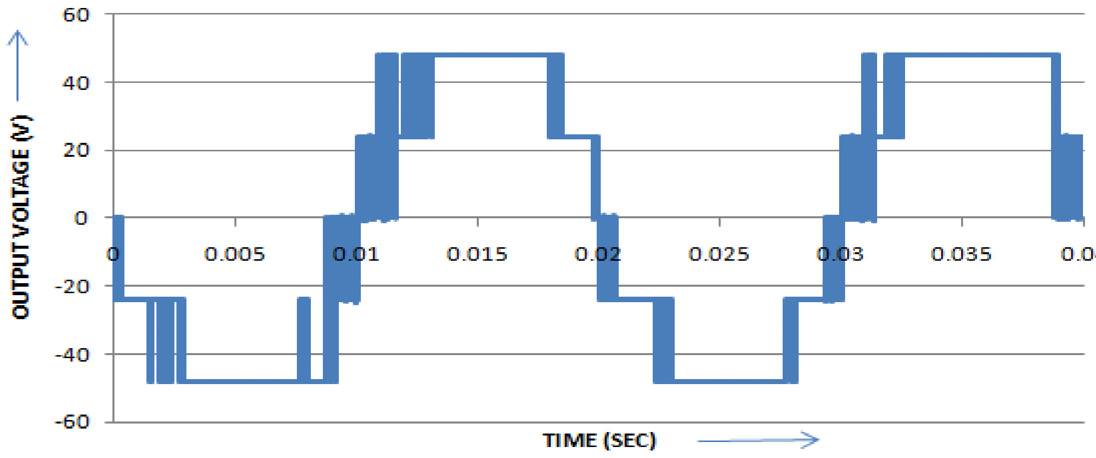



Figure 2.3: Inverter Output Voltage of COP Technique

Fig 2.3 shows experimental output voltage waveform of 5 level CMLI with COP for an input voltage of 48V. From waveform it is observed that output has lesser off state and free from harmonics.

(b) Output Current Waveform

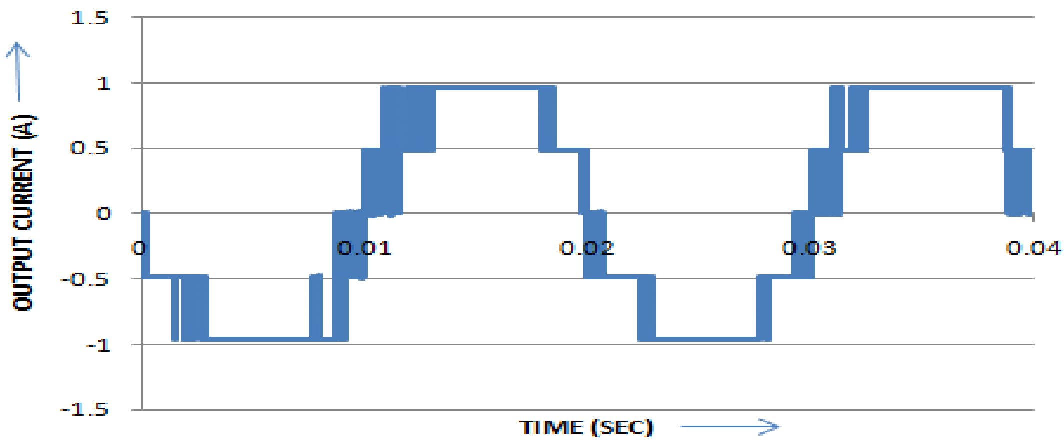



Figure 2.4: Inverter Output Current of COP Technique

Fig 2.4 shows experimental output current measured in 5 level CMLI with 50 Ohm load. The magnitude of load current is 1 Amp and waveform is free from harmonics.

(c) Leakage Current Waveform

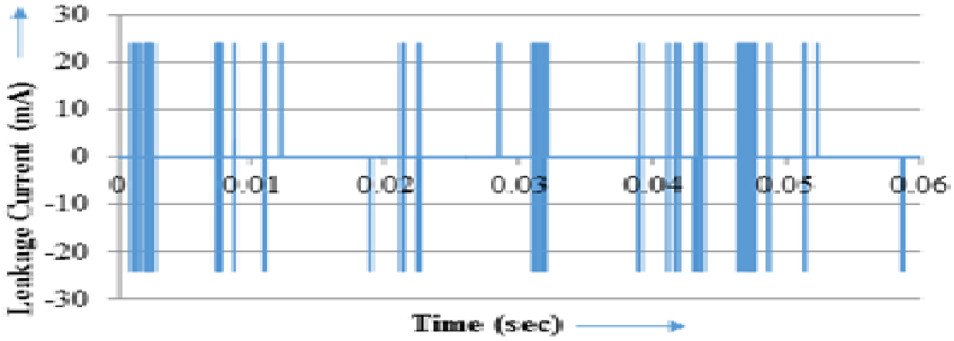



Figure 2.5: Leakage Current Waveform of COP Technique

Figure 2.5 shows the leakage current waveform of 5 level CMLI measured with digital storage Oscilloscope. It is inferred that leakage current is in the range of milli amps and peak value is less than 30mA.

(ii) Existing Hybrid Technique

(a) Output Voltage Waveform

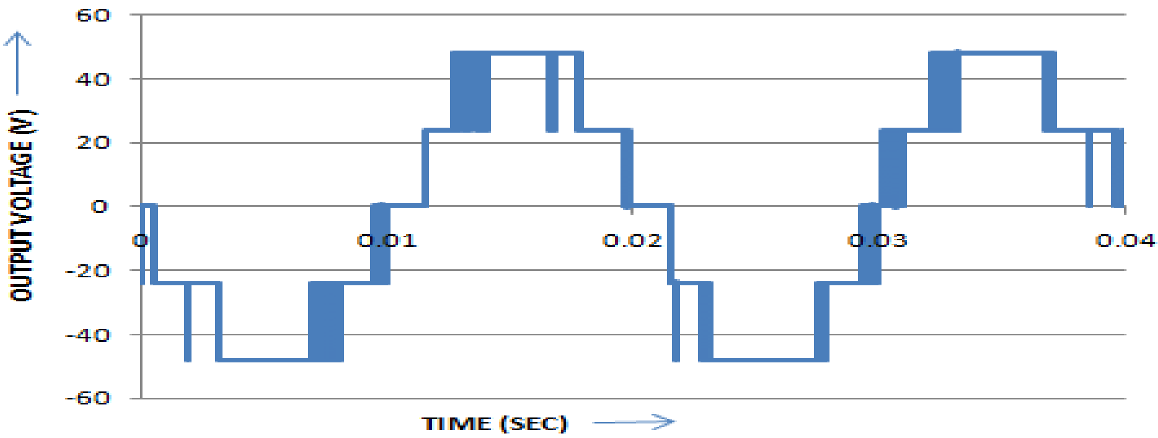



Figure 2.6: Inverter Output Voltage of Hybrid Technique

Figure 2.6 shows experimental output voltage of 5 level CMLI with existing hybrid technique. It is inferred that output has longer off state which lead to flow of leakage current for longer duration though inverter and panel circuits. Also output has notches in negative half cycle.

(b) Output Current Waveform

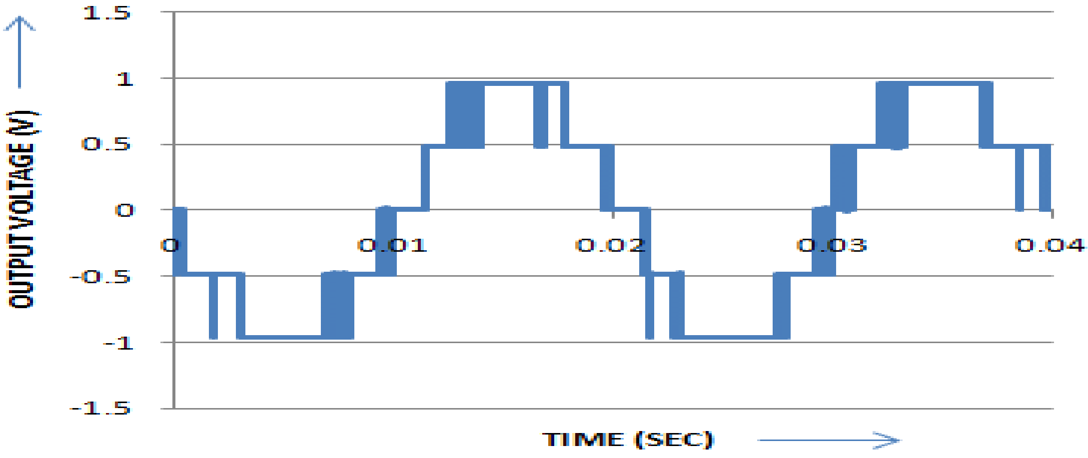



Figure 2.7: Inverter Output Current of Hybrid technique

Figure2.7 shows the staircase type 5 level output current waveform of the existing Hybrid technique.

### 2.7.2 WITH FILTER CIRCUIT, WITH 50 Ohm LOAD

(i) Output Voltage Waveform of Proposed Carrier Overlapping and the Existing Hybrid techniques.

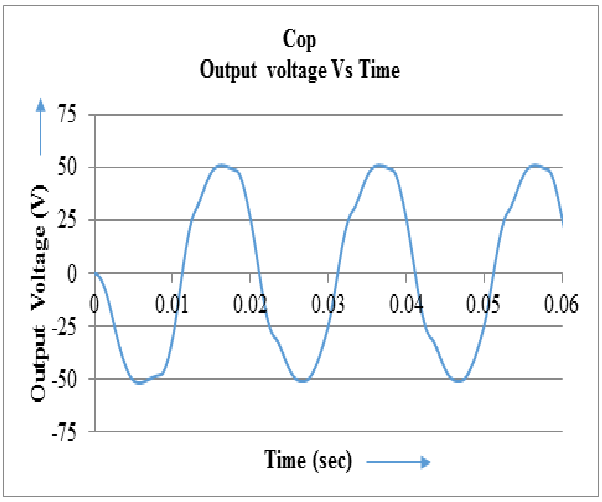



Figure 2.8 Output Voltage Waveform of COP techniques with Filter

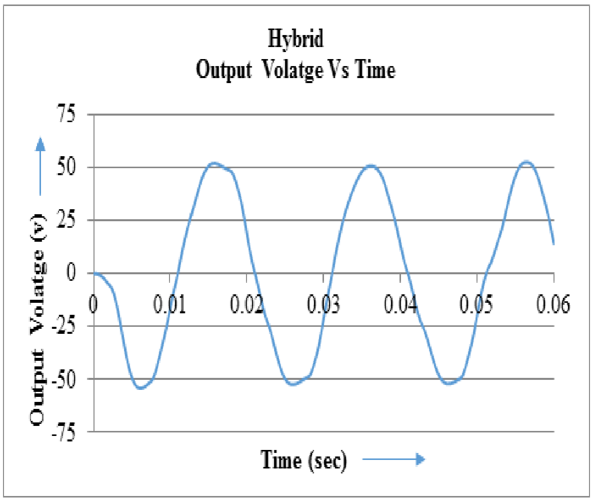



Figure 2.9 Output Voltage Waveform of Hybrid

Figure 2.8 and 2.9 shows the output voltage waveform of both proposed carrier Overlapping method and the Existing Hybrid techniques. It is found that ouput voltage wave form is sinusoidal.

(ii) Output Current Waveform of Proposed Carrier Overlapping and The Existing Hybrid Method.

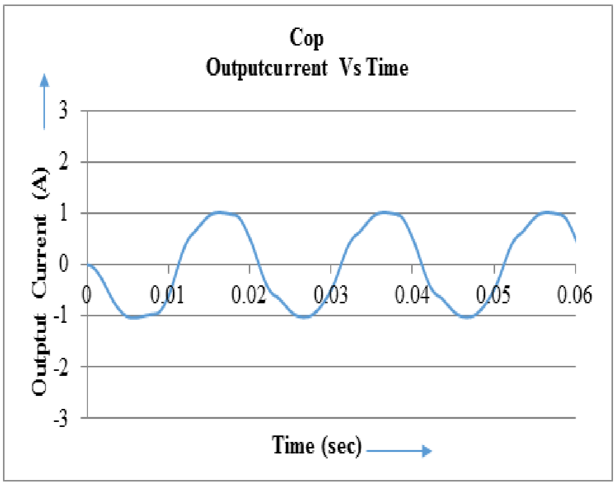



Figure 2.10 Inverter Output Current of COP Technique of with Filter

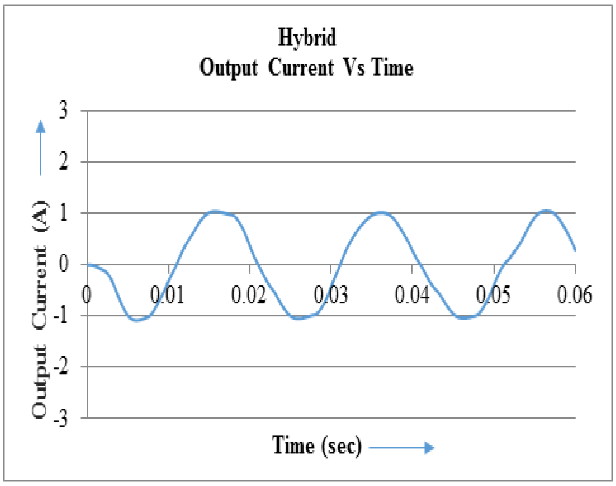



Figure 2.11 Inverter Output Current Hybrid technique with Filter

The Figure 2.10 and 2.11 shows the output current waveform of both proposed carrier Overlapping method and the Existing Hybrid techniques and it is found to be sinusoidal and free from harmonics.

(iii) Leakage Current Waveform of proposed Carrier Overlapping and The Existing Hybrid techniques.

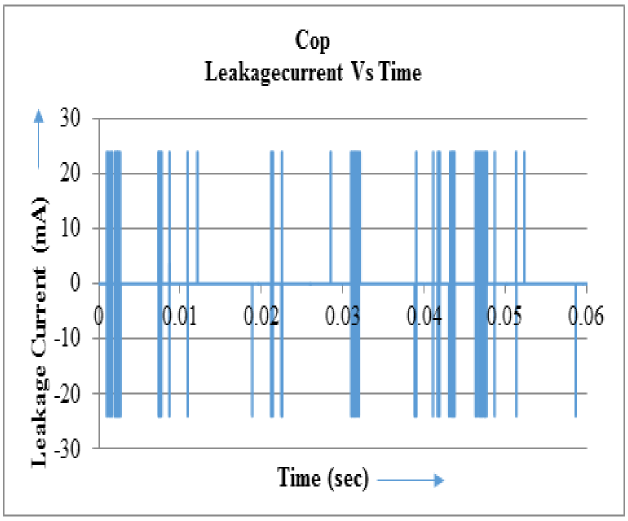



Figure 2.12 Leakage Current of COP Technique With Filter

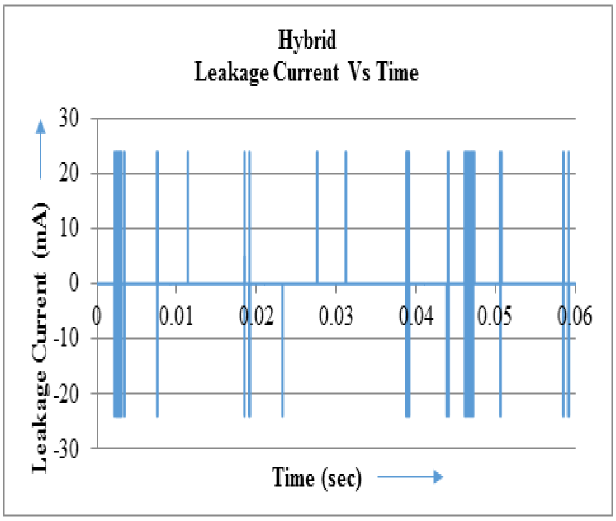



Figure 2.13 Leakage Current for Hybrid Technique With Filter

Figure2.12 and 2.13 shows the Leakage current waveform of both Proposed Carrier Overlapping method and the Existing Hybrid method.

(iv) THD (%) values at 50 Hz.

(a) Existing Hybrid Method Technique

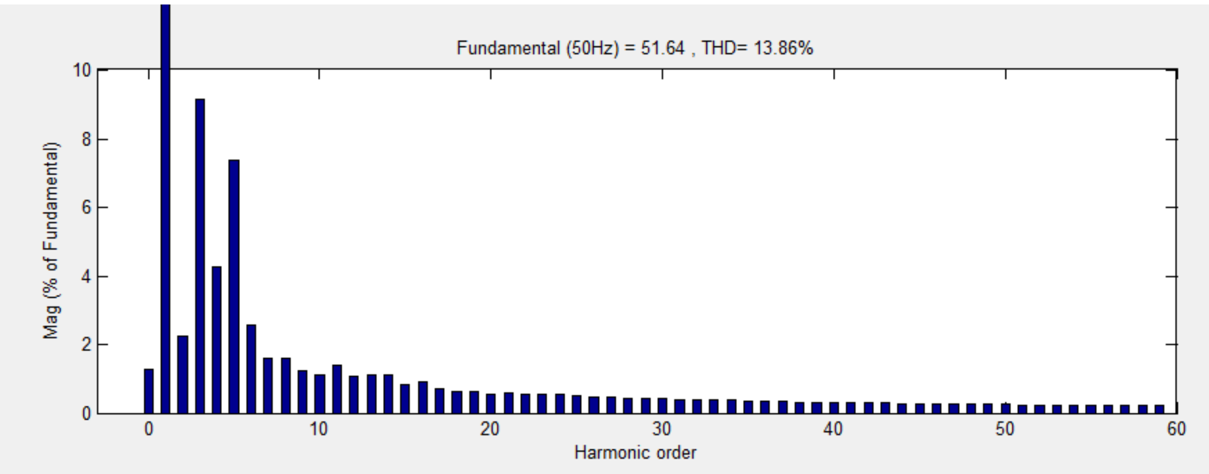



Figure 2.14: THD Spectrum of Hybrid Technique

(b) Proposed Carrier Overlapping Technique

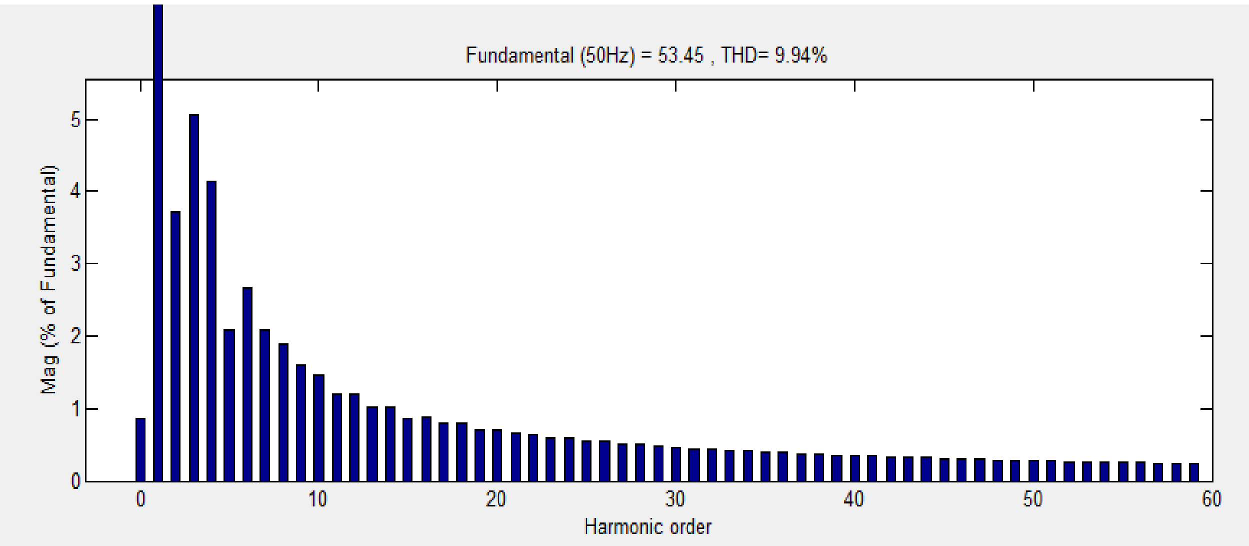



Figure 2.15: THD Spectrum of COP Technique

The above Figures 2.14 and 2.15 of THD shows that the proposed carrier Overlapping technique posses a better reduced value than the existing Hybrid technique (Ref.24)

## 2.8 HARDWARE SETUP AND COMPONENTS:

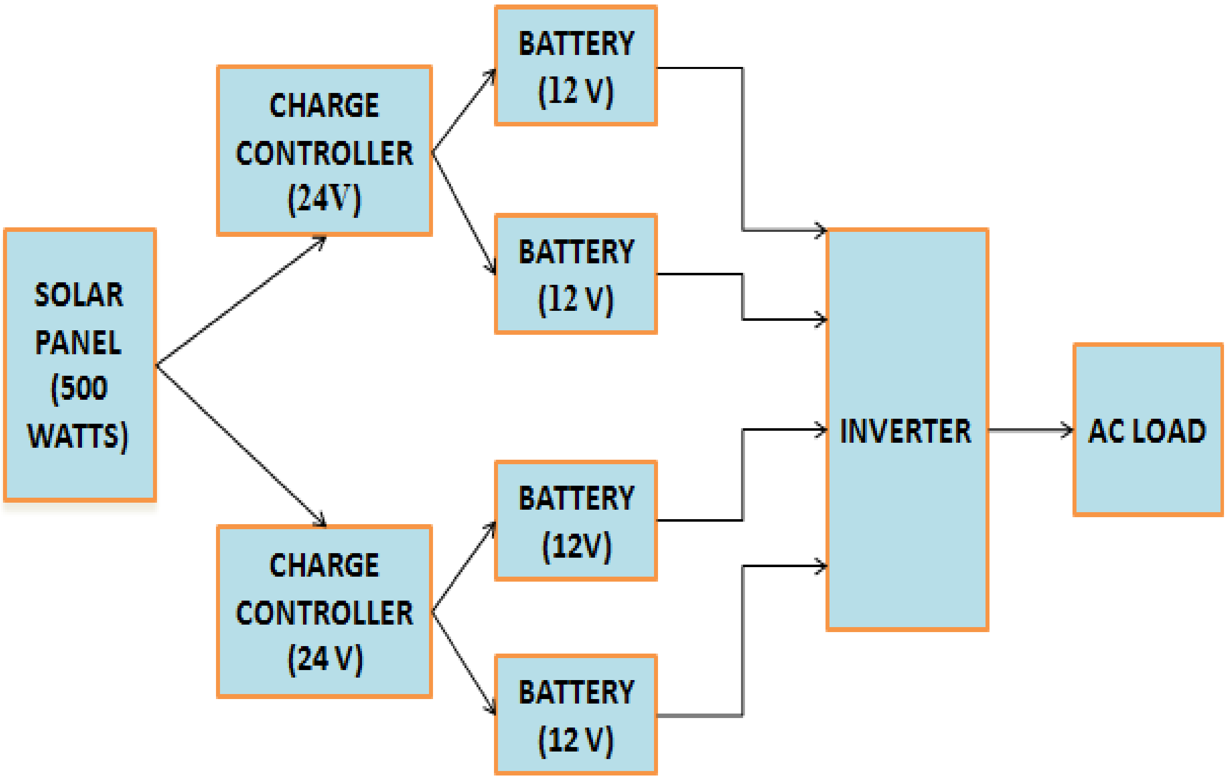



Figure 2.16: Block Diagram of the Experimental Setup

The block diagram shows a clear idea of the built up hardware setup. The Dc power that is being generated by the PV panel is limited to 24V volts each by the 2 charge controllers. Then, each 24 volts gets splits into two 12V and gets stored in the battery for inversion process. The inverter, which has been built take the DC input from the battery and converts into desired AC level.

### 2.8.1 OPTOCOUPLER (6N137):

An Optocoupler, also known as an Opto-isolator or Photo-coupler, is an electronic component that interconnects two separate electrical circuits by means of a light sensitive optical interface. We know that transformer can not only provide a step-down voltage, but they also provide "electrical isolation" between the higher voltage on the primary side and the lower voltage on the secondary side. In other words, transformers isolate the primary input voltage from the secondary output voltage using electromagnetic coupling by means of a magnetic flux circulating within the iron laminated core. But we can also provide electrical isolation between an input source and an output load using just light by using a very common and valuable electronic component called an Optocoupler.

The function of Optocoupler is to isolate the control circuit from power circuit. PWM signal from the FPGA is not directly fed to the power circuit in order to protect the PWM signal it is essential to provide isolation circuit between power circuit and control circuit or else the high power components may damage the low power PWM circuit components.

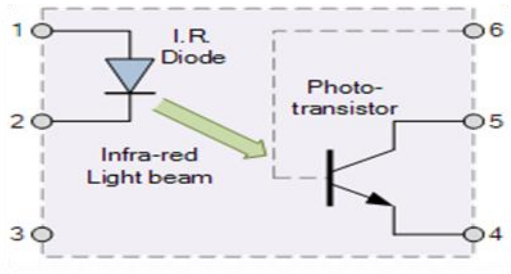



Figure 2.17: Phototransistor Optocoupler

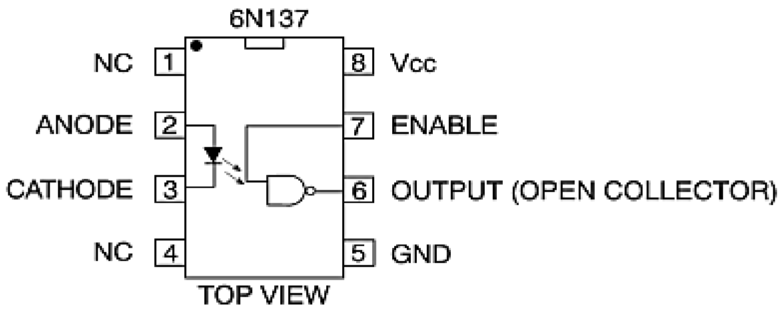



Figure 2.18: Pin Details of Optocoupler 6N137

### 2.8.2 DRIVER CIRCUIT(IC IR2110):

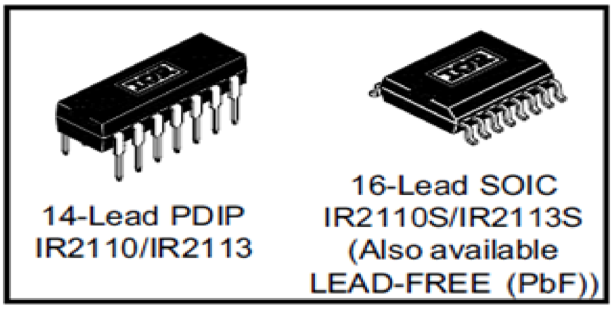
The IR2110 is a high voltage, high speed power IGBT driver with over-current limiting protection circuitry. Logic inputs are compatible with standard CMOS or LSTTL outputs, down to 2.5V logic. The output driver features a high pulse current buffer stage designed for minimum driver cross-conduction. The protection circuitry detects over-current in the driven power transistor and limits the gate drive voltage. Cycle by cycle shutdown is programmed by an external capacitor which directly controls the time interval between detection of the over- current limiting conditions and latched shutdown. The floating channel can be used to drive an N-channel power IGBT in the high or low side configuration which operates up to 500 volts.

A IGBT drive circuit is designed to connect the gate directly to a voltage bus with no intervening resistance other than the impedance of the drive circuit switch. Gate driver acts as a high-power buffer stage between the PWM output of the control device and gates of the primary power switching IGBT. The gate drive requirements for a power IGBT utilized as a high side switch (drain connected to the high voltage rail, as shown in Figure, driven in full enhancement, i.e., lowest voltage drop across its terminals, can be summarized as follows:

Gate voltage must be 10-15V higher than the drain voltage. Being a high side switch, such gate voltage would have to be higher than the rail voltage, which is frequently the highest voltage available in the system.

The gate voltage must be controllable from the logic, which is normally referenced to ground. Thus, the control signals have to be level-shifted to the source of the high side power device, which, in most applications, swings between the two rails.

The power absorbed by the gate drive circuitry should not significantly affect the overall efficiency.



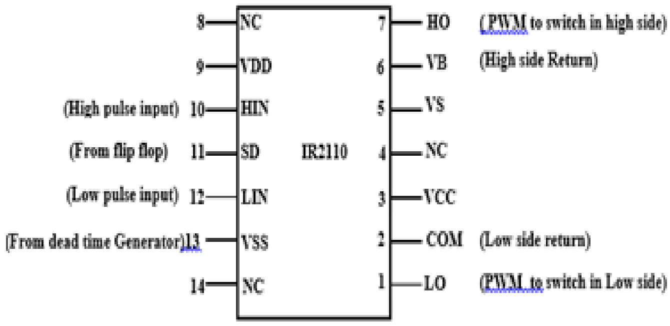




Figure 2.19 and 2.20: Physical Structure And Pin Details Of Driver Ic Ir2110

### 2.8.3 FIELD PROGRAMMABLE GATE ARRAY (XILINX SPARTAN 3E FPGA XC3S100E):

A Field-programmable Gate Array (FPGA) is an integrated circuit designed to be configured by the customer or designer after manufacturing—hence "field-programmable". The FPGA configuration is generally specified using a hardware description language (HDL), similar to that used for an application-specific integrated circuit (ASIC) (circuit diagrams were previously used to specify the configuration, as they were for ASICs, but this is increasingly rare). FPGAs can be used to implement any logical function that an ASIC could perform. The ability to update the functionality after shipping, partial re-configuration of the portion of the design and the low non-recurring engineering costs relative to an ASIC design (not withstanding the generally higher unit cost), offer advantages for many applications.

FEATURES:

- 2,160 logic cell equivalents
- Four 18K-bit block RAMs (72K bits)
- Four 18x18 pipelined hardware multipliers
- On Board programmable oscillator (3 to 200 MHz)
- 4 Channel 8 Bit I2C based ADC and single Channel DAC

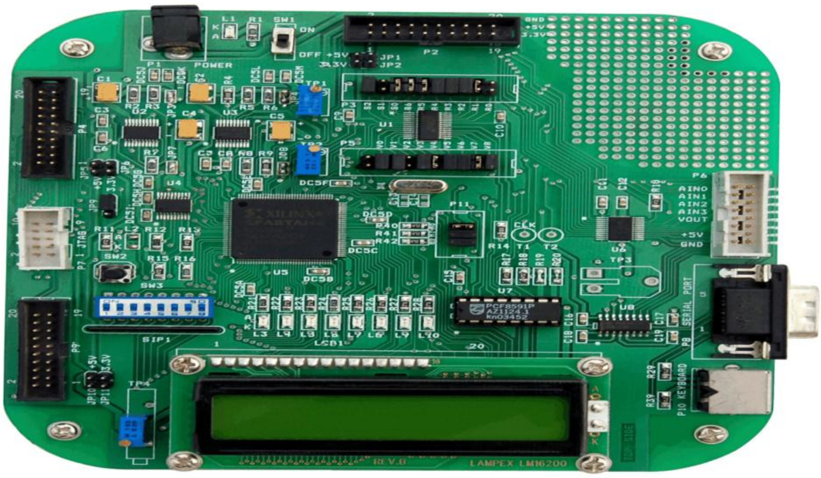


Figure 2.21: Xilinx Spartan 3E FPGA XC3S100E

### 2.8.4 SOLAR PANEL INSTALLED IN EEE DEPARTMENT, PONDICHERRY ENGINEERING COLLEGE

Figure 2.22: Photograph of the Solar Panel mounted in the EEE Department of PEC

Figure 2.23: Front View Of Solar Panel

### 2.8.5 CHARGE CONTROLLER

Figure 2.24: Charge Controller mounted in the EEE Department of  PEC

### 2.8.6 FIVE – LEVEL INVERTER

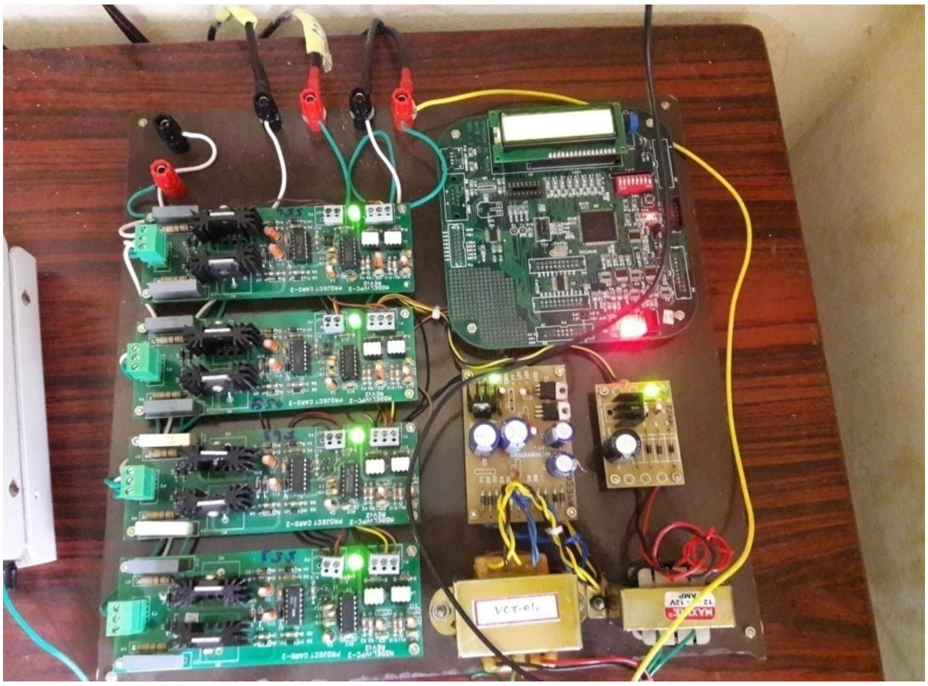


Figure 2.25: Cascaded Multi Level Inverter

### 2.8.7 EXTERNAL PARASITIC CAPACITANCE

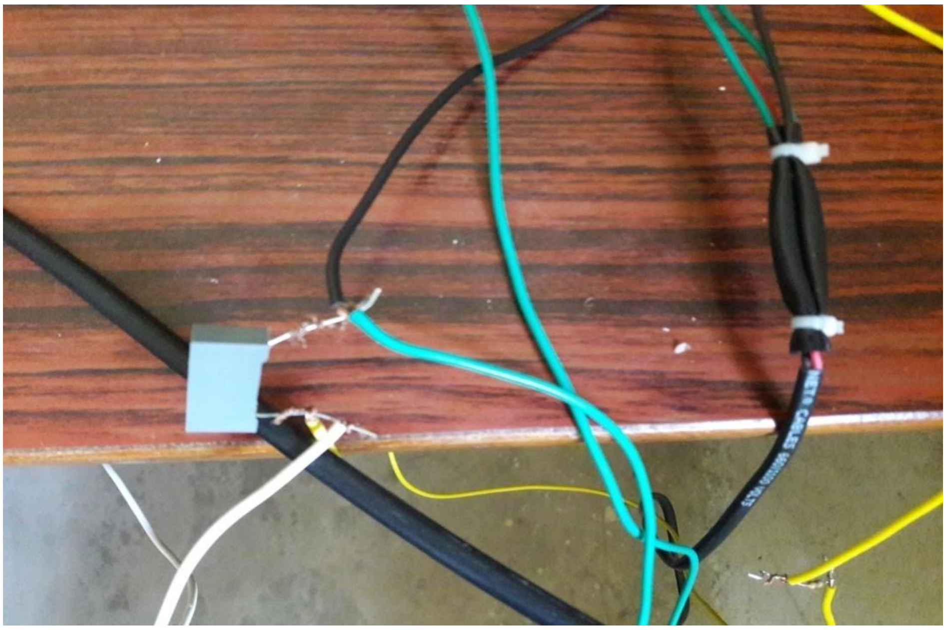


Figure 2.26: External Parasitic Capacitance

### 2.8.8 PROTOTYPE MODEL OF 5 LEVEL INVERTER WITH SOLAR INPUT

Figure 2.27: Photograph of Cascaded Multi Level Inverter Interfaced with PV resource in the EEE Department of PEC

### 2.9 HARDWARE WAVEFORMS AND RESULTS

(i) Proposed Carrier Overlapping Method

(a) Output Voltage Waveform

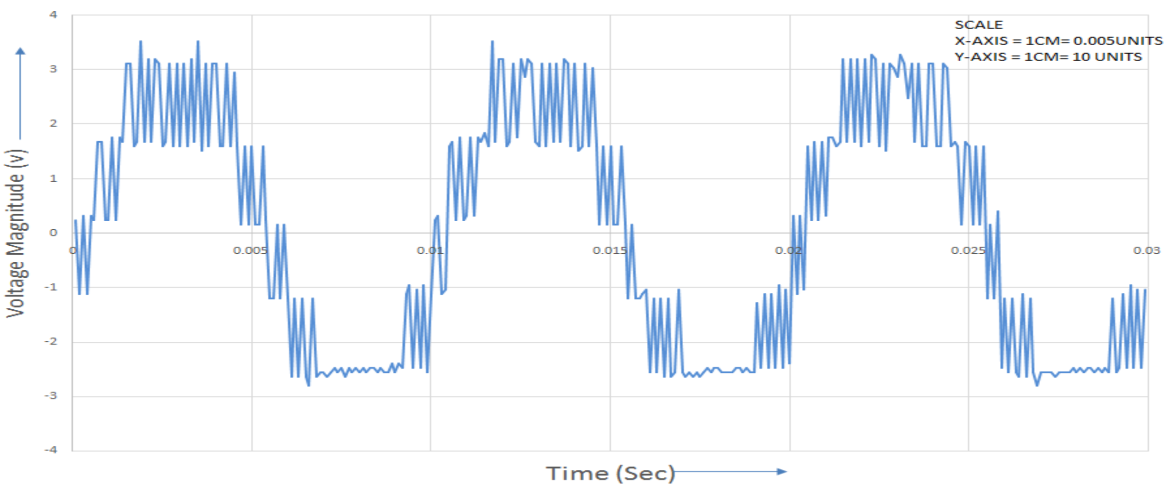



Figure 2.28: Output Voltage Waveform

(c)Leakage Current Waveform

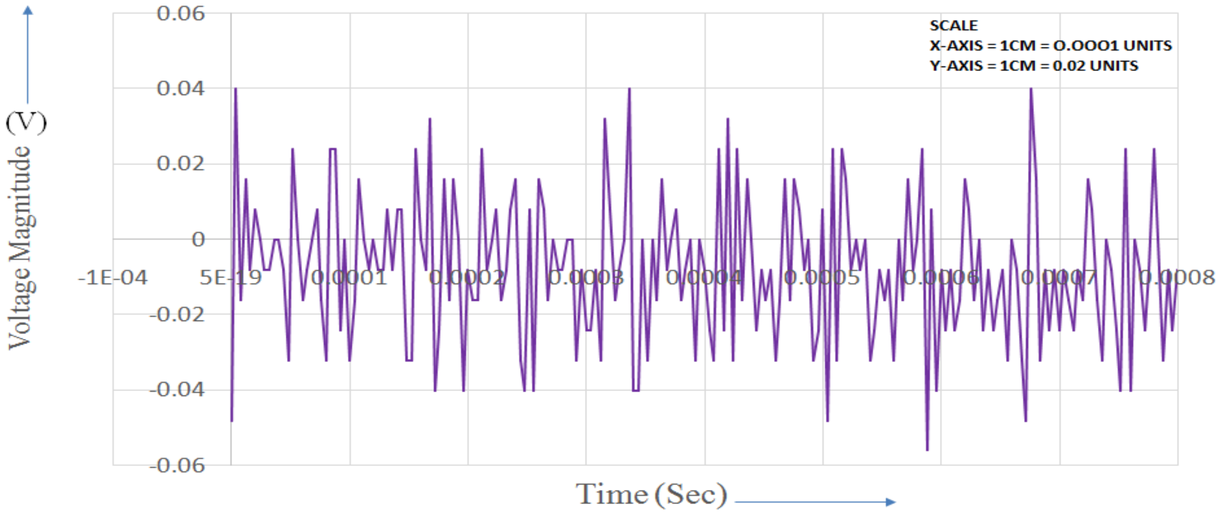



Figure 2.29: Leakage Current Waveform

The above Figures 2.28 and 2.29 shows the output voltage and leakage current waveforms of proposed carrier Overlapping method. Since the leakage current is in milliamps.

(ii) Existing Hybrid Method

(a) Output Voltage Waveform

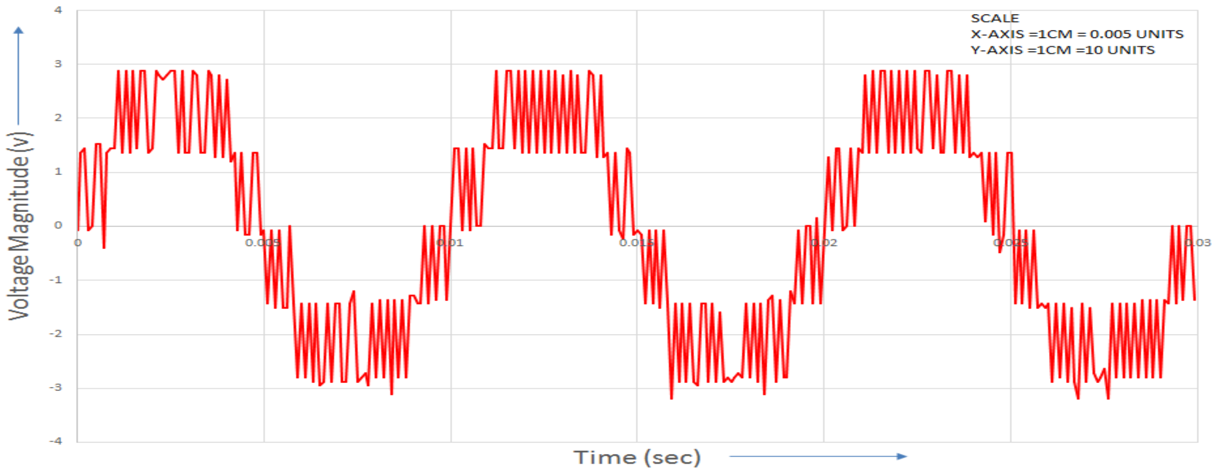



Figure 2.30: Output Voltage Waveform

(b) Leakage Current Waveform

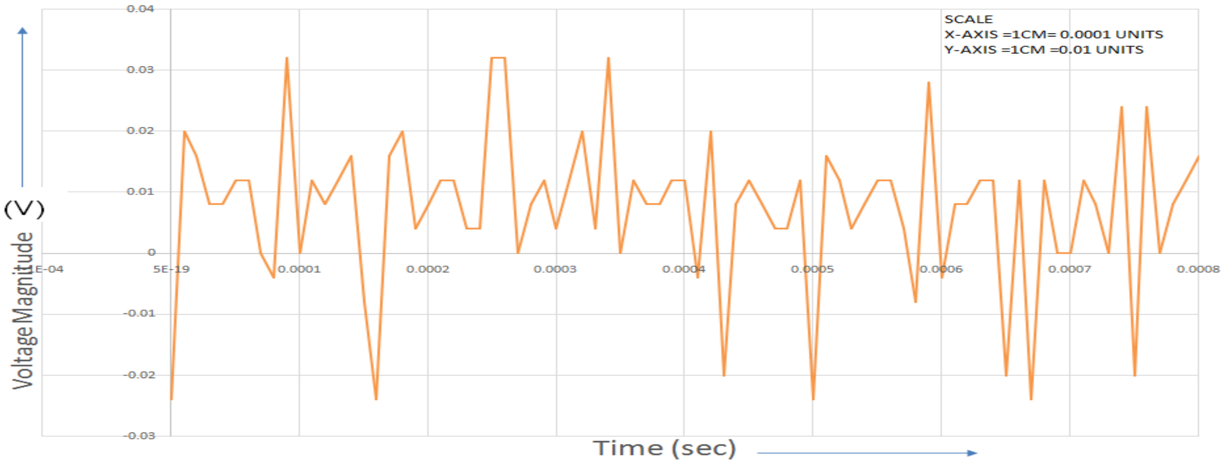



Figure 2.31: Leakage Current Waveform

The above Figures 2.30 and 2.31 shows the output voltage and leakage current waveforms of Existing Hybrid method. Since the leakage current is in milliamps.

## 2.10 HARDWARE RESULTS:

Table 2.4: Hardware Results

| **Type of Modulation** | **Output voltage** | | | **Leakage current (mA)** |
|---|---|---|---|---|
| | **RMS voltage (V)** | **Maximum Voltage (V)** | **Peak to Peak Voltage (V)** | |
| Existing Hybrid Technique [24] | 39.2 | 56 | 112 | 20 |
| **Proposed carrier overlapping technique** | **43.6** | **64** | **128** | **13** |

## 2.11 SUMMARY

The main objective of constructing a five level cascaded inverter is accomplished. The developed experimental model is found to be 20% more efficient than existing systems. Since the system is more efficient than the existing systems, the number of panels required to achieve the desired power level gets reduced. In addition COP modulation technique gives a reduced value of leakage current which increases the life of the panel and reduces the risk for humans.

# CHAPTER 3
# CONCLUSION

The present trends concerns energy security and sustainable development across the various regions of U.T. of Puducherry. The role of renewable energy has therefore become ever more significant. The developed Puducherry is already on the track for walking out from the fossil fuel era and involving mainly the areas of renewable energy technologies and energy efficiency.

In the phase I of this proposal an insight into the energy situation and renewable energy potential of U.T. of Puducherry was analyzed. It was identified that Puducherry regions has economically feasible power generation potential of wind and solar energy. Southern part of southern coastal belt and western coastal belt are very suitable for utility scale wind and solar power generation.

Using HOMER simulation software a grid tied wind-solar hybrid power generation system was modeled for a selected location in the Pondicherry Engineering College, Puducherry, located on the southern coastal belt . Through the simulation process, installation of one number of 10kW wind turbines and 0.5 KW solar PV array was identified as economically most feasible design to supply 68.1 Kwh/day average load connected to grid where good payback period of the design.

In the Phase II analysis the simulation of single phase 5 level cascaded multi level inverter has been simulated by using Phase Opposite Disposition (POD), Hybrid and Carrier Overlapping (COP) control technique. From the THD analysis it is found that the THD for the proposed COP technique are found to be less when compared with other techniques. It is concluded that the proposed COP technique provides lesser percentage of THD and reduced leakage current also it provides more fundamental output voltage MATLAB/ SIMULINK simulation environment. Thus the proposed PWM technique can be implemented for solar PV based multilevel inverter under consideration.

This research project also presented the experimental verification of a cascaded topology based multi level inverter with novel modulation strategy and to reduce the leakage current for single phase transformerless PV based inverter system.

The proposed technique minimizes the common mode voltage in multilevel inverter with fundamental switching frequency. The results of the experiment appear to be better such that common mode voltage is reduced drastically nearly $V_{dc}$ / 4 times. Whereas in existing recent topologies available in the literature like hybrid modulation technique common mode voltage is around $V_{dc}$ / 2 times. At this juncture it is realized that transformerless PV inverter strategy have been an enhanced strategy and successfully employed in distributed PV system. The proposed modulation technique uses only two carrier signals in order to generate the five level inverter output whereas in other modulation strategies it is functioning with four carrier signals. This significance leads to the requirement of lesser effort for constructing hardware and reduced cost.

In addition the developed inverter topology produces more fundamental voltage nearly 20 % when compared with the recent conventional topologies. Moreover, the output voltage waveforms is also merely sinusoidal after enabling with a LC filter across output terminals. Commercially, available inverters have been built with transformer which leads to poor efficiency, higher losses, increase in weight and more space.

For the given PV panel specification, the proposed COP technique in inverter produced more output voltage. In the test analysis for an input voltage of 48V existing Hybrid PWM technique produces around 156.51 V. Whereas, the developed COP technique produces around 179.94 V. It is found that the developed inverter topology produces nearly 20 % increased output voltage.

Therefore, on the account of large scale implementation the number of solar PV panel requirement will be less. Hence, it will also reduce the installation cost to a considerable range. In addition this inverter can be operated without transformer. In case of transformerless operation the existence of leakage current is the main issue which, is harmful to the PV installer. The proposed topology also reduces the leakage current to a considerable range and it is around 0.0010 m A.

In recent years so many efforts have been made to reduce the installation cost of solar PV based power generation system. With the advantages of the above salient features the proposed topology is very attractive for transformerless PV based inverter applications.

# REFERENCES


1. www.powergrindindia.com referred on 12.12.2015 to 30.01.2016

2. www.nrel.com referred on 12.12.2015 to 30.01.2016

3. Bhattacharya, S. C., and Jana, C., "Renewable energy in India: Historical developments and prospects,"Energy, Vol. 34, pp. 981–991, 2009.

4. P. Lilienthal; The HOMER Micropower Optimization Model; DOE Solar Energy Technologies Program Review Meeting October (2004) 25-28.

5. N.H. Baharudin, T.M.N.T. Mansur, R. Ali, Y. Yatim, A.A.A. Wahab; Optimization Design and Economic Analysis of Solar Power System with Sea Water Desalination for Remote Areas; 2011 IEEE Colloquium on Humanities, Science and Engineering Research (CHUSER 2011), Dec 5-6 2011, Penang.

6. Nathan Johnson, Peter Lilienthal, Timothy Schoechle; Modeling distributed premises-based renewables integration using HOMER; Grid Interop 2011, December 5-8, 2011, Phoenix, Arizona.

7. P.Y. Lim, C.V. Nayar; Solar Irradiance and Load Demand Forecasts in the Supervisory Control for Off-grid Hybrid Energy System; Department of Electrical and Computer Engineering. IACSIT International Journal of Engineering and Technology, Vol. 4, No. 4, August 2012,451-455.

8. Rehman S, El-Amin IM, Ahmad F, Shaahid SM, Al-Shehri AM, Bakhashwain JM, et al.Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant; Renewable and Sustainable Energy Reviews 2007;11(4):635–53.

9. Shafiuzzuman Khan Khadem; Feasibility study of Wind Home System in Coastal Region of Bangladesh; Renewable Energy Research Centre, University of Dhaka, Bangladesh. Renewable Energy 1991; 1; 855-7

10. Beluco Alexandre, de Souza Paulo Hroeff, Krenzinger Arno; A method to evaluate the effect of complementarity in time between hydro and solar energy on the performance of hybrid hydro PV generating plants; Renewable Energy 45 (2012) 24-30.

11. Mohammad Saad Alam, David W. Gao; Modeling and Analysis of a Wind/PV/Fuel Cell Hybrid Power System in HOMER; Center of Energy Systems Research, Department of Electrical and Computer Engineering, Tennessee Technological University, Cookeville, TN 38501 USA.

12. Mohamed El Badawe, Tariq Iqbal, George K. Mann; Optimization and a comparison between renewable energy systems for a telecommunication site; Memorial University of Newfoundland.

13. Nader Barsoum, Wong Yew Yiin, Tan Kwong Ling, Goh, W.C.; Modeling and Cost Simulation of Stand-alone Solar and Biomass Energy; Second Asia International Conference on Modeling & Simulation. Power and Energy Engineering Conference (APPEEC) 2011 Asia-Pacific, pp. 1-6, 2011, ISSN 2157-4847

14. Tom Lambert, Paul Gilman, Peter Lilienthal; Micropower System Modeling with HOMER. chapter 19-379-385

15. Omar Hafez, Kankar Bhattacharya; Optimal planning and design of a renewable energy based supply system for microgrids; Renewable Energy 45 (2012) 7-15.

16. Indradip Mitra, S.P. Gon Chaudhuri; Remote Village Electrification Plan through Renewable Energy in the Islands of Indian Sundarbans Journal of the Solar Energy Society of India 15(1):25-35 (2005).

17. Wichert B., Dymond M., Lwrence W. Friese T.; Development of a test facility for photo voltaic diesel hybrid energy systems; Renewable energy-2001.311-319.

18. Mahmoud M.M.; On the Storage Batteries Used in Solar Electric Power Systems and Development of an Algorithm for Determining their Ampere-Hour Capacity; Electric Power SystemsResearch 2004, 71, 85-89.

*19.* Tamil Nadu Energy Development Agency (TEDA) under the aid of Ministry of Non-Conventional Energy Sources (MNES), Government of India, available at: http://teda.in.

20. X. Guo, “A novel CH5 inverter for single-phase transformerless photovoltaic system applications,” IEEE Trans. Circuits and Systems II: Express Briefs, DOI: 10.1109/TCSII.2017.2672779.

21. L. Zhang, K. Sun, L. L. Feng, H. F. Wu, and Y. Xing, “A family of neutral point clamped full-bridge topologies for transformerless photovoltaic grid-tied inverters,” IEEE Trans. Power Electron., vol. 28, no. 2, pp. 730-739, Feb. 2013.

22. Y. Tang, W. Yao, and P. C. Loh, “Highly reliable transformerless photovoltaic inverters with leakage current and pulsating power elimination” IEEE Trans. Ind. Electron., vol. 63, no. 2, pp. 1016–1026, Feb. 2016.

23. T. Kerekes, R. Teodorescu, P. Rodríguez, G. Vázquez, and E. Aldabas “A new high-efficiency single-phase transformerless PV inverter topology,” IEEE Trans. Ind. Electron., vol. 58, no. 1, pp. 184–191, Jan.2011.

24. Rajasekar Selvamuthukumaran, Abhishek Garg, Rajesh Gupta “Hybrid Multicarrier Modulation to Reduce Leakage Current in Transformerless Cascaded Multilevel Inverter for Photovoltaic System”, IEEE Transactions on Power Electronics, Volume: 30, Issue:4,Pages: 1779 – 1783.

25. B. Yang, W. Li, Y. Gu, W. Cui and X. He, "Improved Transformerless Inverter with Common-Mode Leakage Current Elimination for a Photovoltaic Grid-Connected Power System," *IEEE Trans. Power Elect.*, vol.27, no.2, pp.752-762, Feb. 2012.

26. B. Chen, B. Gu, L. Zhang, Z.U. Zahid, J. Lai, Z. Liao and R. Hao, "A High-Efficiency MOSFET Transformerless Inverter for Non isolated Microinverter Applications," *IEEE Trans. Power Elect.*, vol.30, no.7, pp.3610-3622, July 2015.

27. Y. Zhou and H. Li, "Analysis and Suppression of Leakage Current in Cascaded-Multilevel-Inverter-Based PV Systems," *IEEE Trans. Power Elect*., vol.29, no.10, pp.5265-5277, Oct. 2014.

28. F. Hong, J. Liu, B. Ji, Y. Zhou, J. Wang and C. Wang, "Single Inductor Dual Buck Full-Bridge Inverter," *IEEE Trans. Ind. Elect.*, vol.62, no.8, pp.4869-4877, Aug. 2015.

29. O. Lopez, F.D. Freijedo, A.G. Yepes, P. F. Comesaa, J. Malvar, R. Teodorescu and J. D. Gandoy, "Eliminating Ground Current in a Transformerless Photovoltaic Application," , *IEEE Trans. Energy Conv.*, vol.25, no.1, pp.140-147, March 2010.

30. L. Zhang, K. Sun, L. Feng, H. Wu and Y. Xing, "A Family of Neutral Point Clamped Full-Bridge Topologies for Transformerless Photovoltaic Grid-Tied Inverters," *IEEE Trans. Power Elect*., vol.28, no.2, pp.730-739, Feb. 2013.

31. D. Barater, G. Buticchi, A.S. Crinto, G. Franceschini and E. Lorenzani, "Unipolar PWM Strategy for Transformerless PV Grid-Connected Converters," *IEEE Trans. Energy Conv.*, vol.27, no.4, pp.835-843, Dec. 2012.

ANNEXURES

**DATA SHEET-1**
**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

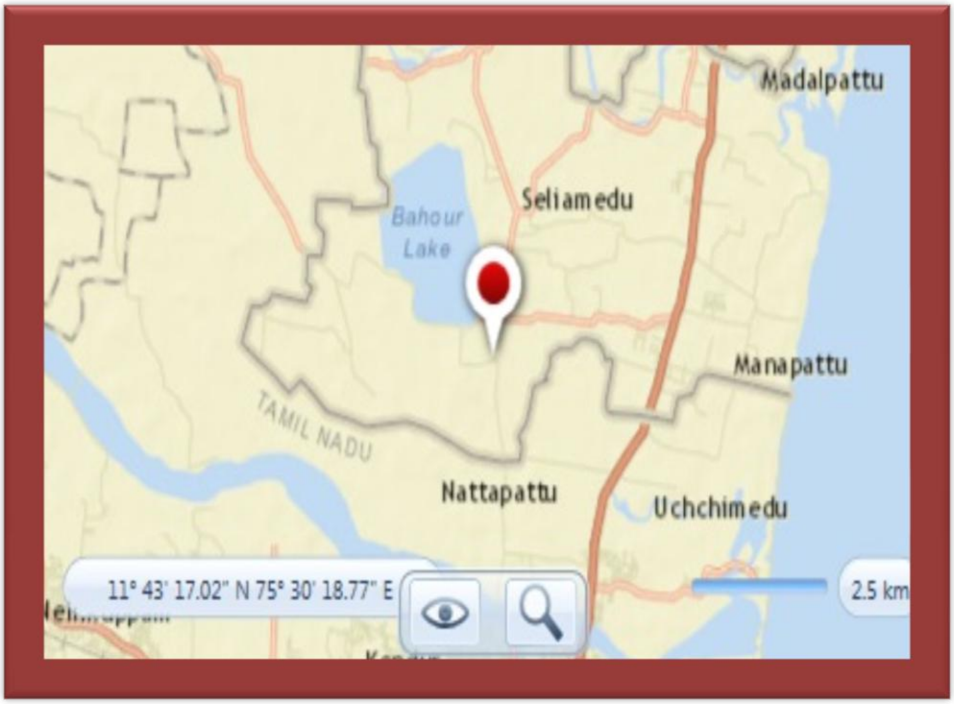
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | PUDUCHERRY |
| Name of the site | Bahour |
| Type of Renewable Resource availability | Solar, Wind, Biomass |
| Total Electrical demand of the area | MAX:38MW MIN :25.1 |

## B. Project Location :

| | |
|---|---|
| Location | 65, East St, Bahour, Puducherry 607402, India |
| Latitude | 11 degrees 48.52 minutes North |
| Longitude | 79 degrees 44.90 minutes East |
| Time zone | Asia/Kolkata |

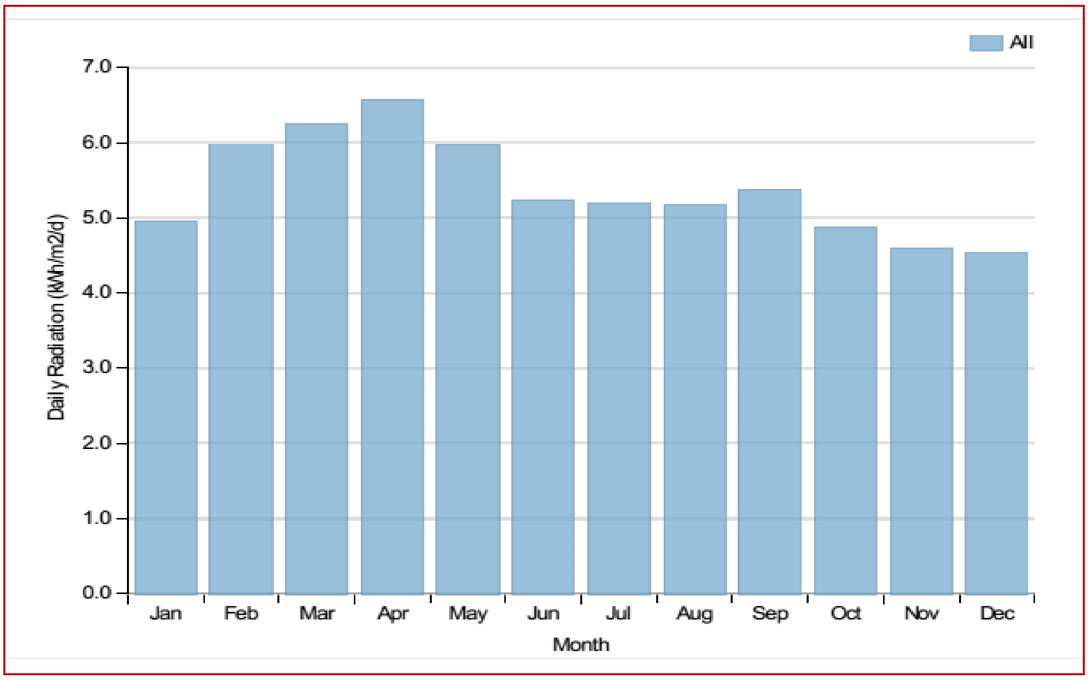
## C. Project site map



## D. Renewable Resource availability levels:

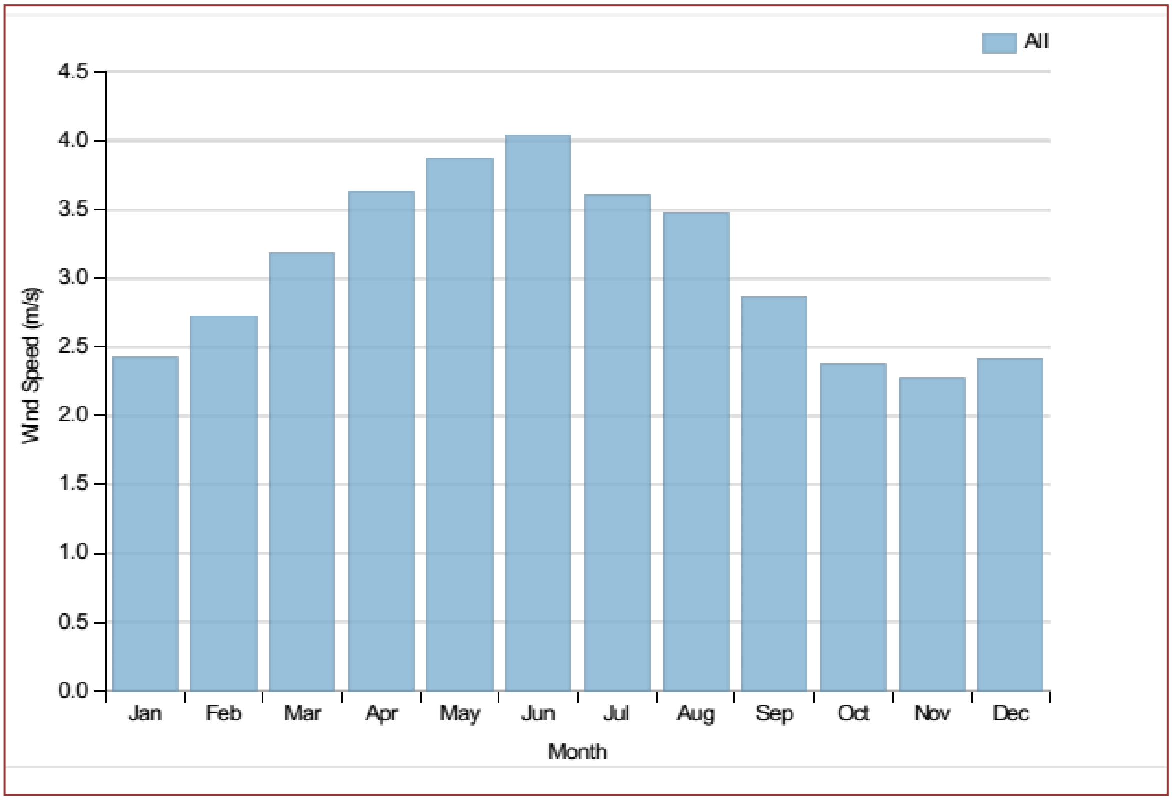
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation (KWh/m$^2$/day |
|---|---|---|
| January | 0.572 | 4.951 |
| February | 0.635 | 5.972 |
| March | 0.614 | 6.242 |
| April | 0.621 | 6.553 |
| May | 0.566 | 5.956 |
| June | 0.502 | 5.228 |
| July | 0.497 | 5.189 |
| August | 0.493 | 5.161 |
| September | 0.526 | 5.374 |
| October | 0.510 | 4.863 |
| November | 0.523 | 4.582 |
| December | 0.541 | 4.533 |
| Scaled annual average | | **5.38 kWh/m2/d** |

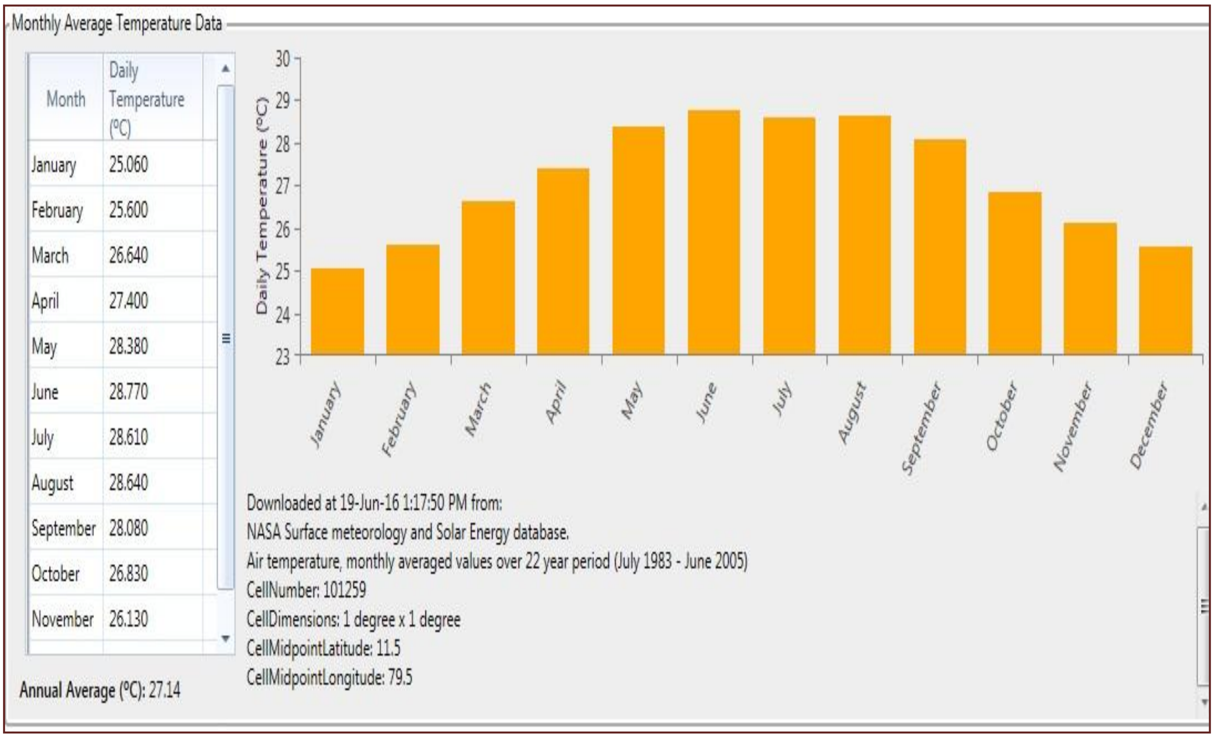


**D.2 WIND:**

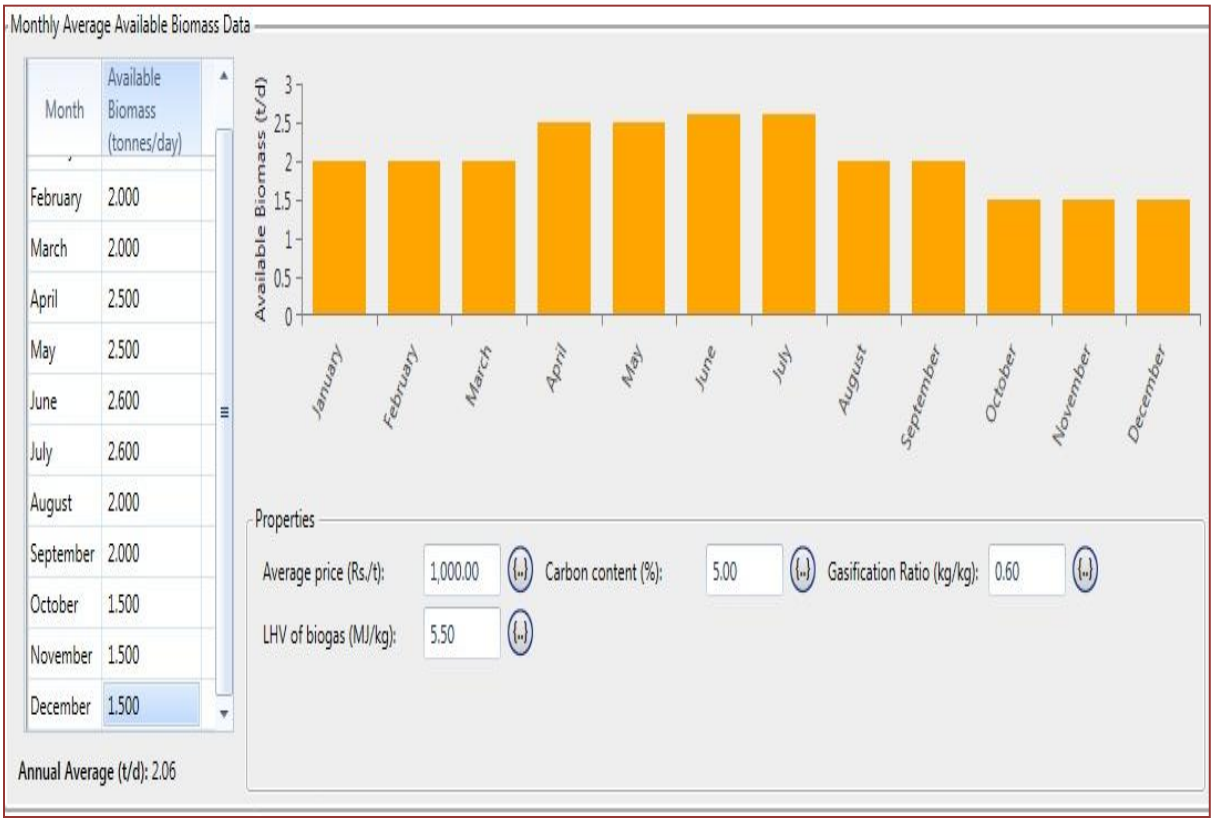
| Month | Average Wind Speed (m/s) |
|---|---|
| January | 2.420 |
| February | 2.720 |
| March | 3.170 |
| April | 3.620 |
| May | 3.860 |
| June | 4.030 |
| July | 3.600 |
| August | 3.470 |
| September | 2.850 |
| October | 2.370 |
| November | 2.270 |
| December | 2.410 |
| Scaled annual average | **3.07 m/s** |



### D.3 Temperature:




### D.4 BIOMASS:



**DATA SHEET-2**

**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

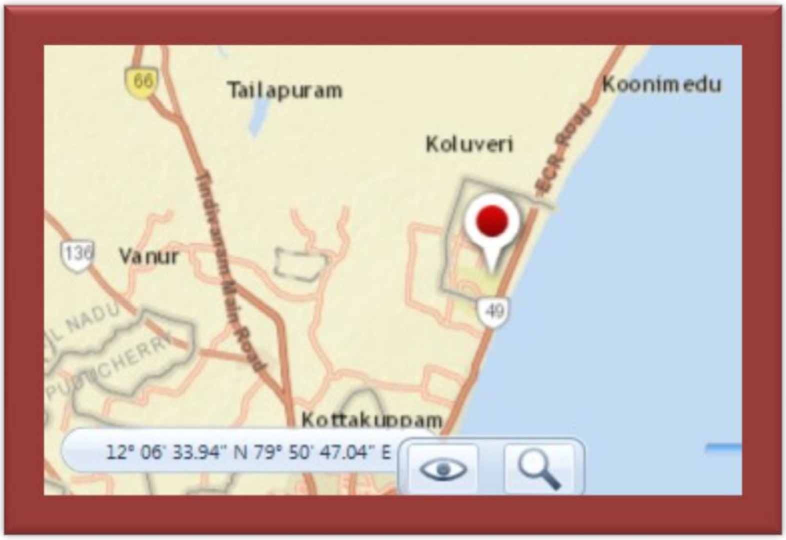
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | PUDUCHERRY |
| Name of the site | Kalapet |
| Type of Renewable Resource availability | Solar, Wind, |
| Total Electrical demand of the area | MAX:12MW MIN :7.7 |

## B. Project Location :

| | |
|---|---|
| Location | Pondicherry University, Kalapet,<br>Puducherry 605014, India |
| Latitude | 12 degrees 1.77 minutes North |
| Longitude | 79 degrees 51.46 minutes East |
| Time zone | Asia/Kolkata |

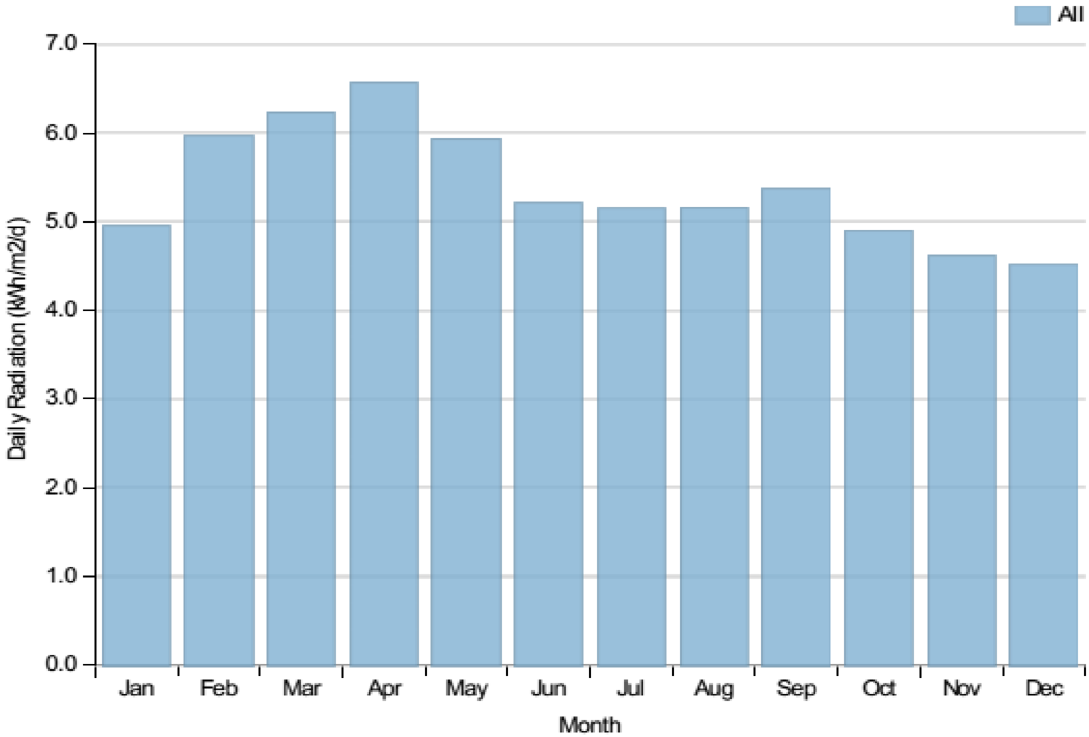
## C. Project site map



## D. Renewable Resource availability levels:

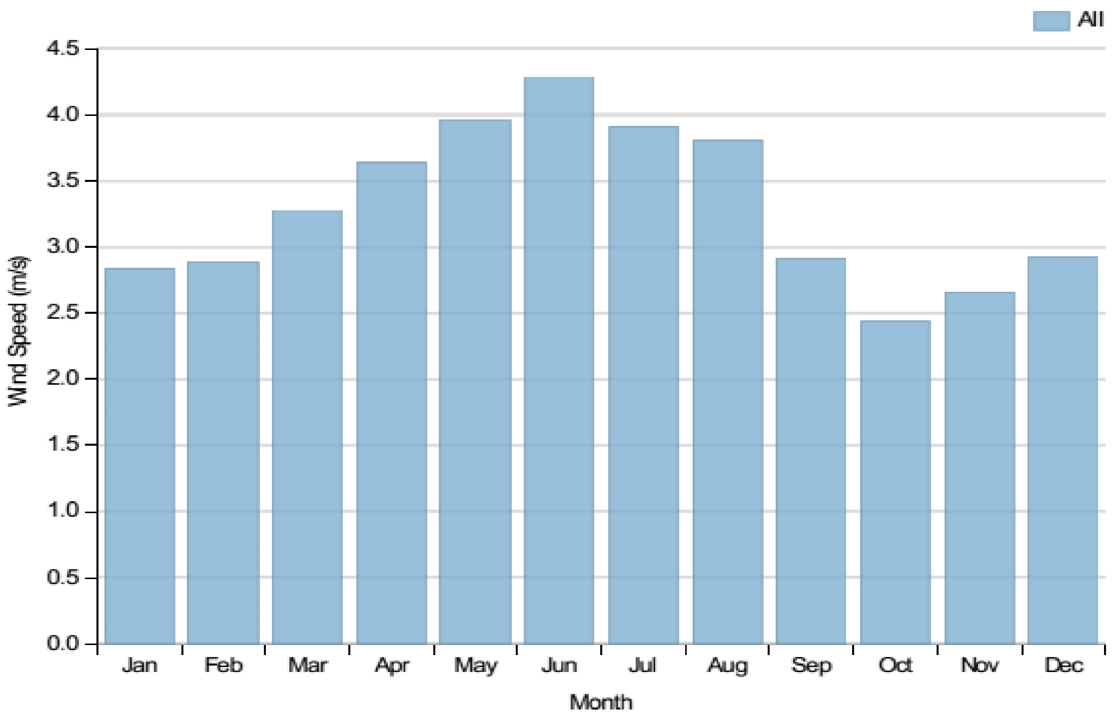
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation (KWh/m$^2$/day |
|---|---|---|
| January | 0.575 | 4.953 |
| February | 0.635 | 5.956 |
| March | 0.612 | 6.214 |
| April | 0.622 | 6.557 |
| May | 0.562 | 5.928 |
| June | 0.498 | 5.197 |
| July | 0.493 | 5.150 |
| August | 0.492 | 5.154 |
| September | 0.526 | 5.369 |
| October | 0.514 | 4.893 |
| November | 0.527 | 4.606 |
| December | 0.541 | 4.518 |
| Scaled annual average | | **5.37 kWh/m2/d** |



**D.2 WIND:**

| Month | Average Wind Speed (m/s) |
|---|---|
| January | 2.830 |
| February | 2.880 |
| March | 3.270 |
| April | 3.630 |
| May | 3.950 |
| June | 4.280 |
| July | 3.900 |
| August | 3.800 |
| September | 2.910 |
| October | 2.430 |
| November | 2.650 |
| December | 2.920 |
| Scaled annual average | **3.29 m/s** |

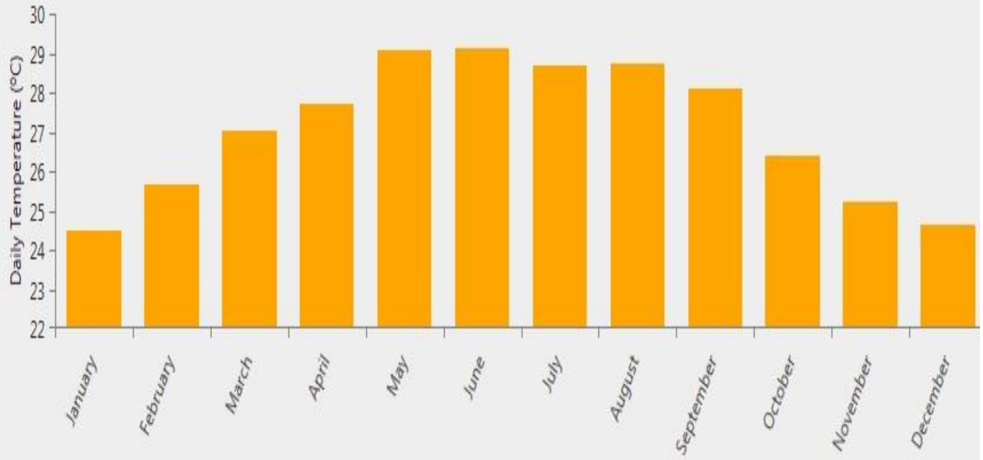


## D.3 Temperature:

Monthly Average Temperature Data

| Month | Daily Temperature (ºC) |
|---|---|
| January | 24.490 |
| February | 25.640 |
| March | 27.030 |
| April | 27.730 |
| May | 29.050 |
| June | 29.130 |
| July | 28.670 |
| August | 28.740 |
| September | 28.110 |
| October | 26.410 |
| November | 25.220 |

Annual Average (ºC): 27.07




Downloaded at 19-Jun-16 4:07:18 PM from:
NASA Surface meteorology and Solar Energy database.
Air temperature, monthly averaged values over 22 year period (July 1983 - June 2005)
CellNumber: 102259
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 12.5
CellMidpointLongitude: 79.5

**DATA SHEET-3**

**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

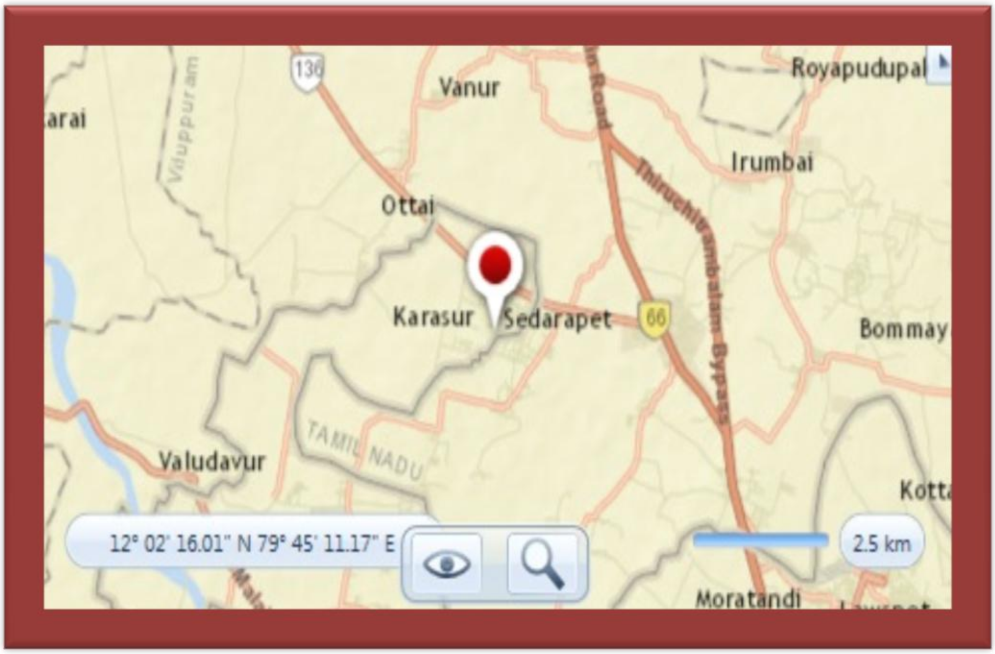
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | PUDUCHERRY |
| Name of the site | Villiyanur |
| Type of Renewable Resource availability | Solar, Wind, Hydrokinetic |
| Total Electrical demand of the area | MAX:21.8MW MIN :17.5 |

## B. Project Location :

| | |
|---|---|
| Location | Industrial Street, Sedarapet,<br>Puducherry 605111, India |
| Latitude | 12 degrees 0.01 minutes North |
| Longitude | 79 degrees 44.90 minutes East |
| Time zone | Asia/Kolkata |

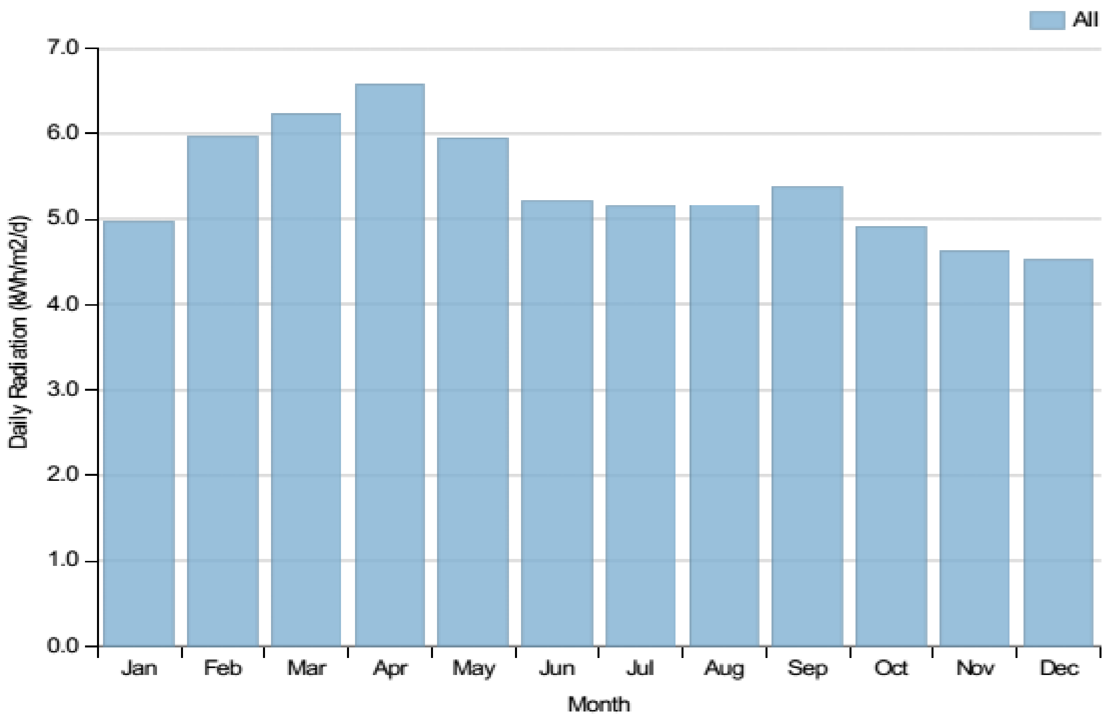
## C. Project site map



## D. Renewable Resource availability levels:

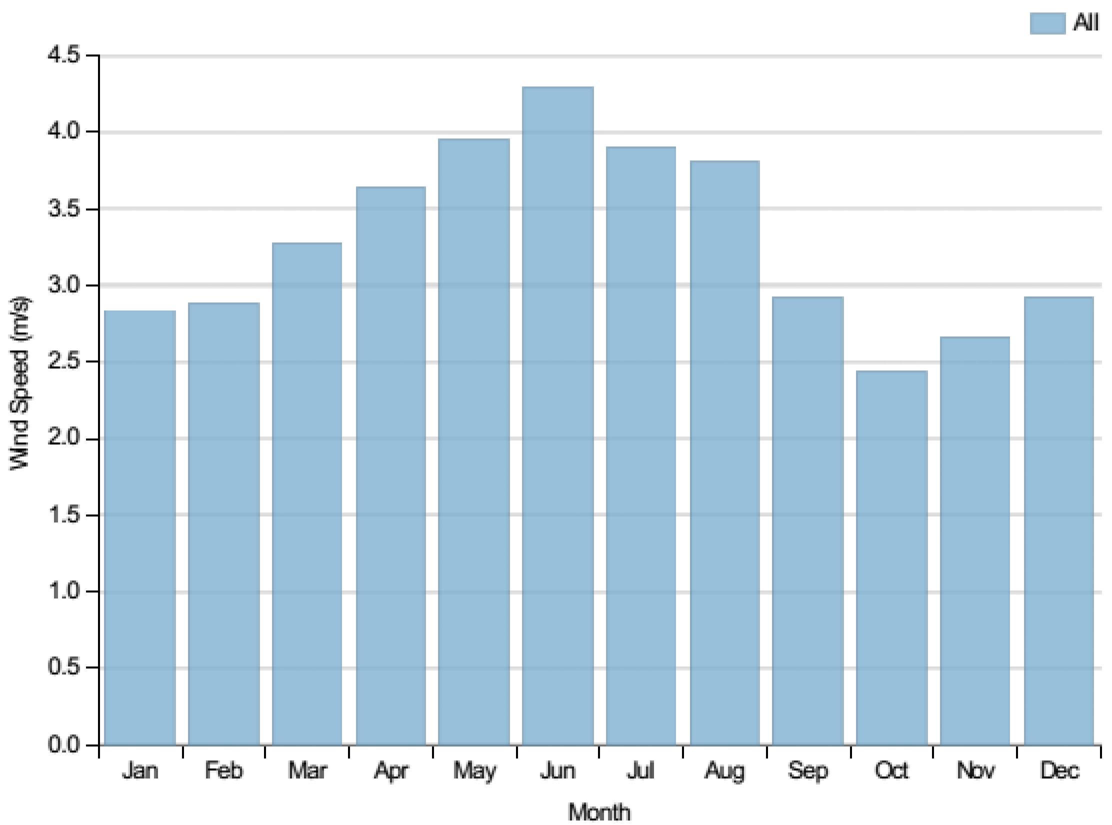
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation (KWh/$m^2$/day |
|---|---|---|
| January | 0.574 | 4.953 |
| February | 0.635 | 5.956 |
| March | 0.612 | 6.214 |
| April | 0.622 | 6.557 |
| May | 0.562 | 5.928 |
| June | 0.498 | 5.197 |
| July | 0.493 | 5.150 |
| August | 0.492 | 5.154 |
| September | 0.526 | 5.369 |
| October | 0.514 | 4.893 |
| November | 0.527 | 4.606 |
| December | 0.541 | 4.518 |
| Scaled annual average | | **5.37 kWh/m2/d** |



## D.2 WIND:

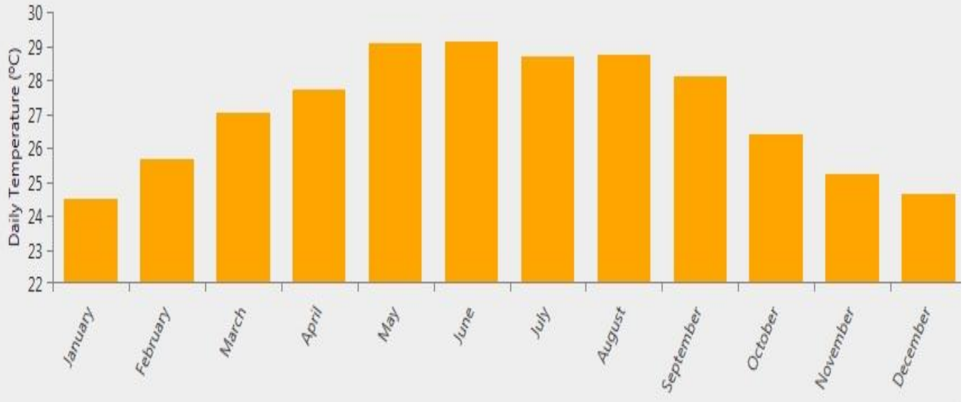
| Month | Average Wind Speed (m/s) |
|---|---|
| January | 2.830 |
| February | 2.880 |
| March | 3.270 |
| April | 3.630 |
| May | 3.950 |
| June | 4.280 |
| July | 3.900 |
| August | 3.800 |
| September | 2.910 |
| October | 2.430 |
| November | 2.650 |
| December | 2.920 |
| Scaled annual average | **3.29 m/s** |



## D.3 Temperature:

Monthly Average Temperature Data

| Month | Daily Temperature (ºC) |
|---|---|
| January | 24.490 |
| February | 25.640 |
| March | 27.030 |
| April | 27.730 |
| May | 29.050 |
| June | 29.130 |
| July | 28.670 |
| August | 28.740 |
| September | 28.110 |
| October | 26.410 |
| November | 25.220 |



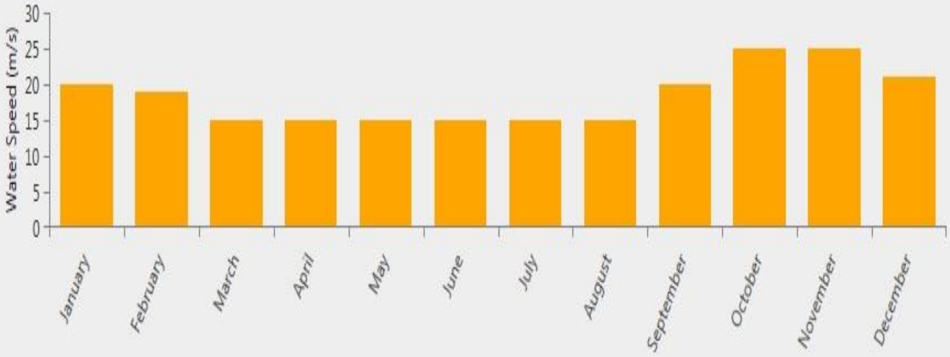

Downloaded at 19-Jun-16 4:13:54 PM from:
NASA Surface meteorology and Solar Energy database.
Air temperature, monthly averaged values over 22 year period (July 1983 - June 2005)
CellNumber: 102259
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 12.5
CellMidpointLongitude: 79.5

Annual Average (ºC): 27.07

## D.4 Hydrokinetic:

Monthly Average Water Speed Data

| Month | Water Speed (m/s) |
|---|---|
| January | 20.000 |
| February | 19.000 |
| March | 15.000 |
| April | 15.000 |
| May | 15.000 |
| June | 15.000 |
| July | 15.000 |
| August | 15.000 |
| September | 20.000 |
| October | 25.000 |
| November | 25.000 |
| December | 21.000 |




Annual Average (m/s): 18.33

**DATA SHEET-4**

**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

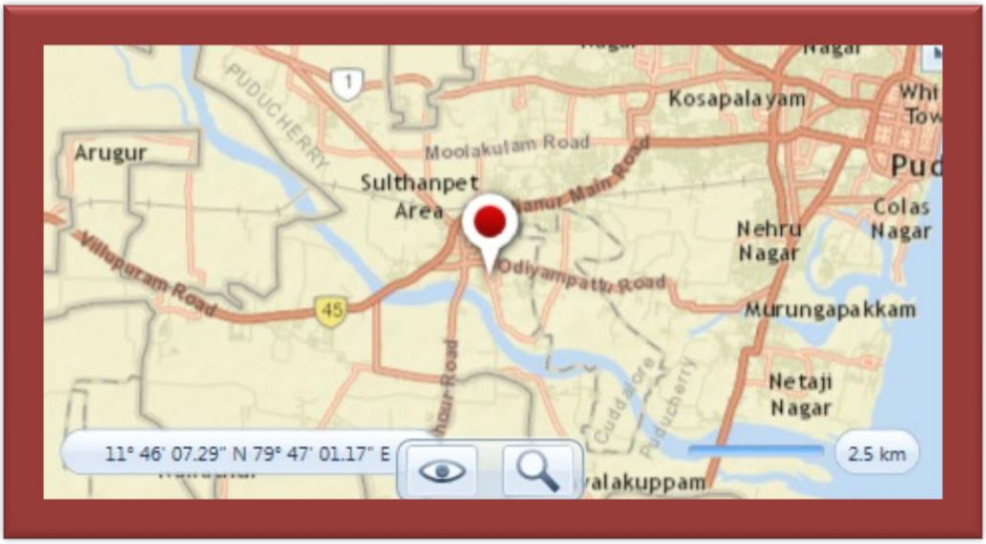
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | PUDUCHERRY |
| Name of the site | sedarapet |
| Type of Renewable Resource availability | Solar, Wind, |
| Total Electrical demand of the area | MAX:31.8MW MIN :26.2 |

## B. Project Location :

| | |
|---|---|
| Location | Kappakara Street, Villianur,<br>Puducherry 605110, India |
| Latitude | 11 degrees 54.53 minutes North |
| Longitude | 79 degrees 45.54 minutes East |
| Time zone | Asia/Kolkata |

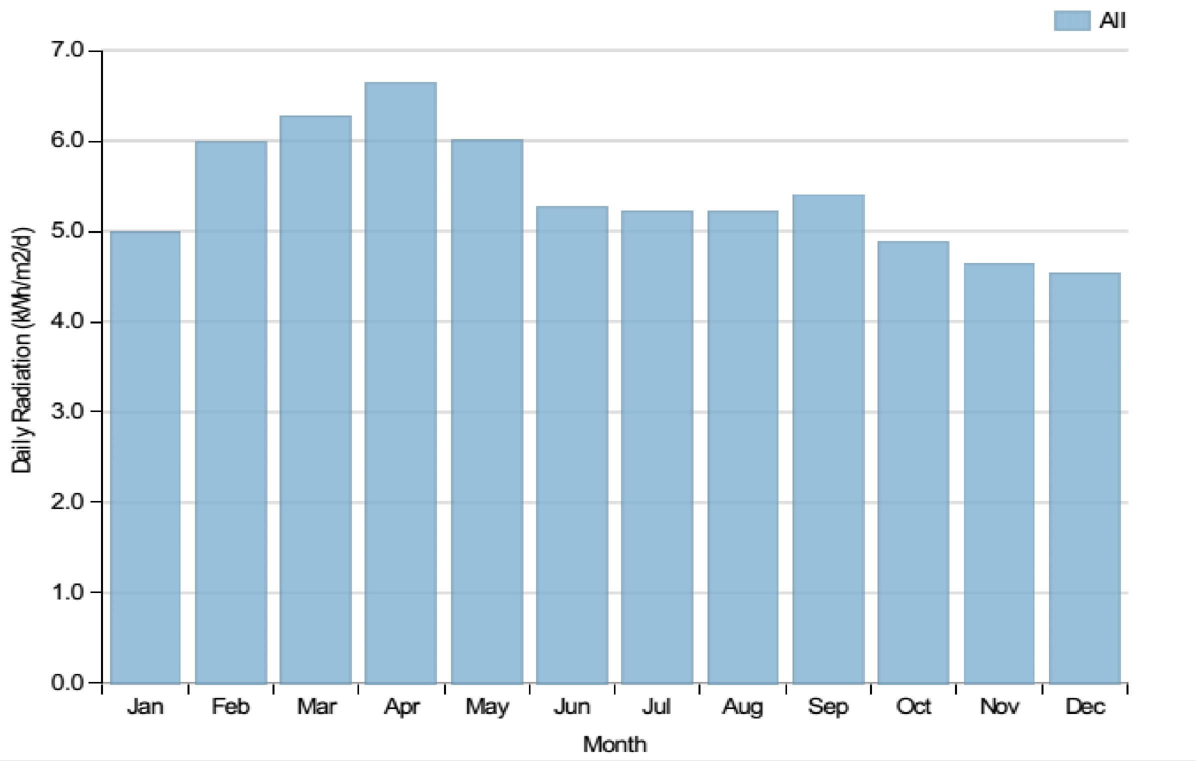
## C. Project site map



## D. Renewable Resource availability levels:

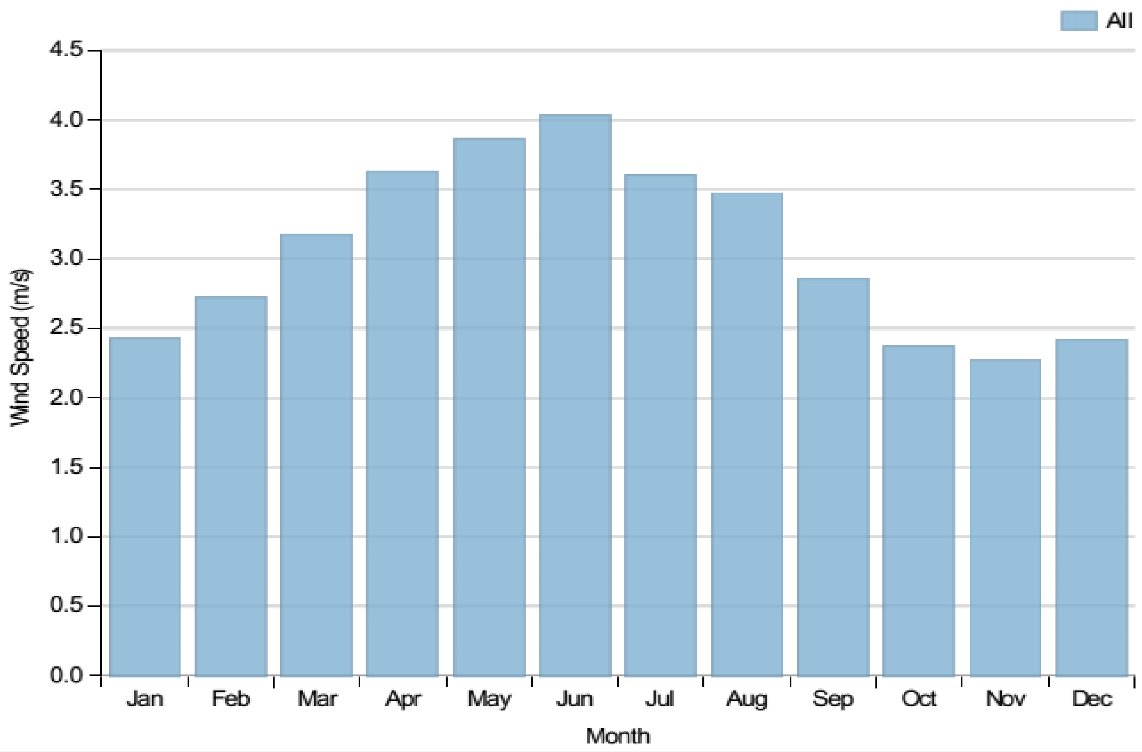
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation (KWh/$m^2$/day |
|---|---|---|
| January | 0.577 | 4.982 |
| February | 0.637 | 5.979 |
| March | 0.616 | 6.261 |
| April | 0.629 | 6.637 |
| May | 0.569 | 5.996 |
| June | 0.505 | 5.265 |
| July | 0.499 | 5.213 |
| August | 0.498 | 5.212 |
| September | 0.528 | 5.395 |
| October | 0.512 | 4.877 |
| November | 0.530 | 4.638 |
| December | 0.541 | 4.526 |
| Scaled annual average | | **5.42 kWh/m2/d** |

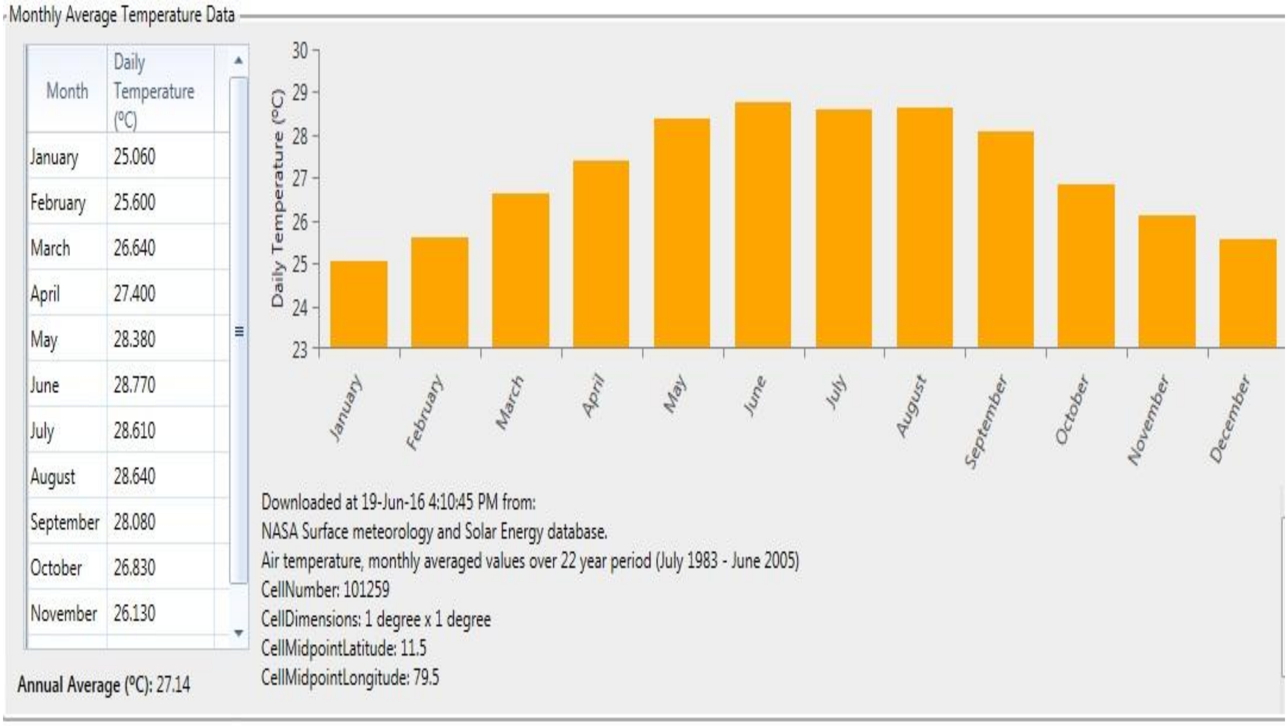


**D.2 <u>WIND:</u>**

| Month | Average Wind Speed (m/s) |
|---|---|
| January | 2.420 |
| February | 2.720 |
| March | 3.170 |
| April | 3.620 |
| May | 3.860 |
| June | 4.030 |
| July | 3.600 |
| August | 3.470 |
| September | 2.850 |
| October | 2.370 |
| November | 2.270 |
| December | 2.410 |
| Scaled annual average | **3.07 m/s** |



## D.3 Temperature:


Monthly Average Temperature Data

| Month | Daily Temperature (ºC) |
|---|---|
| January | 25.060 |
| February | 25.600 |
| March | 26.640 |
| April | 27.400 |
| May | 28.380 |
| June | 28.770 |
| July | 28.610 |
| August | 28.640 |
| September | 28.080 |
| October | 26.830 |
| November | 26.130 |

Annual Average (ºC): 27.14

**DATA SHEET-5**

**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

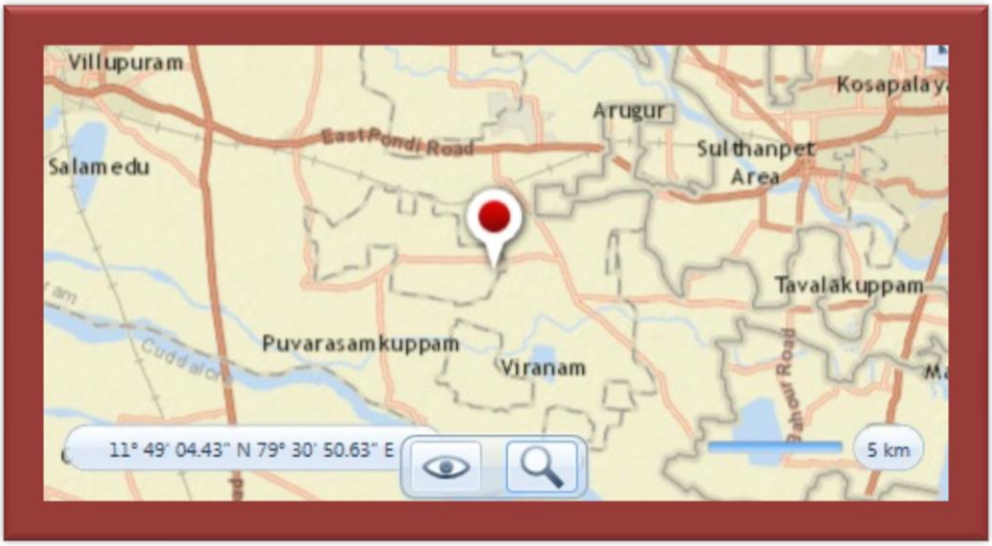
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | PUDUCHERRY |
| Name of the site | Eripakkam |
| Type of Renewable Resource availability | Solar, Wind, |
| Total Electrical demand of the area | MAX:39.4MW MIN :28.1 |

## B. Project Location :

| | |
|---|---|
| Location | Main road , Eripakkam,<br>Puducherry 605106, India |
| Latitude | 11 degrees 52.69 minutes North |
| Longitude | 79 degrees 38.84 minutes East |
| Time zone | Asia/Kolkata |

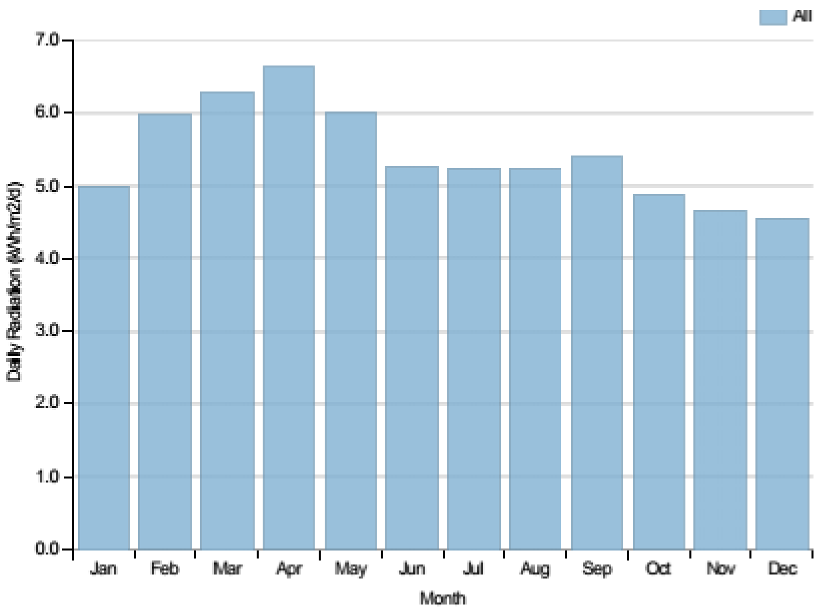
## C. Project site map



## D. Renewable Resource availability levels:

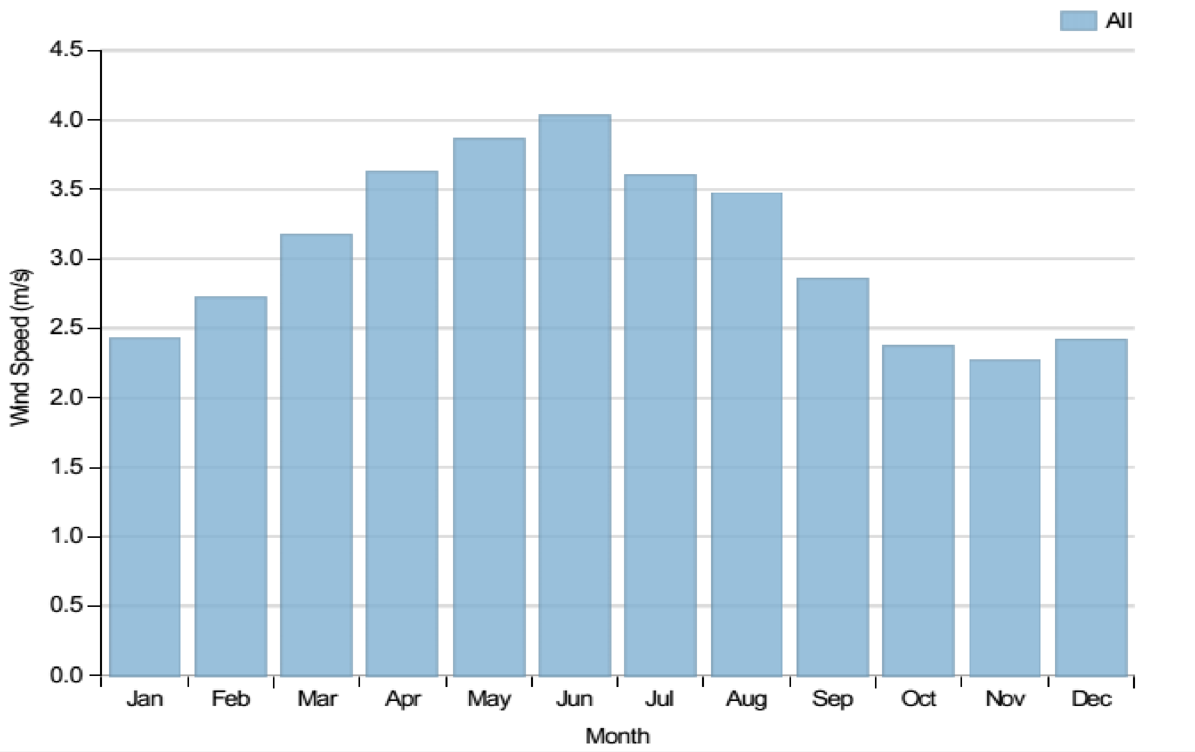
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation (KWh/m$^2$/day |
|---|---|---|
| January | 0.577 | 4.982 |
| February | 0.636 | 5.979 |
| March | 0.616 | 6.261 |
| April | 0.629 | 6.637 |
| May | 0.569 | 5.996 |
| June | 0.505 | 5.265 |
| July | 0.499 | 5.213 |
| August | 0.498 | 5.212 |
| September | 0.528 | 5.395 |
| October | 0.511 | 4.877 |
| November | 0.530 | 4.638 |
| December | 0.541 | 4.526 |
| Scaled annual average | | **5.42 kWh/m2/d** |



**D.2 <u>WIND:</u>**

| Month | Average Wind Speed (m/s) |
|---|---|
| January | 2.420 |
| February | 2.720 |
| March | 3.170 |
| April | 3.620 |
| May | 3.860 |
| June | 4.030 |
| July | 3.600 |
| August | 3.470 |
| September | 2.850 |
| October | 2.370 |
| November | 2.270 |
| December | 2.410 |
| Scaled annual average | **3.07 m/s** |

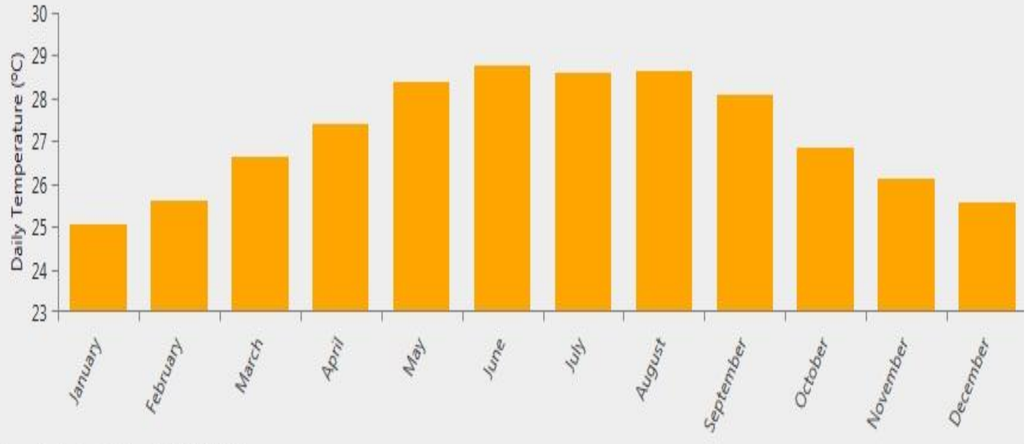


## D.3 Temperature:

Monthly Average Temperature Data

| Month | Daily Temperature (ºC) |
|---|---|
| January | 25.060 |
| February | 25.600 |
| March | 26.640 |
| April | 27.400 |
| May | 28.380 |
| June | 28.770 |
| July | 28.610 |
| August | 28.640 |
| September | 28.080 |
| October | 26.830 |
| November | 26.130 |

Annual Average (ºC): 27.14




Downloaded at 19-Jun-16 4:10:45 PM from:
NASA Surface meteorology and Solar Energy database.
Air temperature, monthly averaged values over 22 year period (July 1983 - June 2005)
CellNumber: 101259
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 11.5
CellMidpointLongitude: 79.5

**DATA SHEET-6**
**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

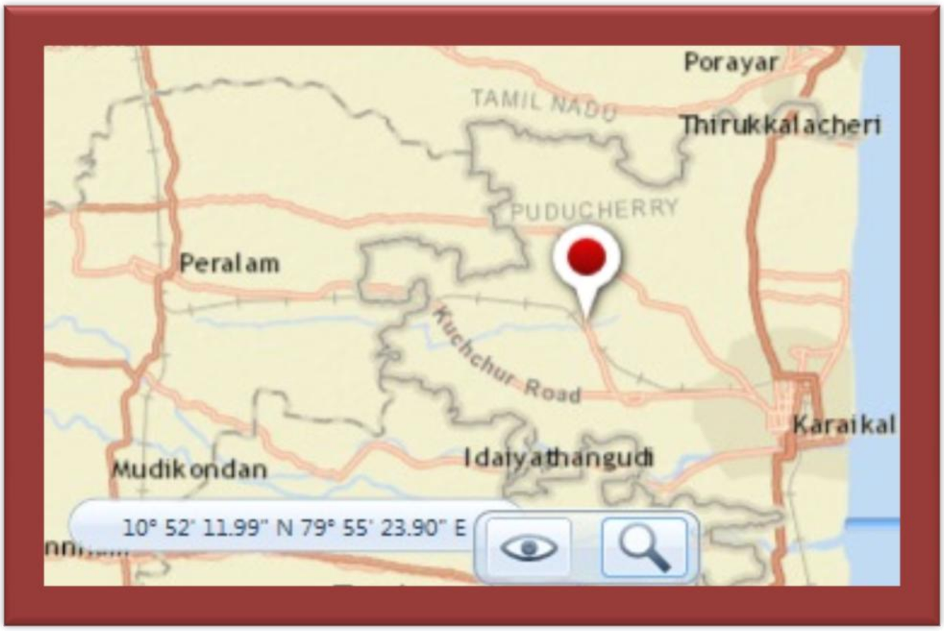
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | KRAIKAL |
| Name of the site | Sorakudi |
| Type of Renewable Resource availability | Solar, Wind, Biomass |
| Total Electrical demand of the area | MAX:32.15MW MIN :25.5 |

## B. Project Location :

| | |
|---|---|
| Location | Main road, Sorakudi, Puducherry 609603, India |
| Latitude | 10 degrees 56.94 minutes North |
| Longitude | 79 degrees 46.66 minutes East |
| Time zone | Asia/Kolkata |

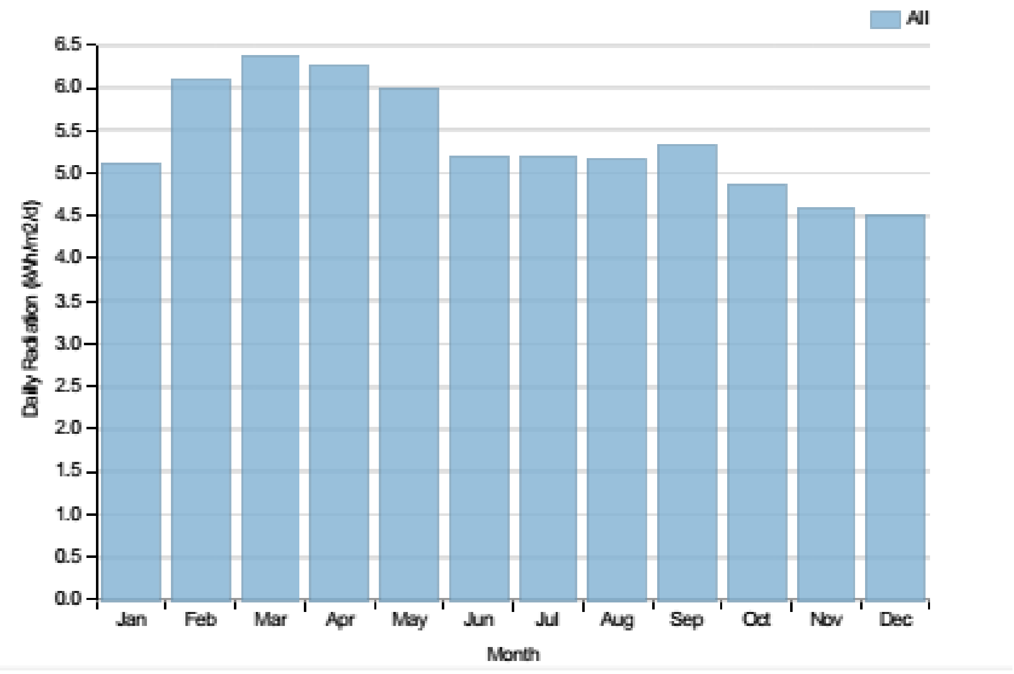
## C. Project site map



## D. Renewable Resource availability levels:

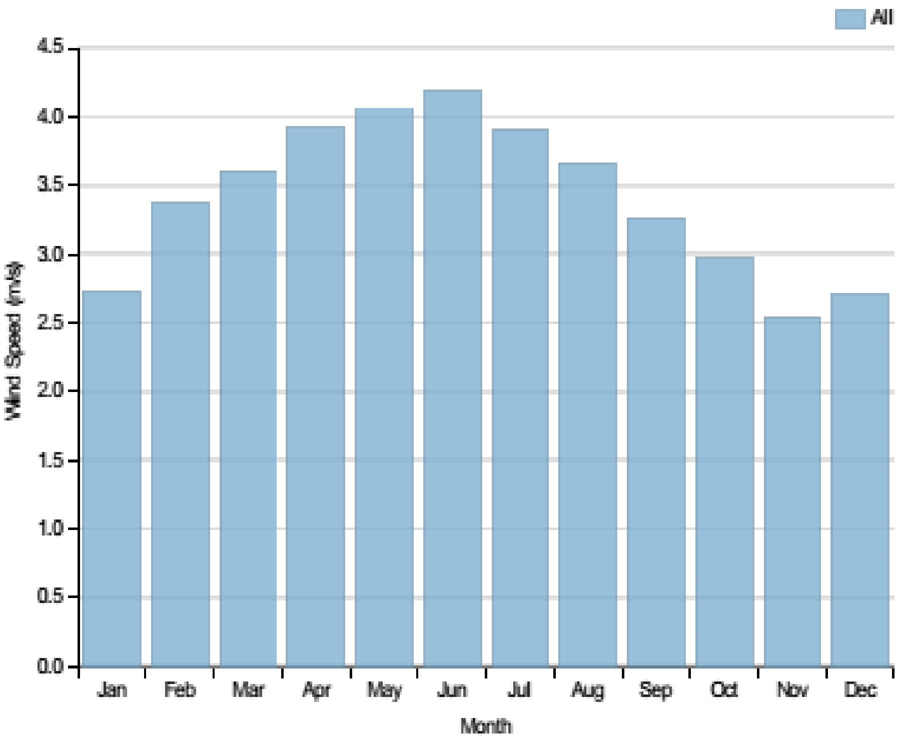
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation ($KWh/m^2/day$) |
|---|---|---|
| January | 0.581 | 5.087 |
| February | 0.642 | 6.090 |
| March | 0.623 | 6.361 |
| April | 0.592 | 6.240 |
| May | 0.570 | 5.974 |
| June | 0.500 | 5.173 |
| July | 0.500 | 5.185 |
| August | 0.493 | 5.151 |
| September | 0.519 | 5.317 |
| October | 0.505 | 4.852 |
| November | 0.516 | 4.578 |
| December | 0.528 | 4.490 |
| Scaled annual average | | **5.37 kWh/m2/d** |

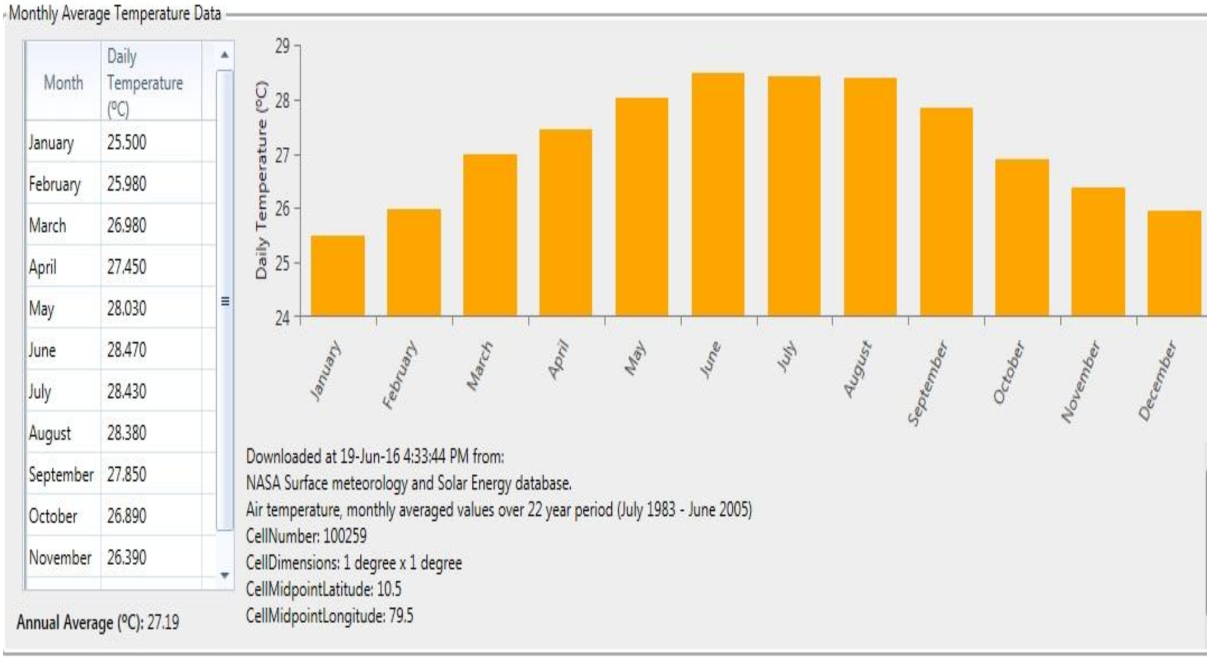


## D.2 WIND:

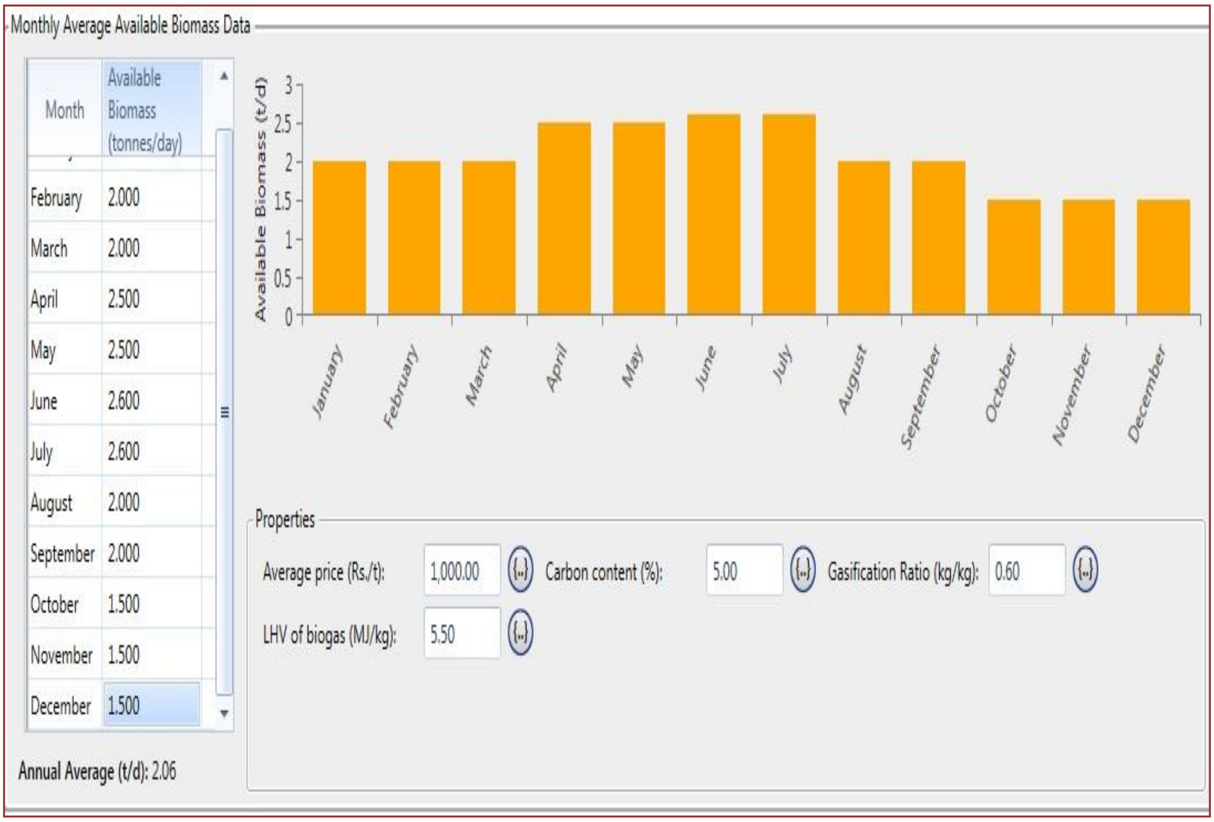
| Month | Average Wind Speed (m/s) |
|---|---|
| January | 2.730 |
| February | 3.370 |
| March | 3.600 |
| April | 3.910 |
| May | 4.060 |
| June | 4.180 |
| July | 3.900 |
| August | 3.660 |
| September | 3.250 |
| October | 2.960 |
| November | 2.530 |
| December | 2.700 |
| Scaled annual average | **3.40 m/s** |



## D.3 Temperature:




## D.4 BIOMASS:



**DATA SHEET-7**

**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

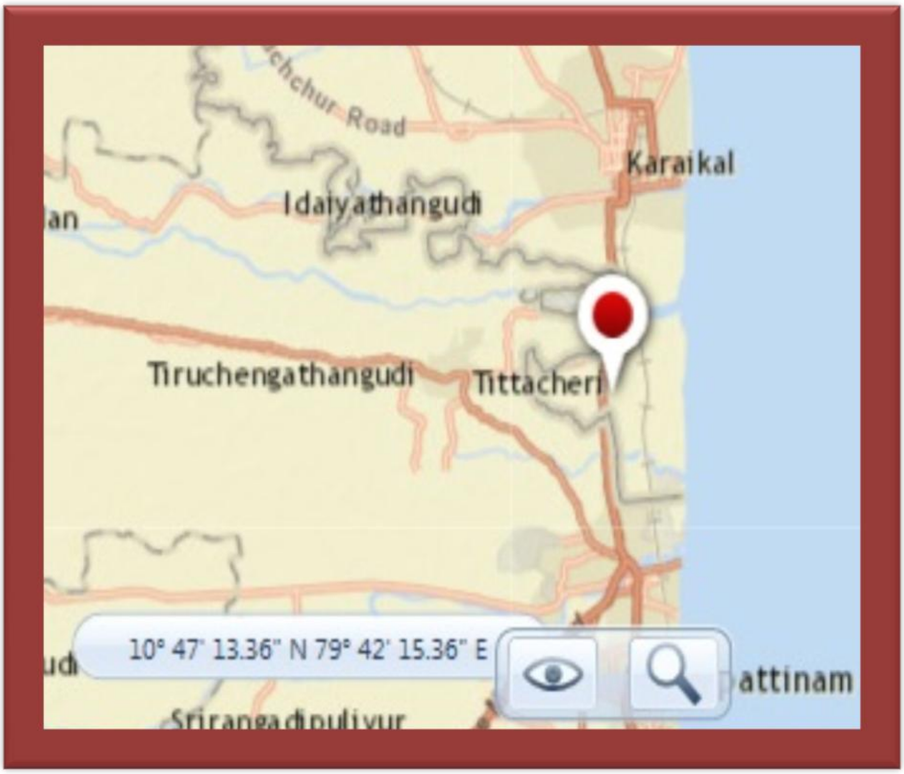
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | KRAIKAL |
| Name of the site | TR Pattinam |
| Type of Renewable Resource availability | Solar, Wind, |
| Total Electrical demand of the area | MAX:31.9MW MIN :15.8 |

## B. Project Location :

| | |
|---|---|
| Location | Vadam Poki St,Polagam, Tirumalairayanpattinam, Puducherry 609603, India |
| Latitude | 10 degrees 51.92 minutes North |
| Longitude | 79 degrees 46.95 minutes East |
| Time zone | Asia/Kolkata |

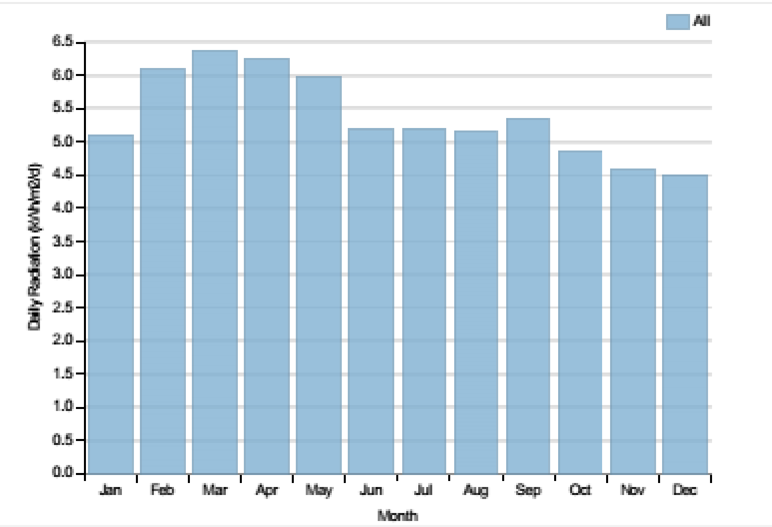
## C. Project site map



## D. Renewable Resource availability levels:

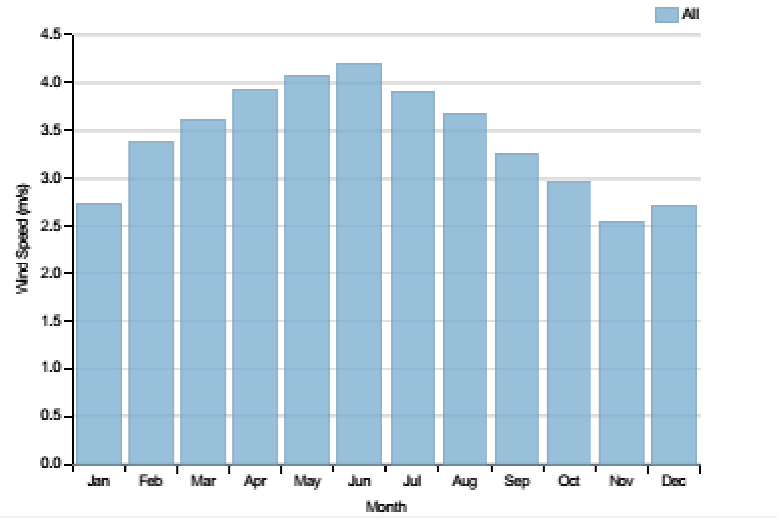
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation ($KWh/m^2/day$) |
|---|---|---|
| January | 0.580 | 5.087 |
| February | 0.641 | 6.090 |
| March | 0.623 | 6.361 |
| April | 0.592 | 6.240 |
| May | 0.571 | 5.974 |
| June | 0.500 | 5.173 |
| July | 0.500 | 5.185 |
| August | 0.493 | 5.151 |
| September | 0.519 | 5.317 |
| October | 0.504 | 4.852 |
| November | 0.515 | 4.578 |
| December | 0.528 | 4.490 |
| Scaled annual average | | **5.37 kWh/m2/d** |



## D.2 WIND:

| Month | Average Wind Speed (m/s) |
|---|---|
| January | 2.730 |
| February | 3.370 |
| March | 3.600 |
| April | 3.910 |
| May | 4.060 |
| June | 4.180 |
| July | 3.900 |
| August | 3.660 |
| September | 3.250 |
| October | 2.960 |
| November | 2.530 |
| December | 2.700 |
| Scaled annual average | **3.40 m/s** |

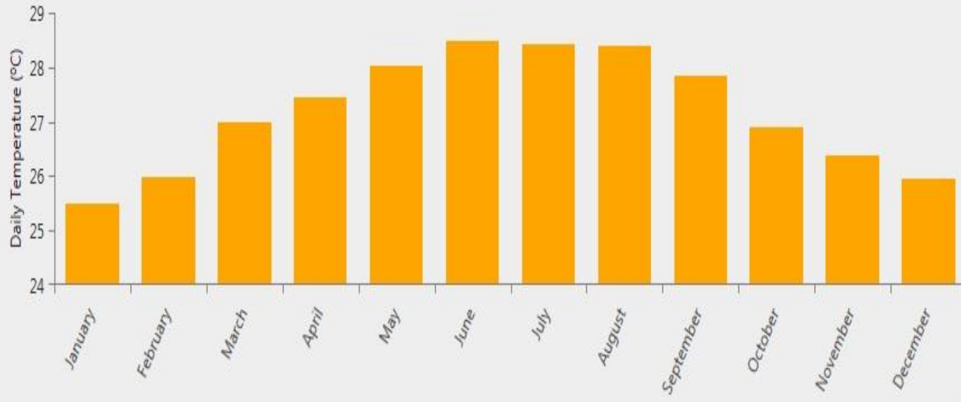


## D.3 Temperature:

Monthly Average Temperature Data

| Month | Daily Temperature (ºC) |
|---|---|
| January | 25.500 |
| February | 25.980 |
| March | 26.980 |
| April | 27.450 |
| May | 28.030 |
| June | 28.470 |
| July | 28.430 |
| August | 28.380 |
| September | 27.850 |
| October | 26.890 |
| November | 26.390 |

Annual Average (ºC): 27.19




Downloaded at 19-Jun-16 4:33:44 PM from:
NASA Surface meteorology and Solar Energy database.
Air temperature, monthly averaged values over 22 year period (July 1983 - June 2005)
CellNumber: 100259
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 10.5
CellMidpointLongitude: 79.5

**DATA SHEET-8**

**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

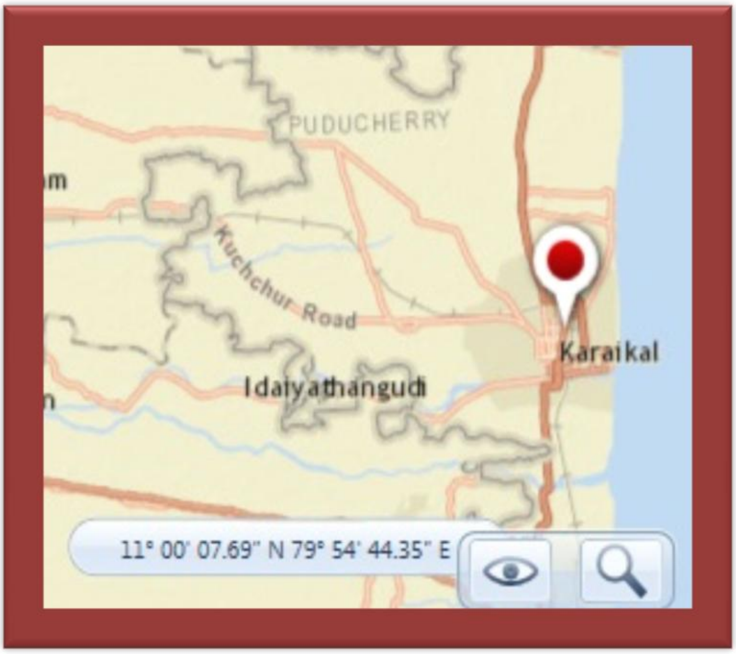
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | KRAIKAL |
| Name of the site | Pillaitheruvasal |
| Type of Renewable Resource availability | Solar, Wind, |
| Total Electrical demand of the area | MAX:15.8MW MIN :10.8 |

## B. Project Location :

| | |
|---|---|
| Location | French Teacher st,Karaikal, Puducherry 609603, India |
| Latitude | 10 degrees 55.52 minutes North |
| Longitude | 79 degrees 50.28 minutes East |
| Time zone | Asia/Kolkata |

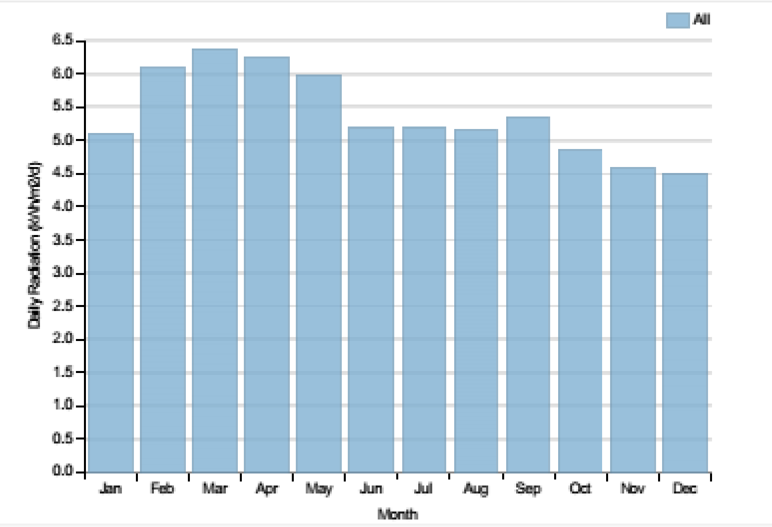
## C. Project site map



## D. Renewable Resource availability levels:

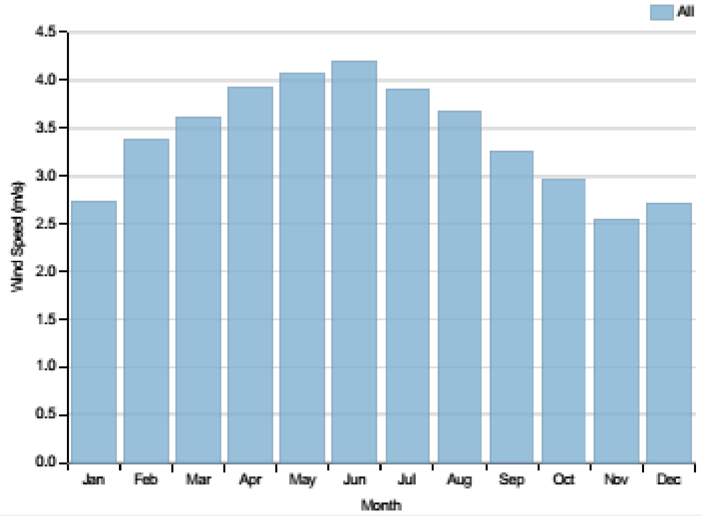
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation (KWh/m$^2$/day |
|---|---|---|
| January | 0.580 | 5.087 |
| February | 0.642 | 6.090 |
| March | 0.623 | 6.361 |
| April | 0.592 | 6.240 |
| May | 0.570 | 5.974 |
| June | 0.500 | 5.173 |
| July | 0.500 | 5.185 |
| August | 0.493 | 5.151 |
| September | 0.519 | 5.317 |
| October | 0.505 | 4.852 |
| November | 0.516 | 4.578 |
| December | 0.528 | 4.490 |
| Scaled annual average | | **5.37 kWh/m2/d** |

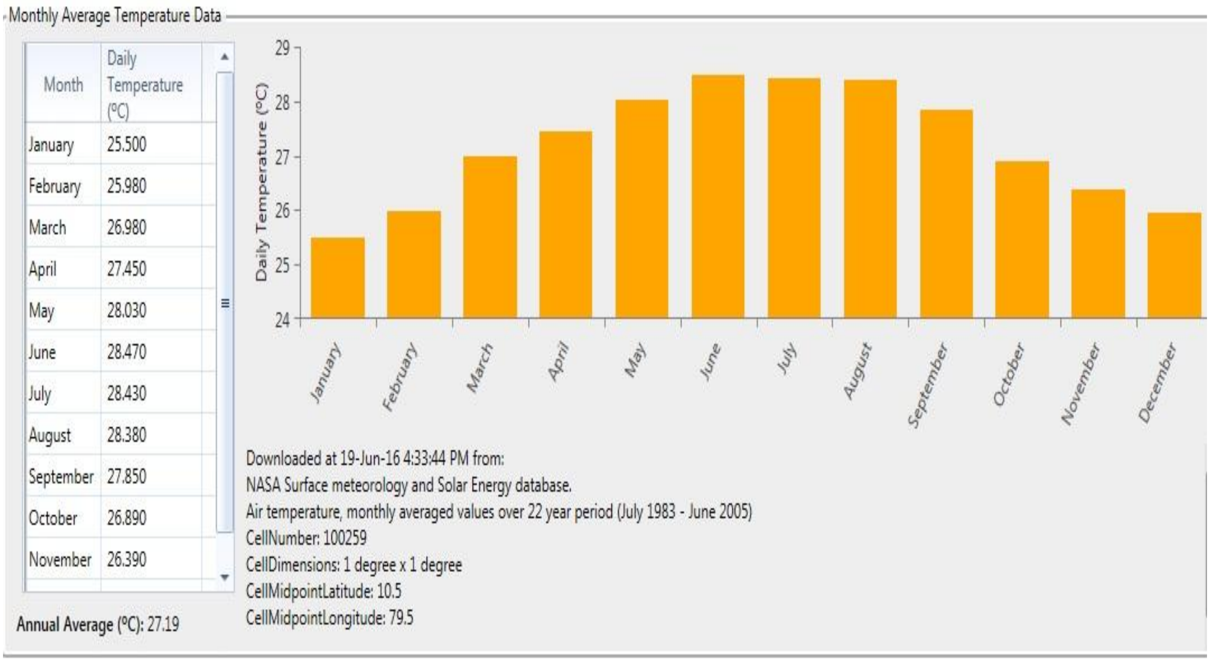


## D.2 WIND:

| Month | Average Wind Speed (m/s) |
|---|---|
| January | 2.730 |
| February | 3.370 |
| March | 3.600 |
| April | 3.910 |
| May | 4.060 |
| June | 4.180 |
| July | 3.900 |
| August | 3.660 |
| September | 3.250 |
| October | 2.960 |
| November | 2.530 |
| December | 2.700 |
| Scaled annual average | **3.40 m/s** |



## D.3 Temperature:



**DATA SHEET-9**

**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

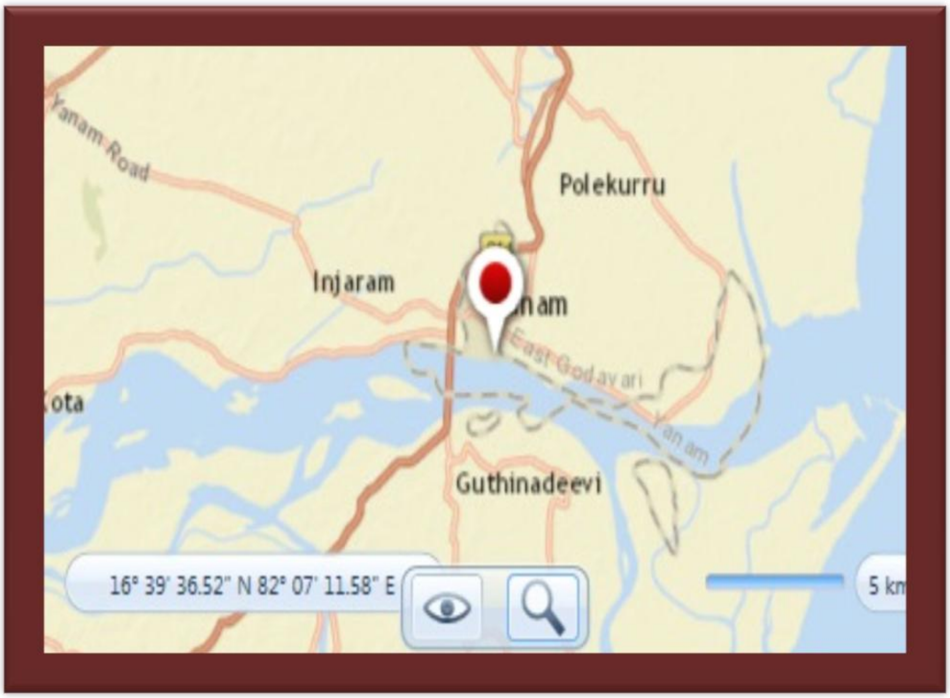
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | Yanam |
| Name of the site | Dariyalathippa |
| Type of Renewable Resource availability | Solar, Wind,Hydrokinetic |
| Total Electrical demand of the area | MAX:23 MW MIN :9 |

## B. Project Location :

| | |
|---|---|
| Location | RIT Road,Dariyalatppa,Yanam<br>Puducherry 533464, India |
| Latitude | 16 degrees 43.63 minutes North |
| Longitude | 82 degrees 13.05 minutes East |
| Time zone | Asia/Kolkata |

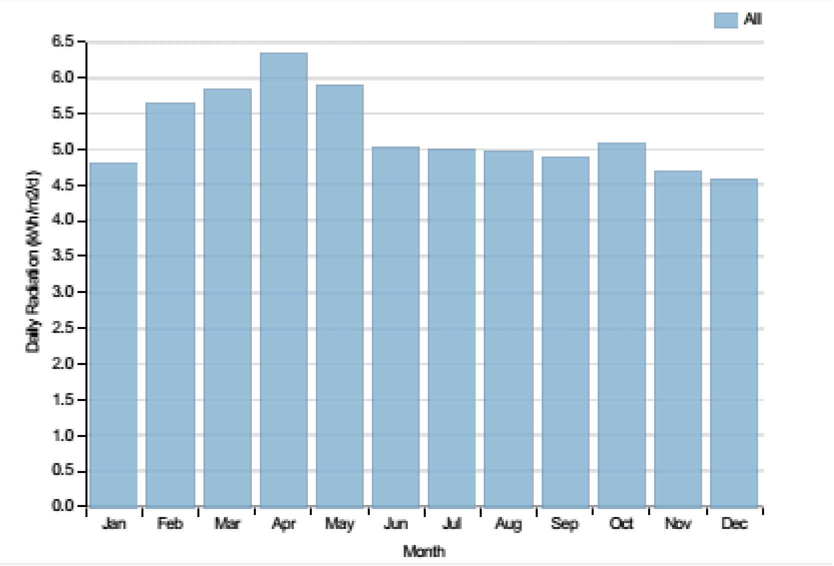
## C. Project site map



## D. Renewable Resource availability levels:

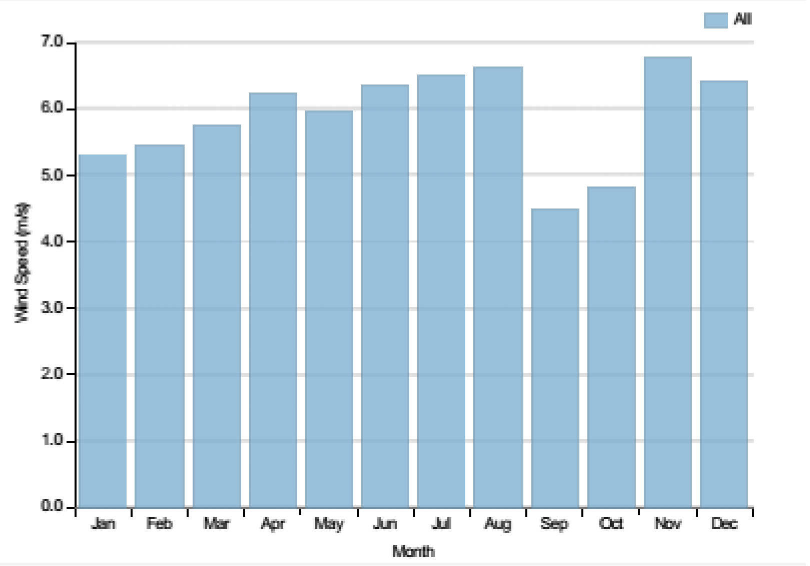
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation (KWh/m$^2$/day |
|---|---|---|
| January | 0.600 | 4.779 |
| February | 0.634 | 5.632 |
| March | 0.589 | 5.832 |
| April | 0.598 | 6.325 |
| May | 0.547 | 5.896 |
| June | 0.465 | 5.014 |
| July | 0.464 | 4.981 |
| August | 0.470 | 4.965 |
| September | 0.487 | 4.883 |
| October | 0.557 | 5.058 |
| November | 0.576 | 4.676 |
| December | 0.597 | 4.569 |
| Scaled annual average | | **5.22 kWh/m2/d** |



**D.2 <u>WIND:</u>**

| Month | Average Wind Speed (m/s) |
|---|---|
| January | 5.300 |
| February | 5.430 |
| March | 5.750 |
| April | 6.210 |
| May | 5.960 |
| June | 6.330 |
| July | 6.500 |
| August | 6.610 |
| September | 4.470 |
| October | 4.790 |
| November | 6.750 |
| January | 5.300 |
| Scaled annual average | **5.88 m/s** |

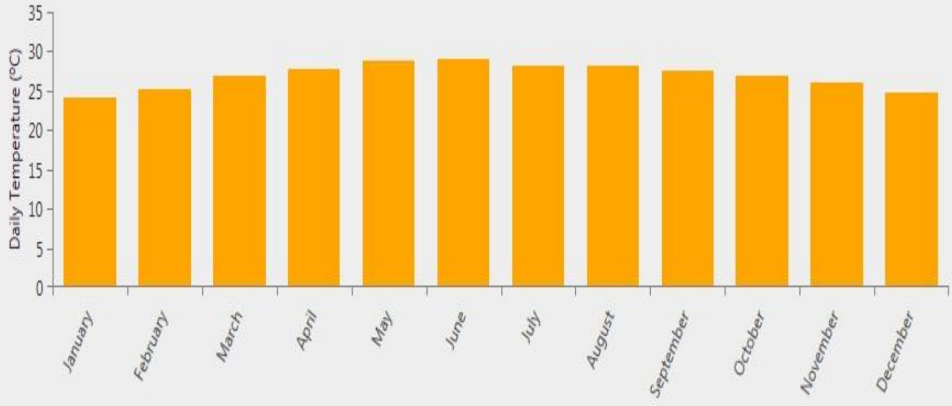


## D.3 Temperature:

Monthly Average Temperature Data

| Month | Daily Temperature (ºC) |
|---|---|
| January | 24.200 |
| February | 25.160 |
| March | 26.830 |
| April | 27.690 |
| May | 28.860 |
| June | 29.110 |
| July | 28.250 |
| August | 28.090 |
| September | 27.580 |
| October | 26.810 |
| November | 26.030 |

Annual Average (ºC): 26.95




Downloaded at 19-Jun-16 4:38:12 PM from:
NASA Surface meteorology and Solar Energy database.
Air temperature, monthly averaged values over 22 year period (July 1983 - June 2005)
CellNumber: 106262
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 16.5
CellMidpointLongitude: 82.5

## D.4 Hydrokinetic:

Monthly Average Water Speed Data

| Month | Water Speed (m/s) |
|---|---|
| January | 30.000 |
| February | 35.000 |
| March | 35.000 |
| April | 35.000 |
| May | 45.000 |
| June | 50.000 |
| July | 50.000 |
| August | 60.000 |
| September | 60.000 |
| October | 45.000 |
| November | 45.000 |
| December | 45.000 |

Annual Average (m/s): 44.58

**DATA SHEET-10**

**RENEWABLE RESOURCE AVAILABILITY –PUDUCHERRY REGION WISE**

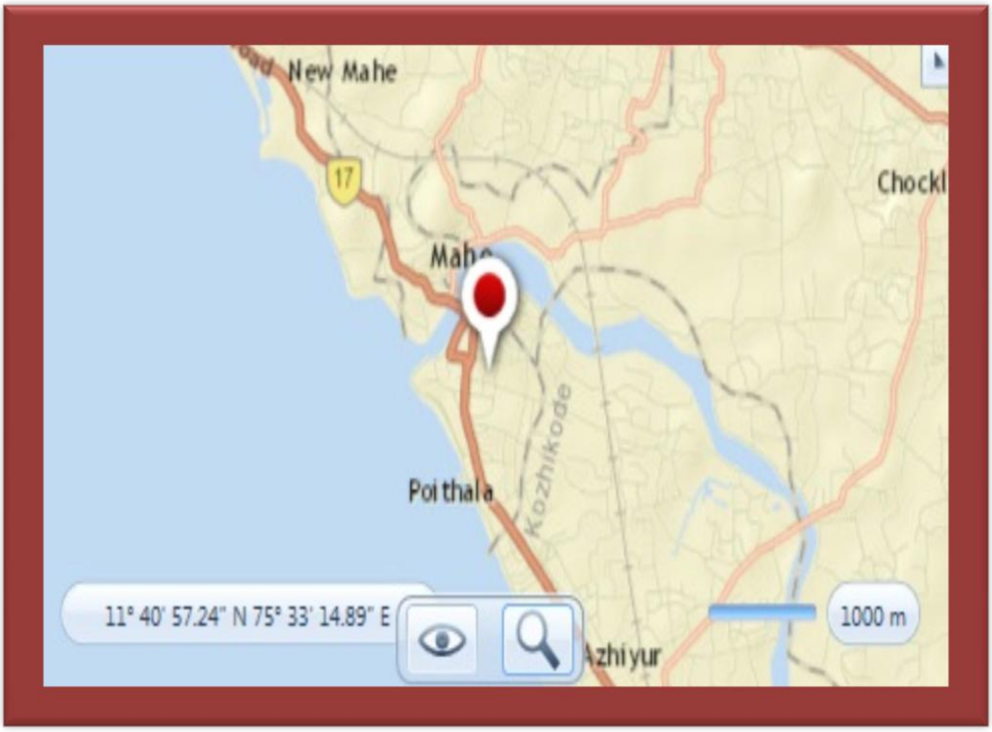
## A. Basic Data:

| | |
|---|---|
| Name of the U.T Region | Mahe |
| Name of the site | polloor |
| Type of Renewable Resource availability | Solar, Wind, |
| Total Electrical demand of the area | MAX:6.3 MW MIN :5.2 |

## B. Project Location :

| | |
|---|---|
| Location | Cemetery Road,Mahe ,Kerala -673310, India |
| Latitude | 11 degrees 42.16 minutes North |
| Longitude | 75 degrees 32.18 minutes East |
| Time zone | Asia/Kolkata |

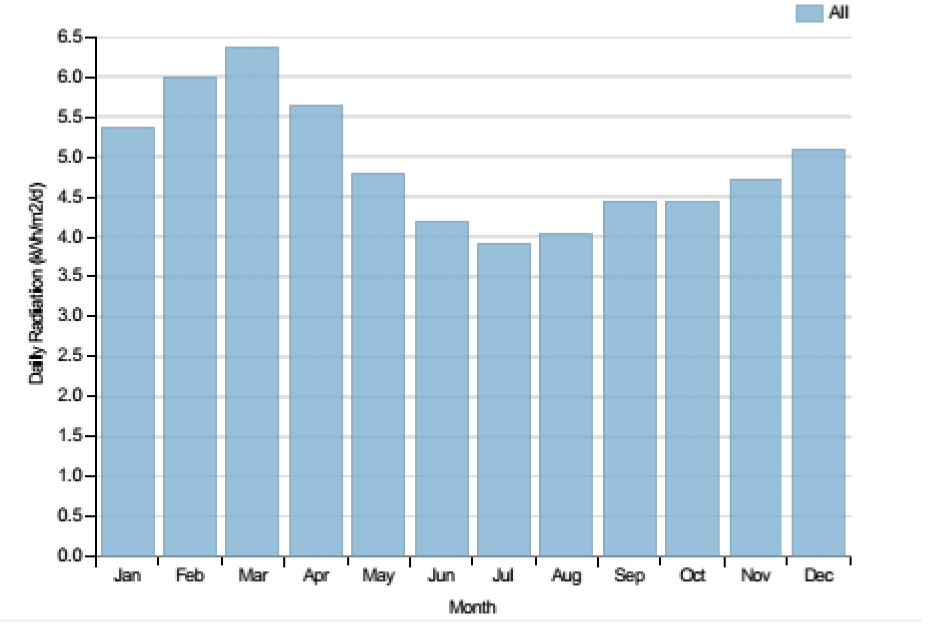
## C. Project site map



## D. Renewable Resource availability levels:

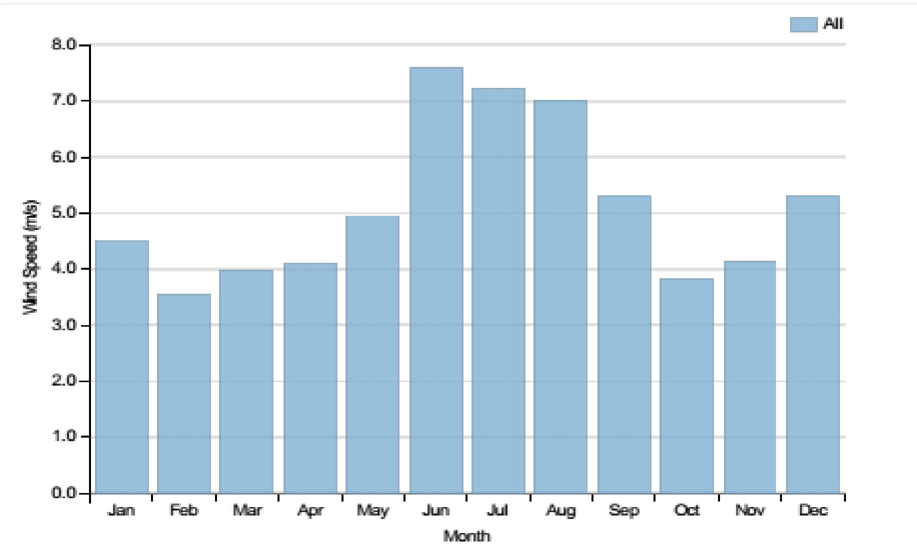
### D.1 SOLAR:

| Month | Clearness Index | Daily Radiation ($KWh/m^2/day$) |
|---|---|---|
| January | 0.620 | 5.369 |
| February | 0.637 | 5.992 |
| March | 0.625 | 6.361 |
| April | 0.535 | 5.642 |
| May | 0.453 | 4.770 |
| June | 0.401 | 4.178 |
| July | 0.375 | 3.907 |
| August | 0.385 | 4.026 |
| September | 0.434 | 4.433 |
| October | 0.463 | 4.420 |
| November | 0.537 | 4.715 |
| December | 0.607 | 5.091 |
| Scaled annual average | | **4.91 kWh/m2/d** |



**D.2 WIND:**

| Month | Average Wind Speed (m/s) |
|---|---|
| January | 4.480 |
| February | 3.520 |
| March | 3.960 |
| April | 4.090 |
| May | 4.940 |
| June | 7.590 |
| July | 7.200 |
| August | 6.990 |
| September | 5.290 |
| October | 3.800 |
| November | 4.120 |
| December | 5.310 |
| Scaled annual average | **5.11 m/s** |

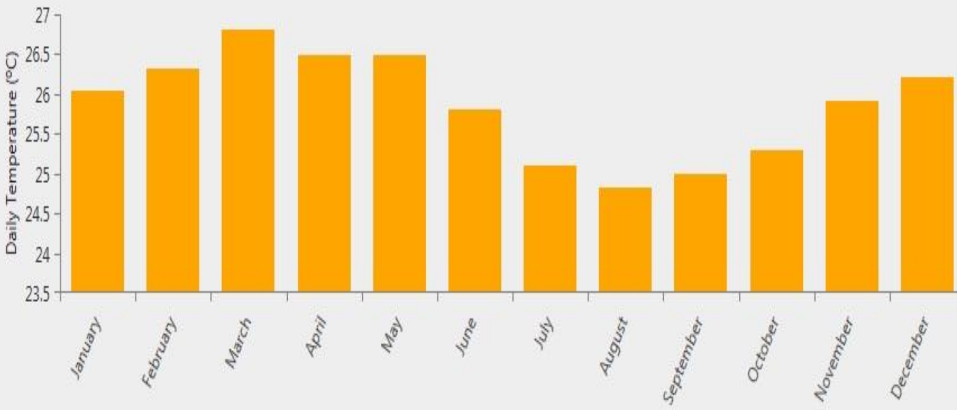


## D.3 Temperature:

Monthly Average Temperature Data

| Month | Daily Temperature (ºC) |
|---|---|
| January | 26.030 |
| February | 26.310 |
| March | 26.800 |
| April | 26.490 |
| May | 26.490 |
| June | 25.800 |
| July | 25.090 |
| August | 24.830 |
| September | 24.990 |
| October | 25.290 |
| November | 25.910 |

Annual Average (ºC): 25.85




Downloaded at 19-Jun-16 4:40:14 PM from:
NASA Surface meteorology and Solar Energy database.
Air temperature, monthly averaged values over 22 year period (July 1983 - June 2005)
CellNumber: 101255
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 11.5
CellMidpointLongitude: 75.5

International
IOR Rectifier

Data Sheet No. PD60147 rev.U

# IR2110(-1-2)(S)PbF/IR2113(-1-2)(S)PbF

## HIGH AND LOW SIDE DRIVER

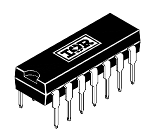
## Features

- Floating channel designed for bootstrap operation
  Fully operational to +500V or +600V
  Tolerant to negative transient voltage
  dV/dt immune
- Gate drive supply range from 10 to 20V
- Undervoltage lockout for both channels
- 3.3V logic compatible
  Separate logic supply range from 3.3V to 20V
  Logic and power ground ±5V offset
- CMOS Schmitt-triggered inputs with pull-down
- Cycle by cycle edge-triggered shutdown logic
- Matched propagation delay for both channels
- Outputs in phase with inputs

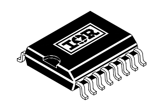
## Product Summary

| | | |
|---|---|---|
| $V_{OFFSET}$ | (IR2110) | 500V max. |
| | (IR2113) | 600V max. |
| $I_O$+/- | | 2A / 2A |
| $V_{OUT}$ | | 10 - 20V |
| $t_{on/off}$ (typ.) | | 120 & 94 ns |
| Delay Matching | (IR2110) | 10 ns max. |
| | (IR2113) | 20ns max. |

## Packages



14-Lead PDIP
IR2110/IR2113

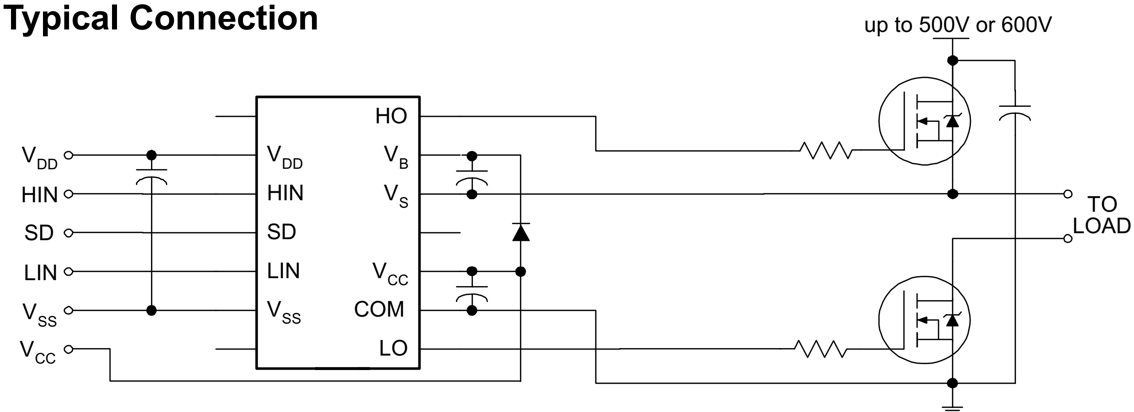


16-Lead SOIC
IR2110S/IR2113S

## Description

The IR2110/IR2113 are high voltage, high speed power MOSFET and IGBT drivers with independent high and low side referenced output channels. Proprietary HVIC and latch immune CMOS technologies enable ruggedized monolithic construction. Logic inputs are compatible with standard CMOS or LSTTL output, down to 3.3V logic. The output drivers feature a high pulse current buffer stage designed for minimum driver cross-conduction. Propagation delays are matched to simplify use in high frequency applications. The floating channel can be used to drive an N-channel power MOSFET or IGBT in the high side configuration which operates up to 500 or 600 volts.

## Typical Connection




(Refer to Lead Assignments for correct pin configuration). This/These diagram(s) show electrical connections only. Please refer to our Application Notes and DesignTips for proper circuit board layout.

## Absolute Maximum Ratings

Absolute maximum ratings indicate sustained limits beyond which damage to the device may occur. All voltage parameters are absolute voltages referenced to COM. The thermal resistance and power dissipation ratings are measured under board mounted and still air conditions. Additional information is shown in Figures 28 through 35.

| Symbol | Definition | | Min. | Max. | Units |
|---|---|---|---|---|---|
| $V_B$ | High side floating supply voltage | (IR2110) | -0.3 | 525 | V |
| | | (IR2113) | -0.3 | 625 | |
| $V_S$ | High side floating supply offset voltage | | $V_B$ - 25 | $V_B$ + 0.3 | |
| $V_{HO}$ | High side floating output voltage | | $V_S$ - 0.3 | $V_B$ + 0.3 | |
| $V_{CC}$ | Low side fixed supply voltage | | -0.3 | 25 | |
| $V_{LO}$ | Low side output voltage | | -0.3 | $V_{CC}$ + 0.3 | |
| $V_{DD}$ | Logic supply voltage | | -0.3 | $V_{SS}$ + 25 | |
| $V_{SS}$ | Logic supply offset voltage | | $V_{CC}$ - 25 | $V_{CC}$ + 0.3 | |
| $V_{IN}$ | Logic input voltage (HIN, LIN & SD) | | $V_{SS}$ - 0.3 | $V_{DD}$ + 0.3 | |
| $dV_s/dt$ | Allowable offset supply voltage transient (figure 2) | | — | 50 | V/ns |
| $P_D$ | Package power dissipation @ $T_A \le$ +25°C | (14 lead DIP) | — | 1.6 | W |
| | | (16 lead SOIC) | — | 1.25 | |
| $R_{THJA}$ | Thermal resistance, junction to ambient | (14 lead DIP) | — | 75 | °C/W |
| | | (16 lead SOIC) | — | 100 | |
| $T_J$ | Junction temperature | | — | 150 | °C |
| $T_S$ | Storage temperature | | -55 | 150 | |
| $T_L$ | Lead temperature (soldering, 10 seconds) | | — | 300 | |

## Recommended Operating Conditions

The input/output logic timing diagram is shown in figure 1. For proper operation the device should be used within the recommended conditions. The $V_S$ and $V_{SS}$ offset ratings are tested with all supplies biased at 15V differential. Typical ratings at other bias conditions are shown in figures 36 and 37.

| Symbol | Definition | | Min. | Max. | Units |
|---|---|---|---|---|---|
| $V_B$ | High side floating supply absolute voltage | | $V_S$ + 10 | $V_S$ + 20 | V |
| $V_S$ | High side floating supply offset voltage | (IR2110) | Note 1 | 500 | |
| | | (IR2113) | Note 1 | 600 | |
| $V_{HO}$ | High side floating output voltage | | $V_S$ | $V_B$ | |
| $V_{CC}$ | Low side fixed supply voltage | | 10 | 20 | |
| $V_{LO}$ | Low side output voltage | | 0 | VCC | |
| $V_{DD}$ | Logic supply voltage | | $V_{SS}$ + 3 | $V_{SS}$ + 20 | |
| $V_{SS}$ | Logic supply offset voltage | | -5 (Note 2) | 5 | |
| $V_{IN}$ | Logic input voltage (HIN, LIN & SD) | | $V_{SS}$ | $V_{DD}$ | |
| $T_A$ | Ambient temperature | | -40 | 125 | °C |

Note 1: Logic operational for $V_S$ of -4 to +500V. Logic state held for $V_S$ of -4V to $-V_{BS}$. (Please refer to the Design Tip DT97-3 for more details).
Note 2: When $V_{DD}$ < 5V, the minimum $V_{SS}$ offset is limited to $-V_{DD}$.

## Dynamic Electrical Characteristics

$V_{BIAS}$ ($V_{CC}$, $V_{BS}$, $V_{DD}$) = 15V, $C_L$ = 1000 pF, $T_A$ = 25°C and $V_{SS}$ = COM unless otherwise specified. The dynamic electrical characteristics are measured using the test circuit shown in Figure 3.

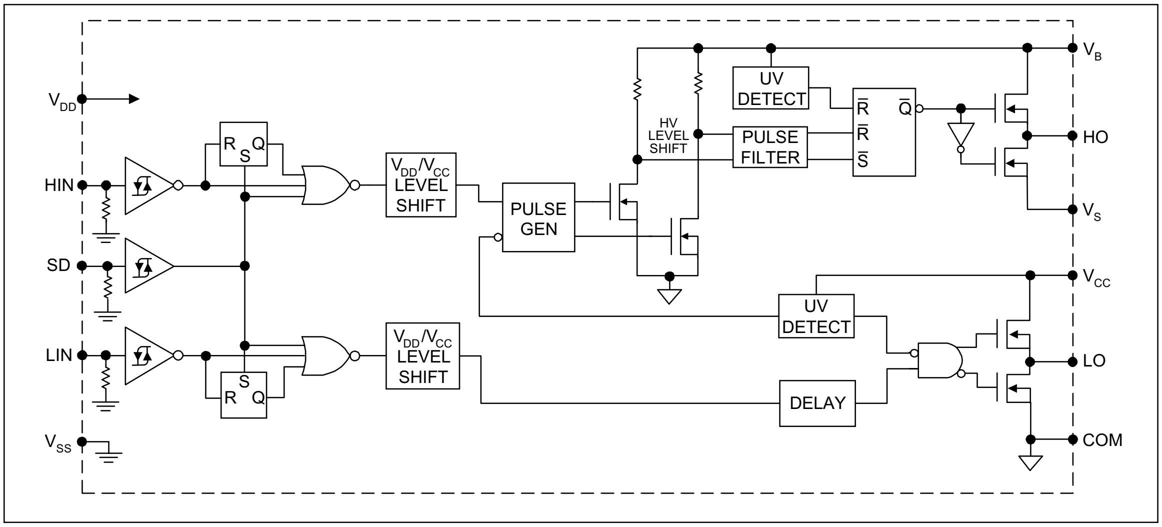
| Symbol | Definition | | Figure | Min. | Typ. | Max. | Units | Test Conditions |
|---|---|---|---|---|---|---|---|---|
| $t_{on}$ | Turn-on propagation delay | | 7 | — | 120 | 150 | ns | $V_S$ = 0V |
| $t_{off}$ | Turn-off propagation delay | | 8 | — | 94 | 125 | | $V_S$ = 500V/600V |
| $t_{sd}$ | Shutdown propagation delay | | 9 | — | 110 | 140 | | $V_S$ = 500V/600V |
| $t_r$ | Turn-on rise time | | 10 | — | 25 | 35 | | |
| $t_f$ | Turn-off fall time | | 11 | — | 17 | 25 | | |
| MT | Delay matching, HS & LS | (IR2110) | — | — | — | 10 | | |
| | turn-on/off | (IR2113) | — | — | — | 20 | | |

## Static Electrical Characteristics

$V_{BIAS}$ ($V_{CC}$, $V_{BS}$, $V_{DD}$) = 15V, $T_A$ = 25°C and $V_{SS}$ = COM unless otherwise specified. The $V_{IN}$, $V_{TH}$ and $I_{IN}$ parameters are referenced to $V_{SS}$ and are applicable to all three logic input leads: HIN, LIN and SD. The $V_O$ and $I_O$ parameters are referenced to COM and are applicable to the respective output leads: HO or LO.

| Symbol | Definition | Figure | Min. | Typ. | Max. | Units | Test Conditions |
|---|---|---|---|---|---|---|---|
| $V_{IH}$ | Logic "1" input voltage | 12 | 9.5 | — | — | V | |
| $V_{IL}$ | Logic "0" input voltage | 13 | — | — | 6.0 | | |
| $V_{OH}$ | High level output voltage, $V_{BIAS}$ - $V_O$ | 14 | — | — | 1.2 | | $I_O$ = 0A |
| $V_{OL}$ | Low level output voltage, $V_O$ | 15 | — | — | 0.1 | | $I_O$ = 0A |
| $I_{LK}$ | Offset supply leakage current | 16 | — | — | 50 | µA | $V_B$=$V_S$ = 500V/600V |
| $I_{QBS}$ | Quiescent $V_{BS}$ supply current | 17 | — | 125 | 230 | | $V_{IN}$ = 0V or $V_{DD}$ |
| $I_{QCC}$ | Quiescent $V_{CC}$ supply current | 18 | — | 180 | 340 | | $V_{IN}$ = 0V or $V_{DD}$ |
| $I_{QDD}$ | Quiescent $V_{DD}$ supply current | 19 | — | 15 | 30 | | $V_{IN}$ = 0V or $V_{DD}$ |
| $I_{IN+}$ | Logic "1" input bias current | 20 | — | 20 | 40 | | $V_{IN}$ = $V_{DD}$ |
| $I_{IN-}$ | Logic "0" input bias current | 21 | — | — | 1.0 | | $V_{IN}$ = 0V |
| $V_{BSUV+}$ | $V_{BS}$ supply undervoltage positive going threshold | 22 | 7.5 | 8.6 | 9.7 | V | |
| $V_{BSUV-}$ | $V_{BS}$ supply undervoltage negative going threshold | 23 | 7.0 | 8.2 | 9.4 | | |
| $V_{CCUV+}$ | $V_{CC}$ supply undervoltage positive going threshold | 24 | 7.4 | 8.5 | 9.6 | | |
| $V_{CCUV-}$ | $V_{CC}$ supply undervoltage negative going threshold | 25 | 7.0 | 8.2 | 9.4 | | |
| $I_{O+}$ | Output high short circuit pulsed current | 26 | 2.0 | 2.5 | — | A | $V_O$ = 0V, $V_{IN}$ = $V_{DD}$ PW ≤ 10 µs |
| $I_{O-}$ | Output low short circuit pulsed current | 27 | 2.0 | 2.5 | — | | $V_O$ = 15V, $V_{IN}$ = 0V PW ≤ 10 µs |

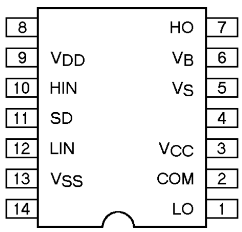
## Functional Block Diagram



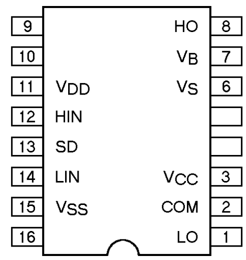

## Lead Definitions

| Symbol | Description |
|---|---|
| $V_{DD}$ | Logic supply |
| HIN | Logic input for high side gate driver output (HO), in phase |
| SD | Logic input for shutdown |
| LIN | Logic input for low side gate driver output (LO), in phase |
| $V_{SS}$ | Logic ground |
| $V_B$ | High side floating supply |
| HO | High side gate drive output |
| $V_S$ | High side floating supply return |
| $V_{CC}$ | Low side supply |
| LO | Low side gate drive output |
| COM | Low side return |

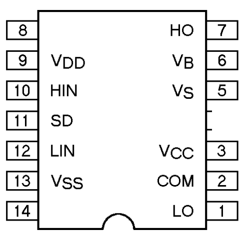
## Lead Assignments



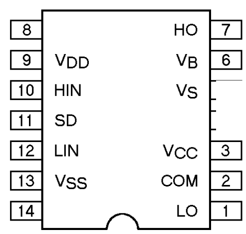

14 Lead PDIP
**IR2110/IR2113**




16 Lead SOIC (Wide Body)
**IR2110S/IR2113S**




14 Lead PDIP w/o lead 4
**IR2110-1/IR2113-1**




14 Lead PDIP w/o leads 4 & 5
**IR2110-2/IR2113-2**

**Part Number**

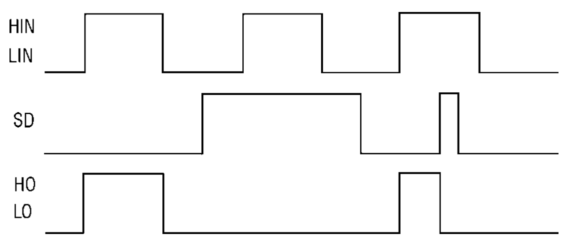



**Figure 1. Input/Output Timing Diagram**

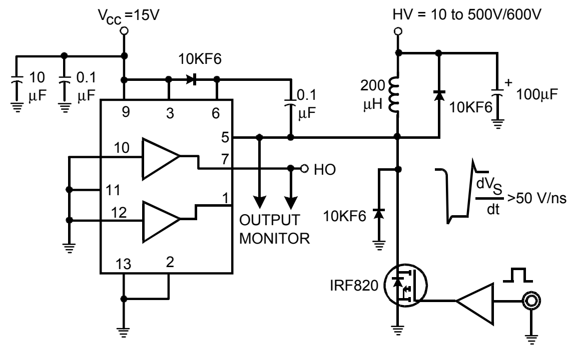



**Figure 2. Floating Supply Voltage Transient Test Circuit**

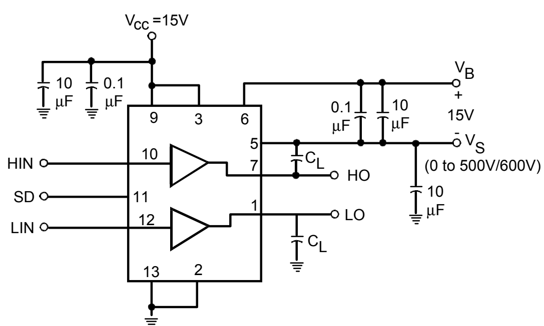



**Figure 3. Switching Time Test Circuit**

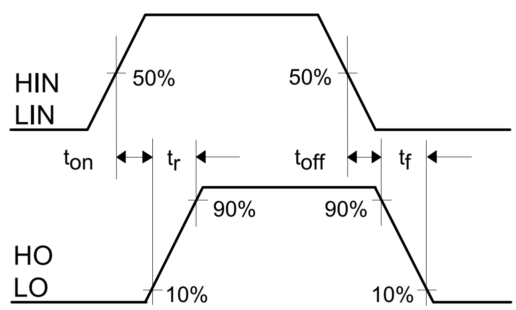



**Figure 4. Switching Time Waveform Definition**

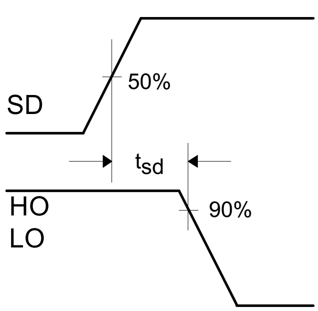



**Figure 5. Shutdown Waveform Definitions**

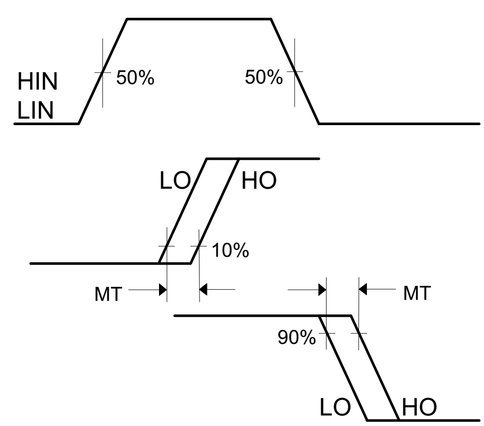



**Figure 6. Delay Matching Waveform Definitions**

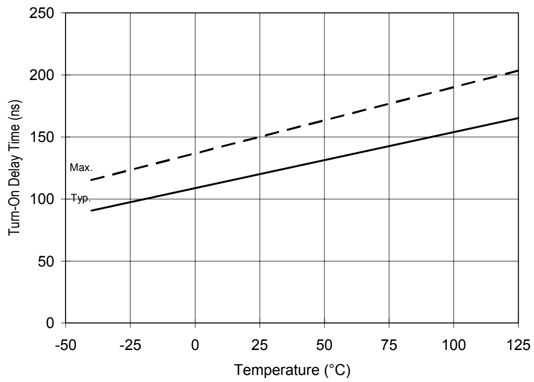



**Figure 7A. Turn-On Time vs. Temperature**

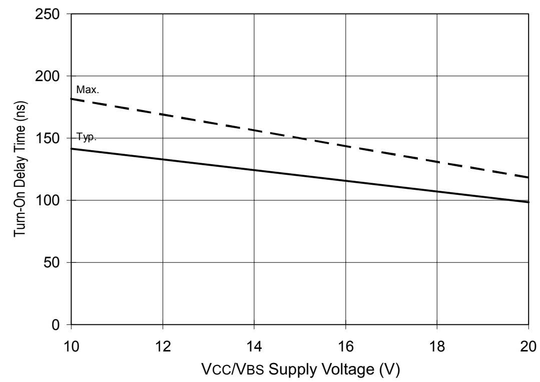



**Figure 7B. Turn-On Time vs. VCC/VBS Supply Voltage**

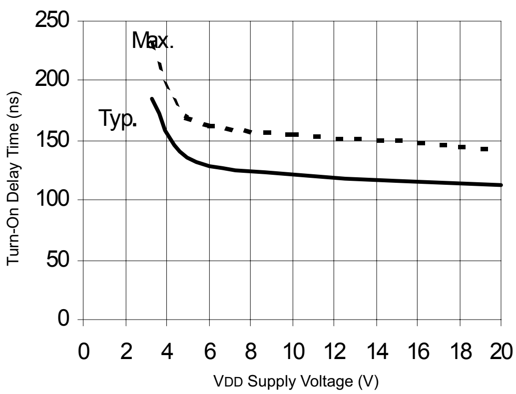



**Figure 7C. Turn-On Time vs. VDD Supply Voltage**

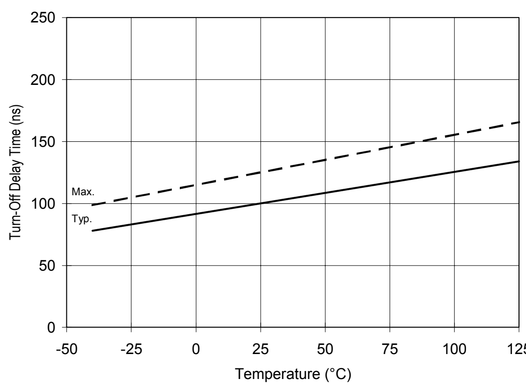



**Figure 8A. Turn-Off Time vs. Temperature**

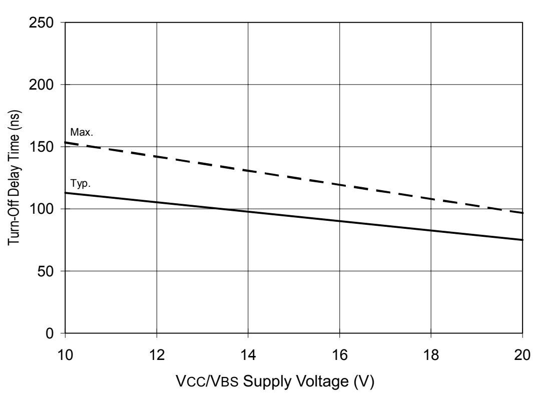



**Figure 8B. Turn-Off Time vs. VCC/VBS Supply Voltage**

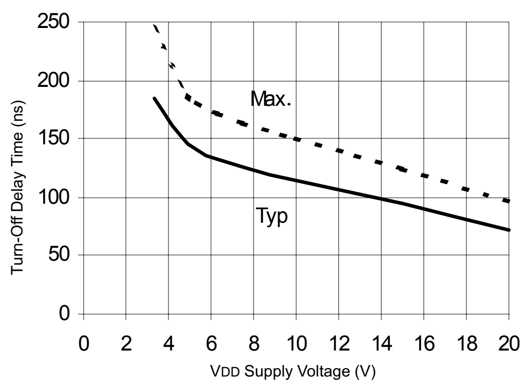



**Figure 8C. Turn-Off Time vs. VDD Supply Voltage**

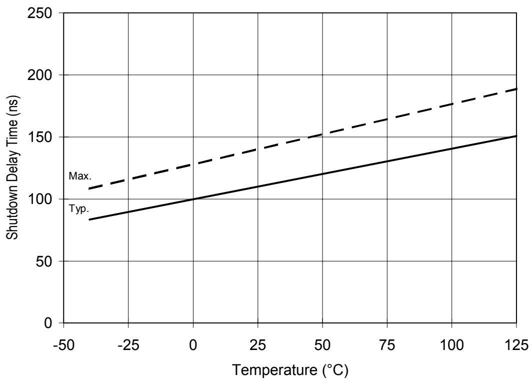



**Figure 9A. Shutdown Time vs. Temperature**

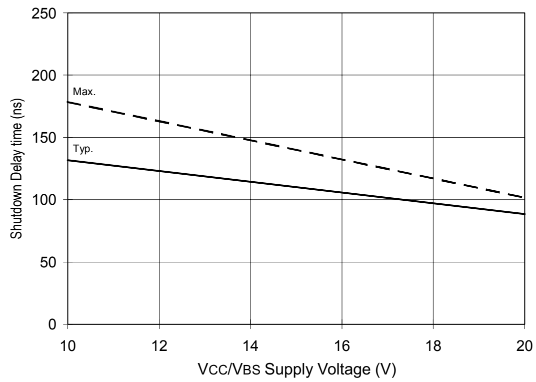



**Figure 9B. Shutdown Time vs. VCC/VBS Supply Voltage**

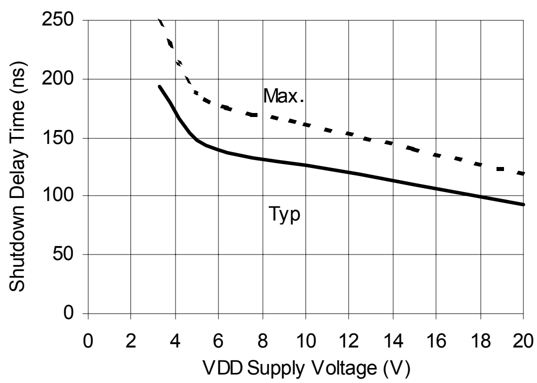



**Figure 9C. Shutdown Time vs. VDD Supply Voltage**

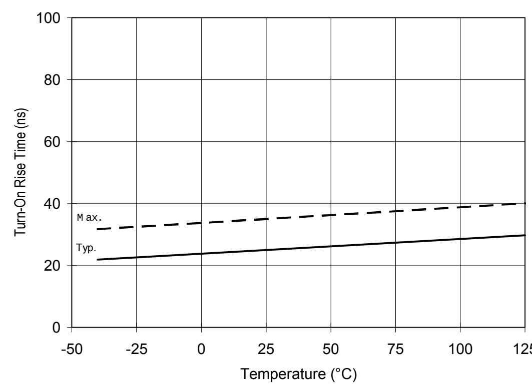



**Figure 10A. Turn-On Rise Time vs. Temperature**

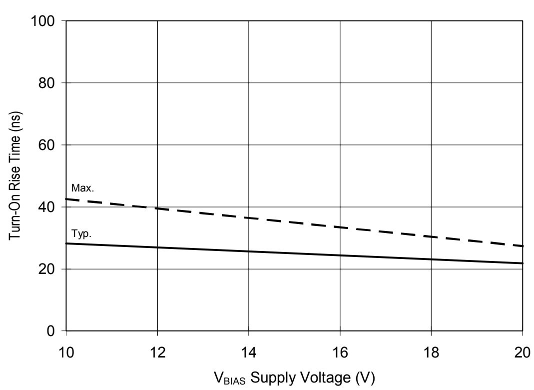



**Figure 10B. Turn-On Rise Time vs. Voltage**

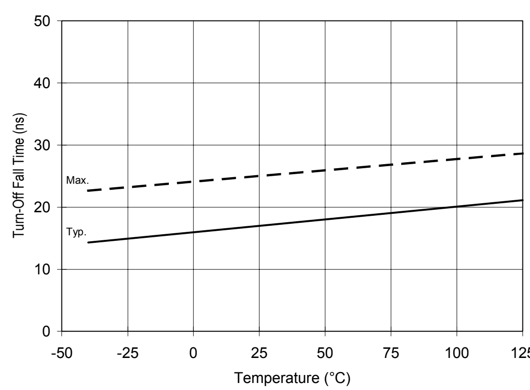



**Figure 11A. Turn-Off Fall Time vs. Temperature**

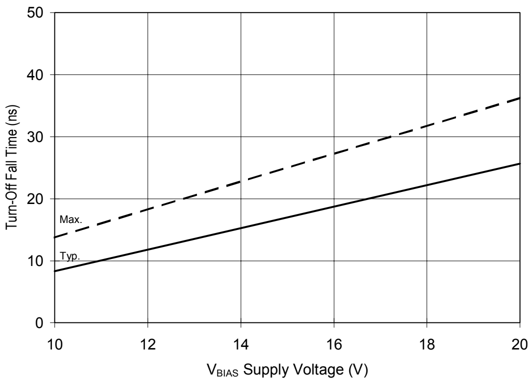



**Figure 11B. Turn-Off Fall Time vs. Voltage**

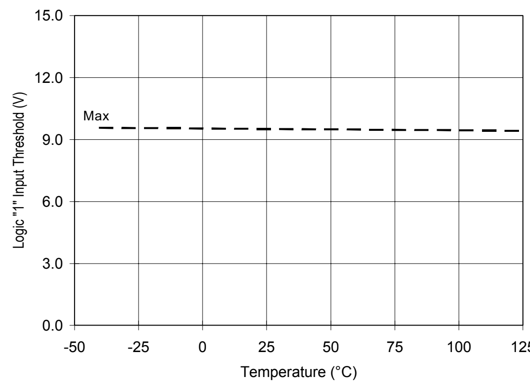



**Figure 12A. Logic "1" Input Threshold vs. Temperature**

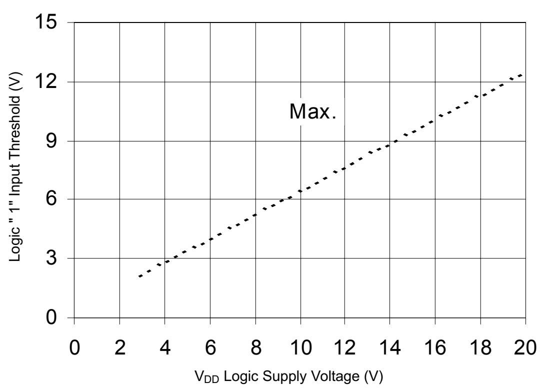



**Figure 12B. Logic "1" Input Threshold vs. Voltage**

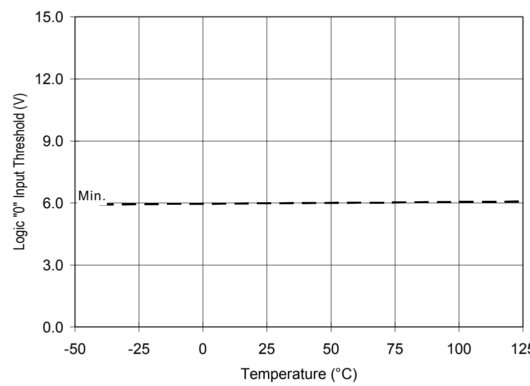



**Figure 13A. Logic "0" Input Threshold vs. Temperature**

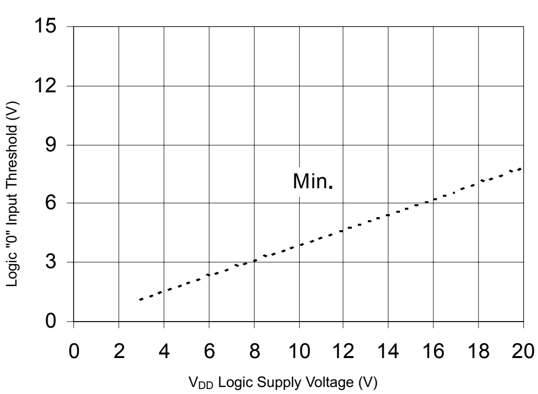



**Figure 13B. Logic "0" Input Threshold vs. Voltage**

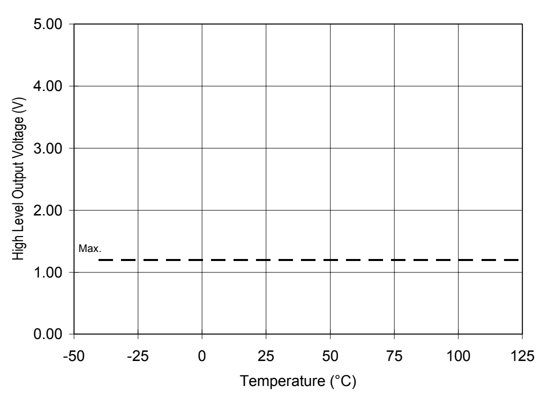



**Figure 14A. High Level Output vs. Temperature**

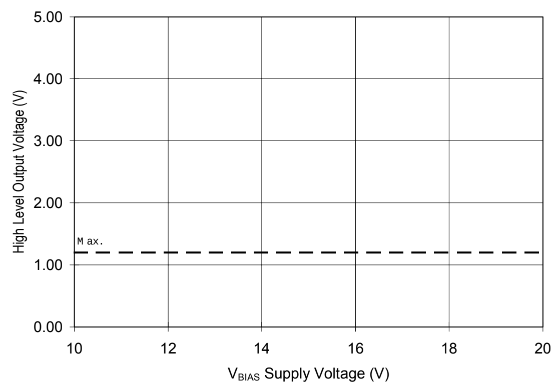



Figure 14B. High Level Output vs. Voltage

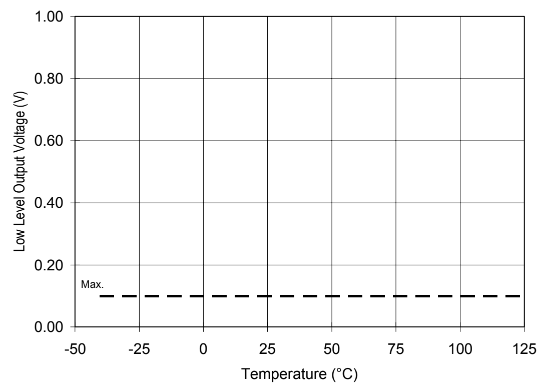



Figure 15A. Low Level Output vs. Temperature

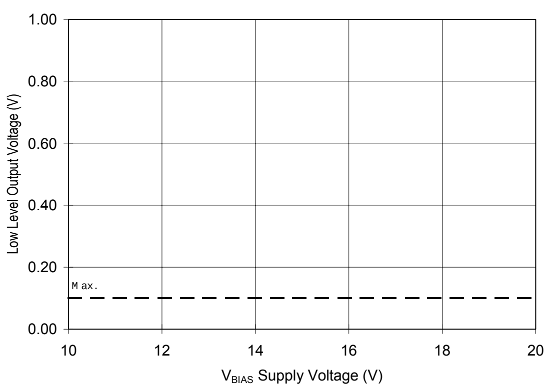



Figure 15B. Low Level Output vs. Voltage

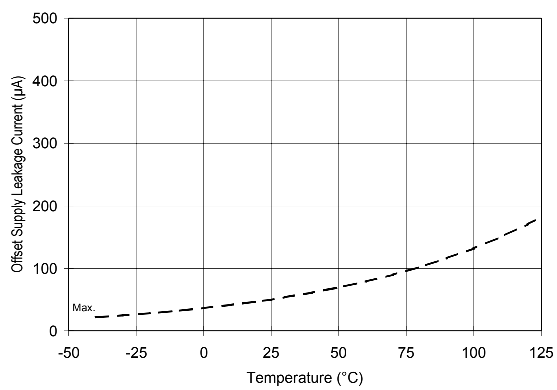



Figure 16A. Offset Supply Current vs. Temperature

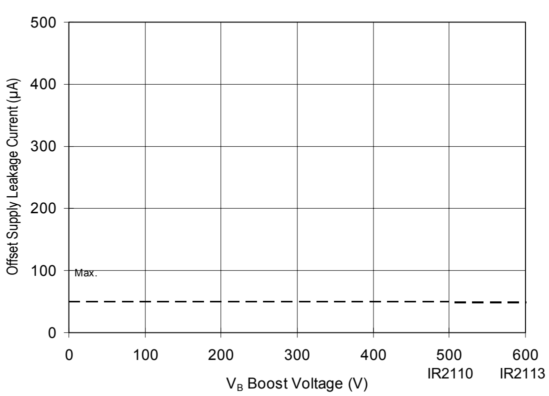



Figure 16B. Offset Supply Current vs. Voltage

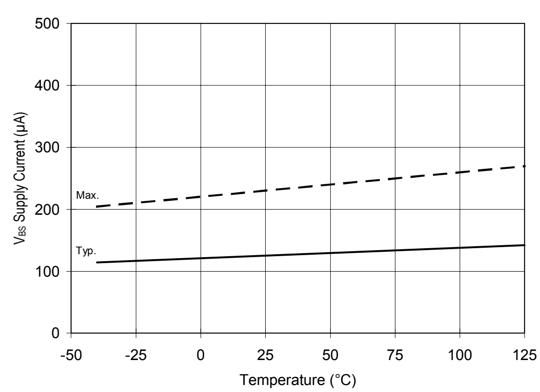



Figure 17A. $V_{BS}$ Supply Current vs. Temperature

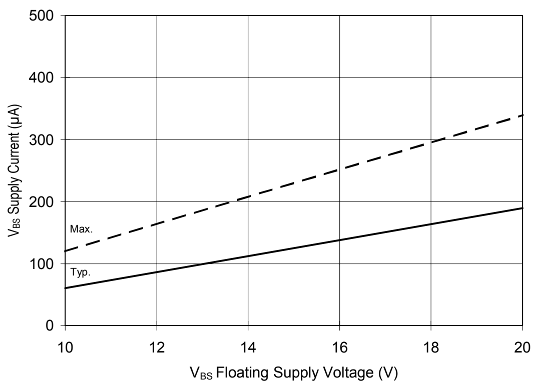



**Figure 17B. $V_{BS}$ Supply Current vs. Voltage**

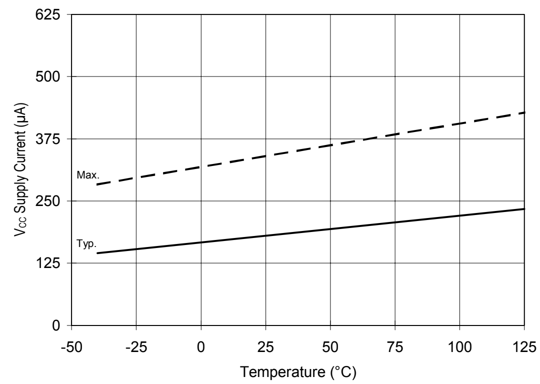



**Figure 18A. $V_{CC}$ Supply Current vs. Temperature**

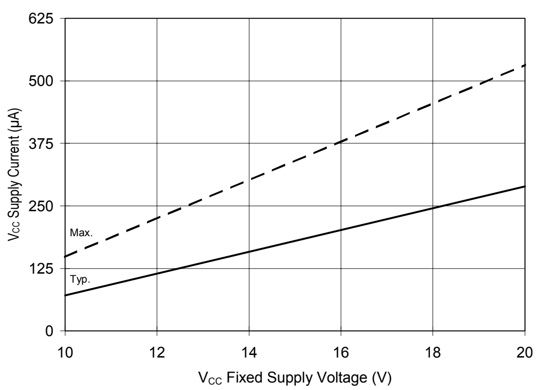



**Figure 18B. $V_{CC}$ Supply Current vs. Voltage**

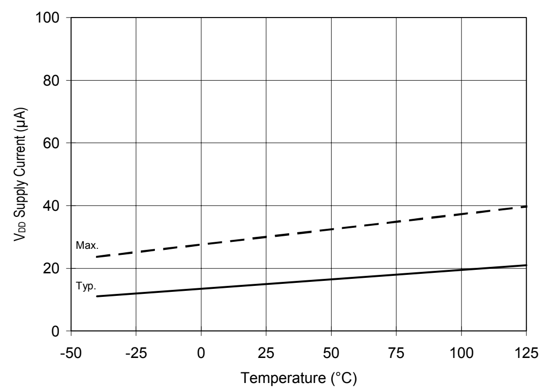



**Figure 19A. $V_{DD}$ Supply Current vs. Temperature**

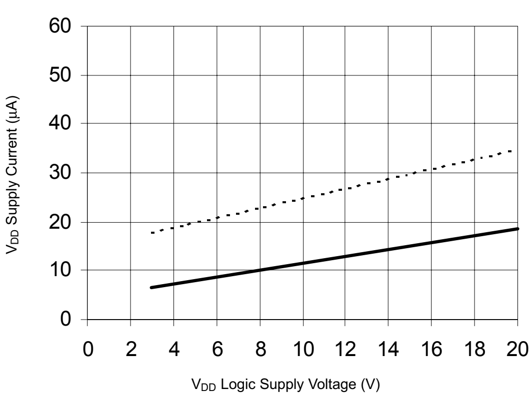



**Figure 19B. $V_{DD}$ Supply Current vs. $V_{DD}$ Voltage**

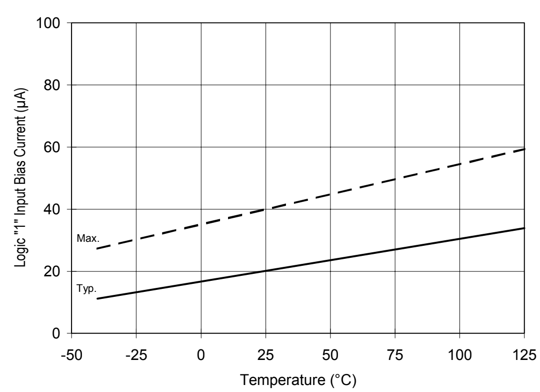



**Figure 20A. Logic "1" Input Current vs. Temperature**

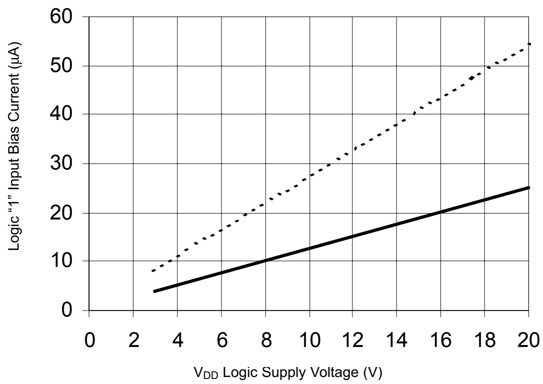



Figure 20B. Logic “1” Input Current vs. $V_{DD}$ Voltage

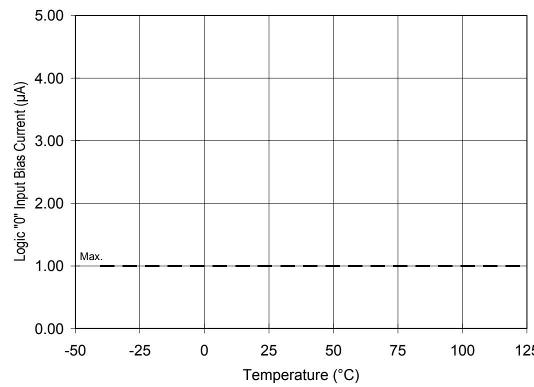



Figure 21A. Logic “0” Input Current vs. Temperature

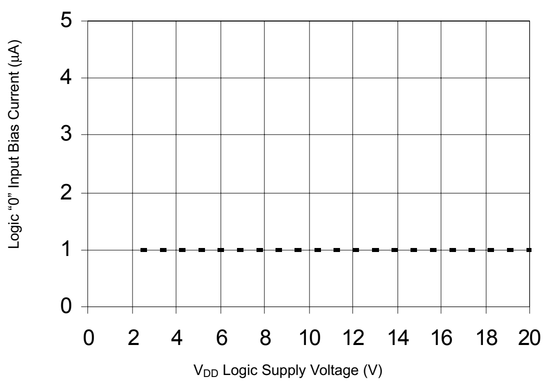



Figure 21B. Logic “0” Input Current vs. $V_{DD}$ Voltage

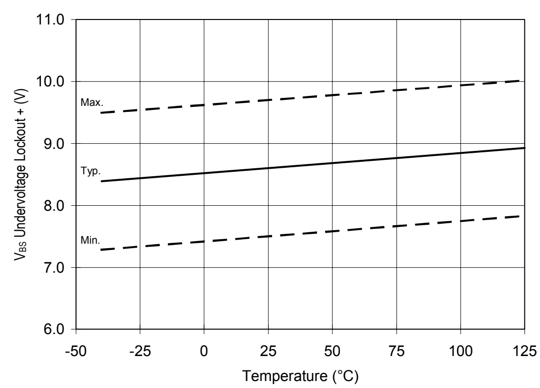



Figure 22. $V_{BS}$ Undervoltage (+) vs. Temperature

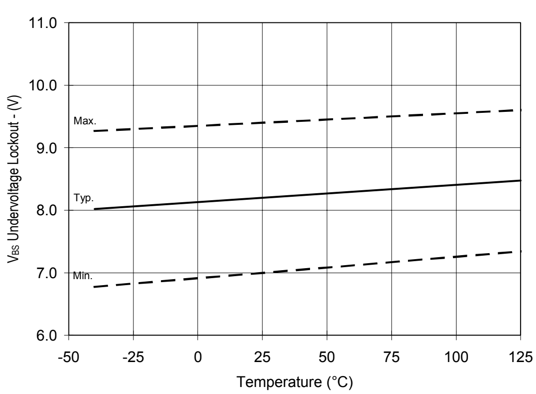



Figure 23. $V_{BS}$ Undervoltage (-) vs. Temperature

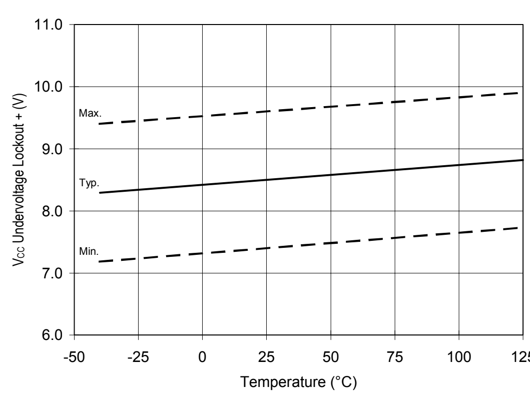



Figure 24. $V_{CC}$ Undervoltage (+) vs. Temperature

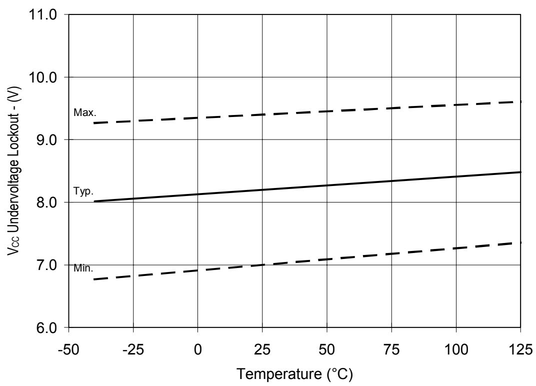



**Figure 25. $V_{CC}$ Undervoltage (-) vs. Temperature**

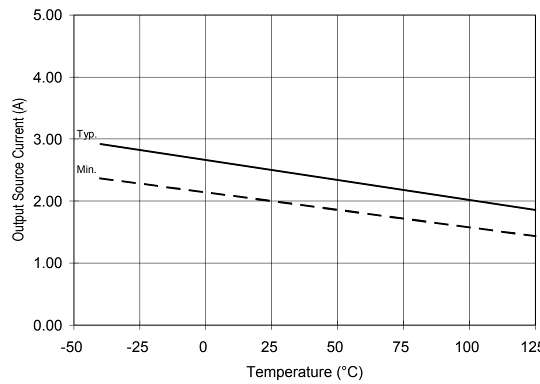



**Figure 26A. Output Source Current vs. Temperature**

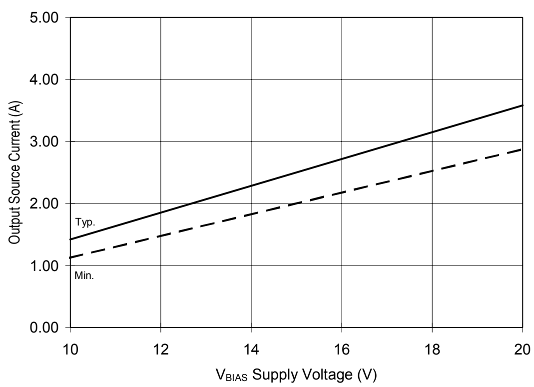



**Figure 26B. Output Source Current vs. Voltage**

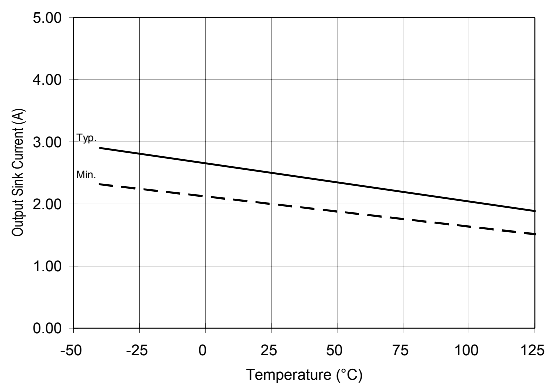



**Figure 27A. Output Sink Current vs. Temperature**

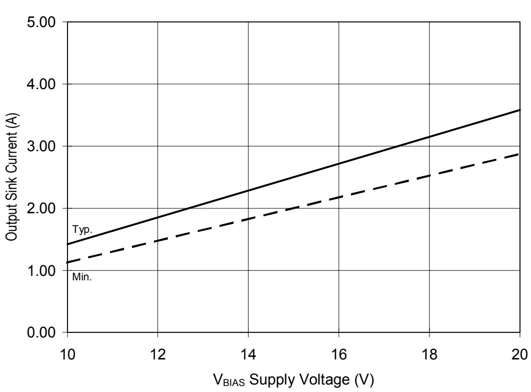



**Figure 27B. Output Sink Current vs. Voltage**

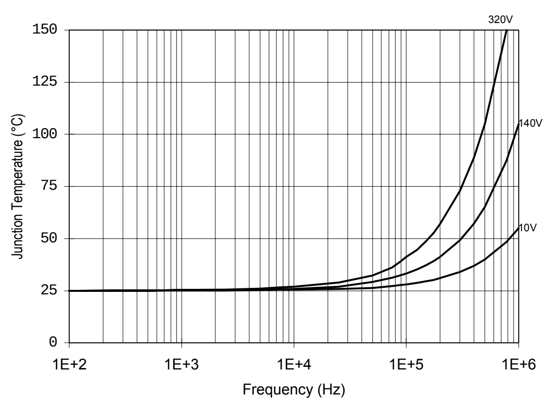



**Figure 28. IR2110/IR2113 $T_J$ vs. Frequency (IRFBC20) $R_{GATE} = 33\Omega$, $V_{CC} = 15V$**

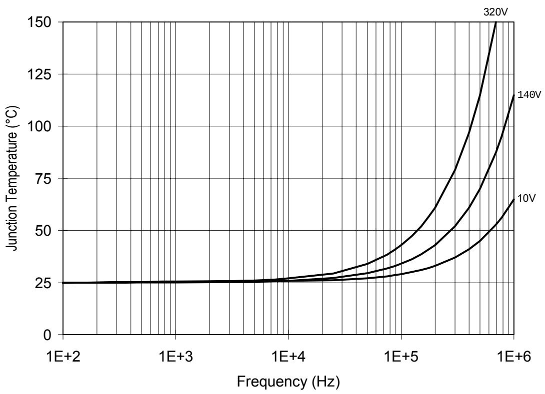



**Figure 29. IR2110/IT2113 $T_J$ vs. Frequency (IRFBC30) $R_{GATE}$ = 22Ω, $V_{CC}$ = 15V**

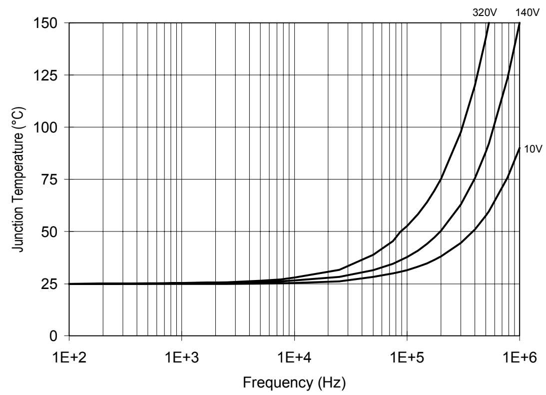



**Figure 30. IR2110/IR2113 $T_J$ vs. Frequency (IRFBC40) $R_{GATE}$ = 15Ω, $V_{CC}$ = 15V**

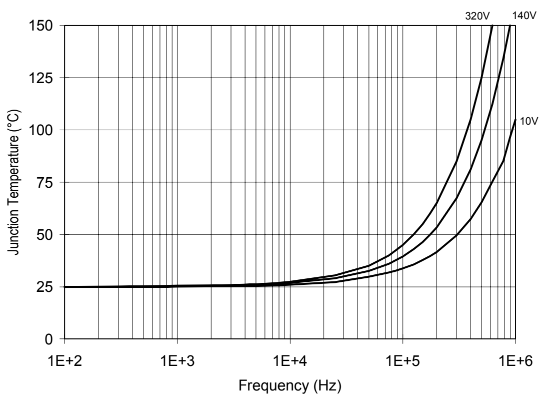



**Figure 31. IR2110/IR2113 $T_J$ vs. Frequency (IRFPE50) $R_{GATE}$ = 10Ω, $V_{CC}$ = 15V**

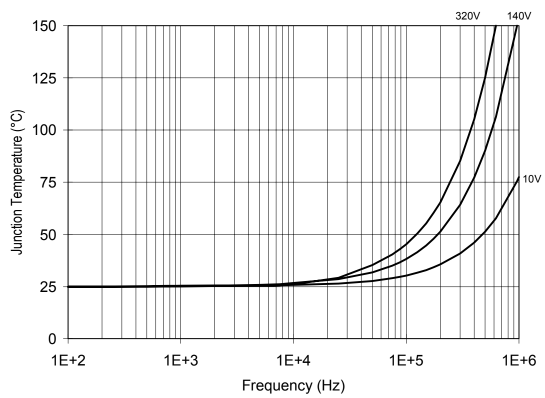



**Figure 32. IR2110S/IR2113S $T_J$ vs. Frequency (IRFBC20) $R_{GATE}$ = 33Ω, $V_{CC}$ = 15V**

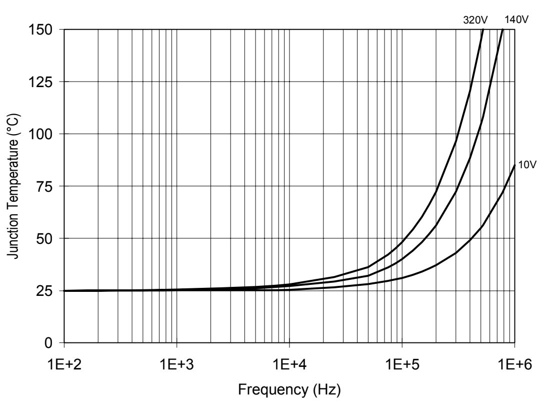



**Figure 33. IR2110S/IR2113S $T_J$ vs. Frequency (IRFBC30) $R_{GATE}$ = 22Ω, $V_{CC}$ = 15V**

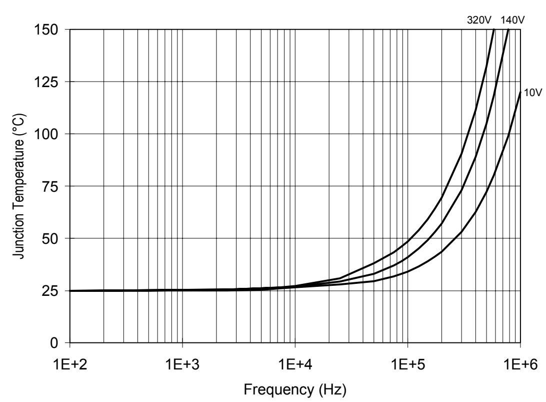



**Figure 34. IR2110S/IR2113S $T_J$ vs. Frequency (IRFBC40) $R_{GATE}$ = 15Ω, $V_{CC}$ = 15V**

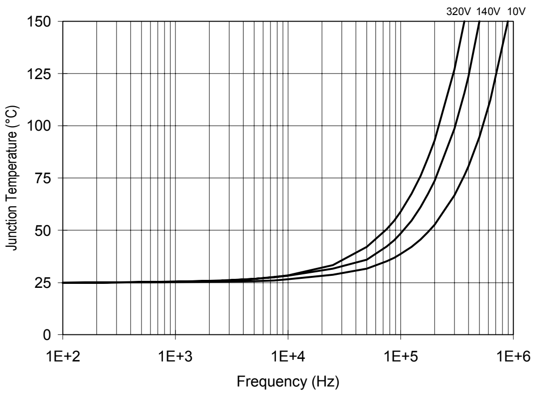



**Figure 35. IR2110S/IR2113S $T_J$ vs. Frequency (IRFPE50) $R_{GATE}$ = 10Ω, $V_{CC}$ = 15V**

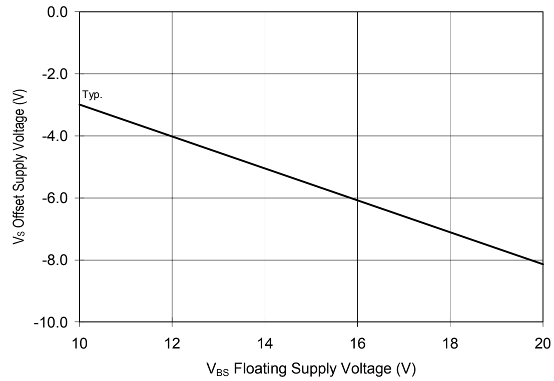



**Figure 36. Maximum $V_S$ Negative Offset vs. $V_{BS}$ Supply Voltage**

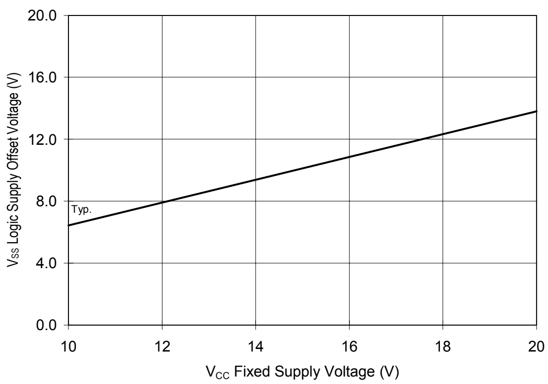
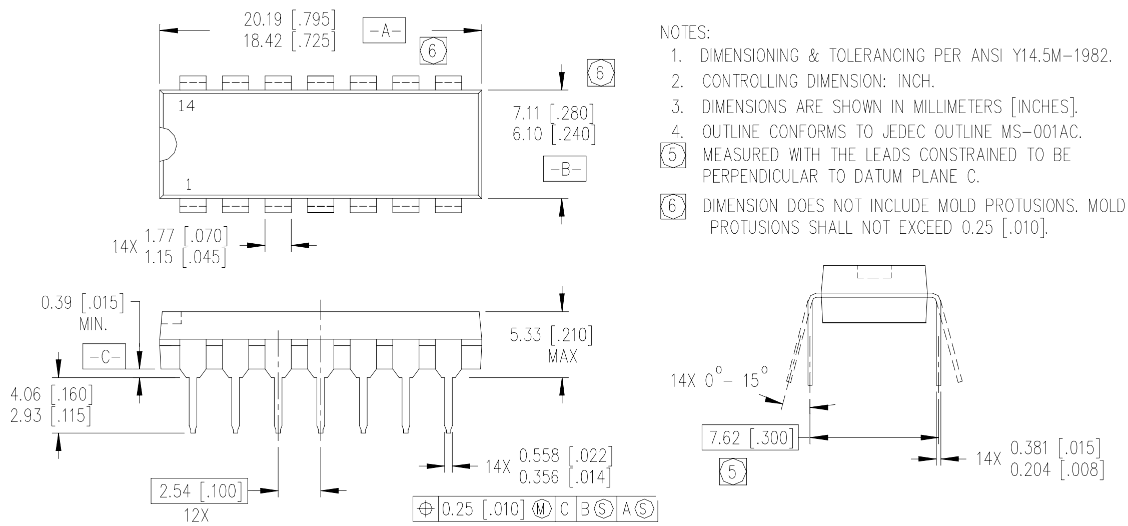


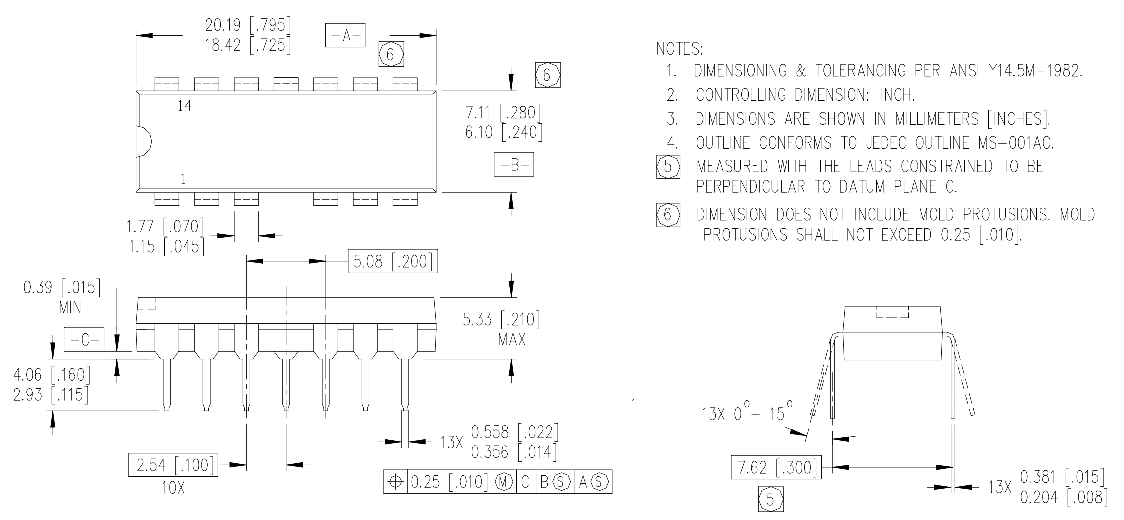

**Figure 37. Maximum $V_{SS}$ Positive Offset vs. $V_{CC}$ Supply Voltage**

## Case Outlines



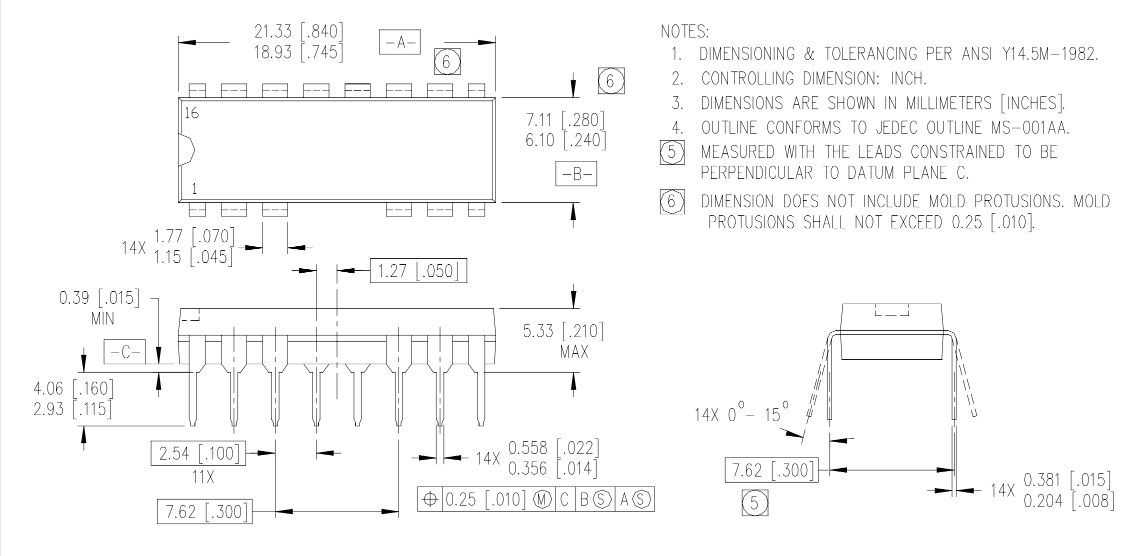

**14-Lead PDIP**

01-6010
01-3002 03 (MS-001AC)



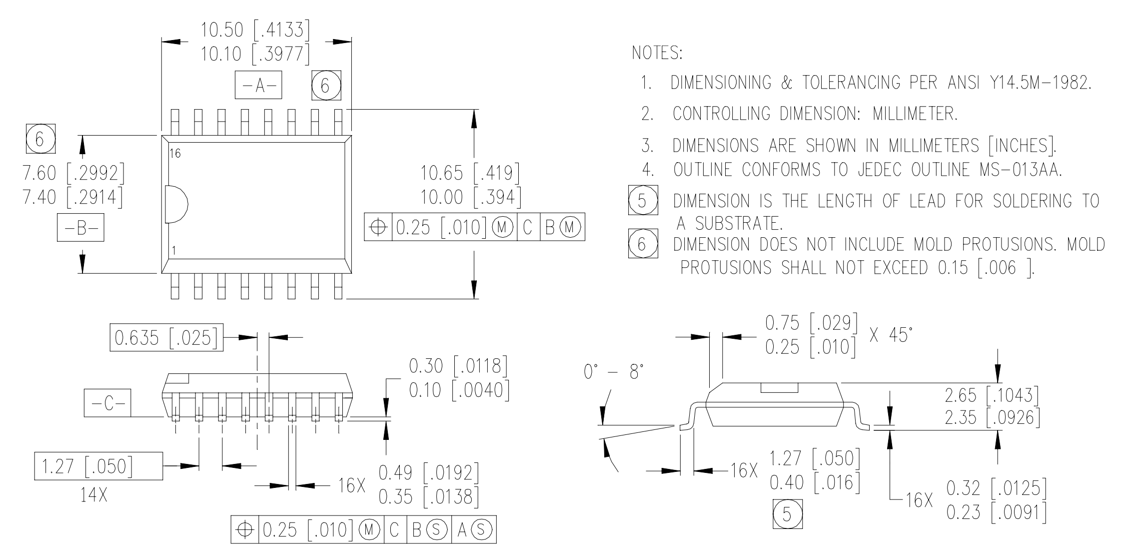

**14-Lead PDIP w/o Lead 4**

01-6010
01-3008 02 (MS-001AC)




**16 Lead PDIP w/o Leads 4 & 5**

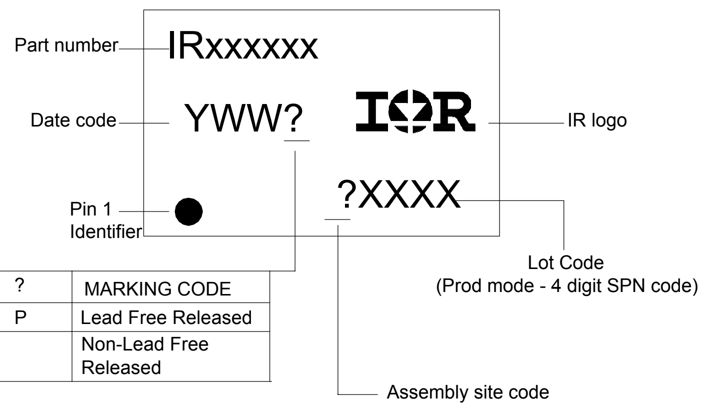
01-6015
01-3010 02




**16-Lead SOIC (wide body)**

01 6015
01-3014 03 (MS-013AA)

## LEADFREE PART MARKING INFORMATION




| ? | MARKING CODE |
|---|---|
| P | Lead Free Released |
| | Non-Lead Free Released |

## ORDER INFORMATION

### Part only available Lead Free

14-Lead PDIP IR2110 order IR2110PbF
14-Lead PDIP IR2110-1 order IR2110-1PbF
14-Lead PDIP IR2110-2 order IR2110-2PbF
14-Lead PDIP IR2113 order IR2113PbF
14-Lead PDIP IR2113-1 order IR2113-1PbF
14-Lead PDIP IR2113-2 order IR2113-2PbF
16-Lead SOIC IR2110S order IR2110SPbF
16-Lead SOIC IR2113S order IR2113SPbF

International
IOR Rectifier
**IR WORLD HEADQUARTERS:** 233 Kansas St., El Segundo, California 90245 Tel: (310) 252-7105
**This product has been qualified per industrial level**
*Data and specifications subject to change without notice 3/23/2005*

FAIRCHILD
SEMICONDUCTOR®

February 2009

# FGPF30N30
# 300V, 30A PDP IGBT

## Features

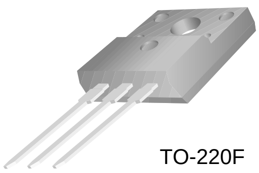
- High Current Capability
- Low saturation voltage: $V_{CE(sat)}$ =1.4V @ $I_C$ = 20A
- High Input Impedance
- Fast switching
- RoHS Complaint

## Application

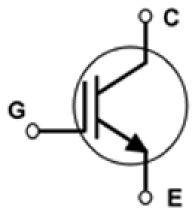
. PDP System

## General Description

Employing Unified IGBT Technology, Fairchild's PDP IGBTs provides low conduction and switching loss. FGPF30N30 offers the optimum solution for PDP applications where low-condution loss is essential.



TO-220F
1
1.Gate 2.Collector 3.Emitter




## Absolute Maximum Ratings

| Symbol | Description | | FGPF30N30 | Units |
|---|---|---|---|---|
| $V_{CES}$ | Collector-Emitter Voltage | | 300 | V |
| $V_{GES}$ | Gate-Emitter Voltage | | ± 30 | V |
| $I_{C\ pulse(1)}$ | Pulsed Collector Current | @ $T_C$ = 25°C | 80 | A |
| $P_D$ | Maximum Power Dissipation | @ $T_C$ = 25°C | 46 | W |
| | Maximum Power Dissipation | @ $T_C$ = 100°C | 18.5 | W |
| $T_J$ | Operating Junction Temperature | | -55 to +150 | °C |
| $T_{stg}$ | Storage Temperature Range | | -55 to +150 | °C |
| $T_L$ | Maximum Lead Temp. for soldering Purposes, 1/8" from case for 5 seconds | | 300 | °C |

## Thermal Characteristics

| Symbol | Parameter | Typ. | Max. | Units |
|---|---|---|---|---|
| $R_{\theta JC}$(IGBT) | Thermal Resistance, Junction-to-Case | -- | 2.7 | °C/W |
| $R_{\theta JA}$ | Thermal Resistance, Junction-to-Ambient | -- | 62.5 | °C/W |

**Notes:**
(1)Repetitive test , pluse width = 100usec , Duty = 0.1
* Ic_pluse limited by max Tj

## Package Marking and Ordering Information

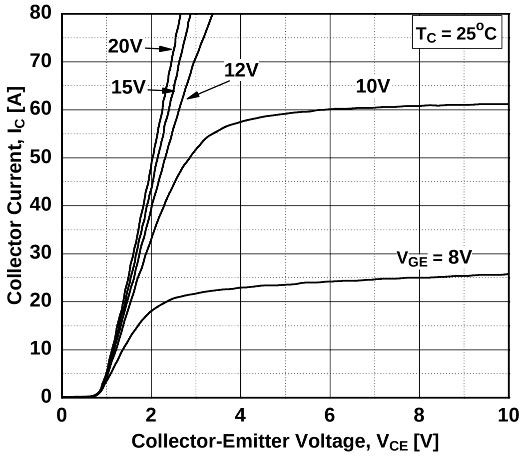
| Device Marking | Device | Package | Packaging Type | Qty per Tube | Max Qty per Box |
|---|---|---|---|---|---|
| FGPF30N30 | FGPF30N30TU | TO-220F | Rail / Tube | 50ea | - |

## Electrical Characteristics $T_C$ = 25°C unless otherwise noted

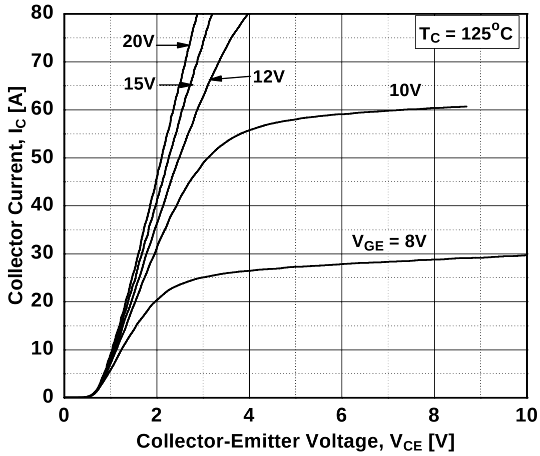
| Symbol | Parameter | Test Conditions | Min. | Typ. | Max. | Units |
|---|---|---|---|---|---|---|
| **Off Characteristics** | | | | | | |
| $BV_{CES}$ | Collector-Emitter Breakdown Voltage | $V_{GE}$ = 0V, $I_C$ = 250uA | 300 | -- | -- | V |
| $\Delta B_{VCES}/\Delta T_J$ | Temperature Coefficient of Breakdown Voltage | $V_{GE}$ = 0V, $I_C$ = 250uA | -- | 0.6 | -- | V/°C |
| $I_{CES}$ | Collector Cut-Off Current | $V_{CE} = V_{CES}$, $V_{GE}$ = 0V | -- | -- | 100 | uA |
| $I_{GES}$ | G-E Leakage Current | $V_{GE} = V_{GES}$, $V_{CE}$ = 0V | -- | -- | ± 250 | nA |
| **On Characteristics** | | | | | | |
| $V_{GE(th)}$ | G-E Threshold Voltage | $I_C$ = 250uA, $V_{CE} = V_{GE}$ | 2.5 | 4.0 | 5.0 | V |
| $V_{CE(sat)}$ | Collector to Emitter Saturation Voltage | $I_C$ =10A, $V_{GE}$ = 15V | -- | 1.2 | 1.5 | V |
| | | $I_C$ =20A, $V_{GE}$ = 15V | -- | 1.4 | -- | V |
| | | $I_C$ = 30A, $V_{GE}$ = 15V $T_C$ = 25°C | -- | 1.8 | -- | V |
| | | $I_C$ = 30A, $V_{GE}$ = 15V $T_C$ = 125°C | -- | 1.9 | -- | V |
| **Dynamic Characteristics** | | | | | | |
| $C_{ies}$ | Input Capacitance | $V_{CE}$ = 30V, $V_{GE}$ = 0V f = 1MHz | -- | 685 | -- | pF |
| $C_{oes}$ | Output Capacitance | | -- | 95 | -- | pF |
| $C_{res}$ | Reverse Transfer Capacitance | | -- | 30 | -- | pF |
| **Switching Characteristics** | | | | | | |
| $t_{d(on)}$ | Turn-On Delay Time | $V_{CC}$ = 200 V, $I_C$ = 20A $R_G$ = 20Ω, $V_{GE}$ = 15V Resistive Load, $T_C$ = 25°C | -- | 10 | -- | ns |
| $t_r$ | Rise Time | | -- | 44 | -- | ns |
| $t_{d(off)}$ | Turn-Off Delay Time | | -- | 76 | -- | ns |
| $t_f$ | Fall Time | | -- | 180 | 300 | ns |
| $t_{d(on)}$ | Turn-On Delay Time | $V_{CC}$ = 200 V, $I_C$ = 20A $R_G$ = 20Ω, $V_{GE}$ = 15V Resistive Load, $T_C$ = 125°C | -- | 10 | - | ns |
| $t_r$ | Rise Time | | -- | 46 | -- | ns |
| $t_{d(off)}$ | Turn-Off Delay Time | | -- | 82 | -- | ns |
| $t_f$ | Fall Time | | -- | 270 | -- | ns |
| $Q_g$ | Total Gate Charge | $V_{CE}$ = 200 V, $I_C$ = 20A $V_{GE}$ = 15V | -- | 39 | -- | nC |
| $Q_{ge}$ | Gate-Emitter Charge | | -- | 6 | -- | nC |
| $Q_{gc}$ | Gate-Collector Charge | | -- | 16 | -- | nC |

## Typical Performance CharacteristicsTypical Saturation VoltageCharacteristics

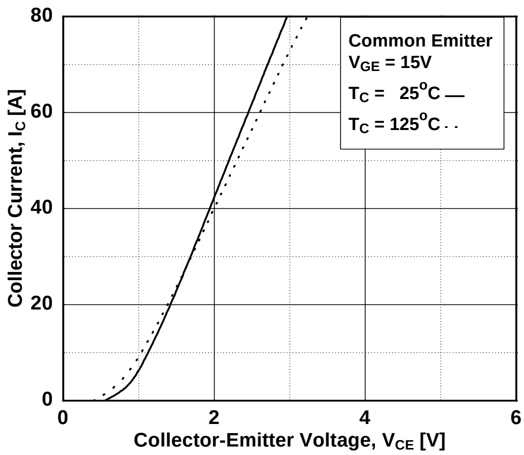
### Figure 1. Typical Output Characteristics



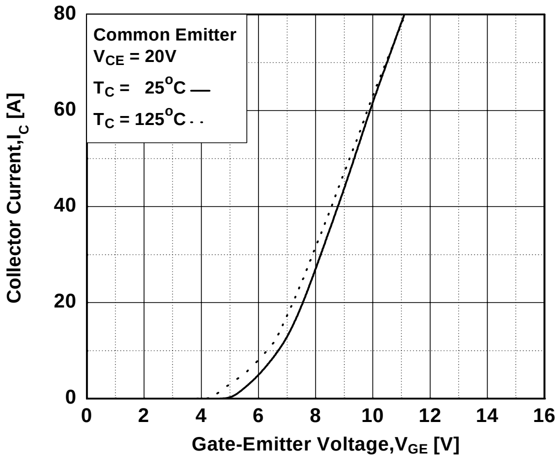

### Figure 2. Typical Output Characteristics



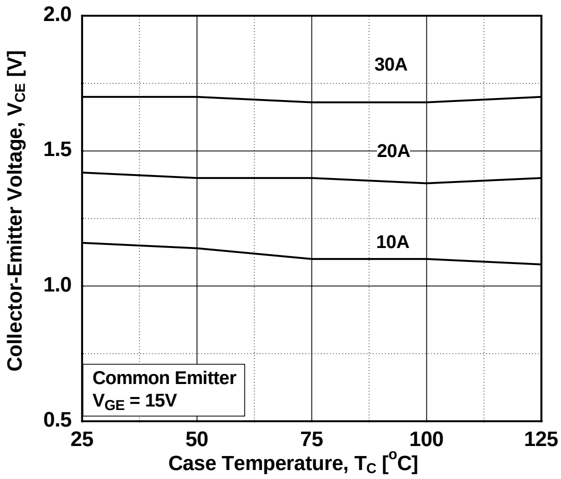

### Figure 3. Saturation Voltage



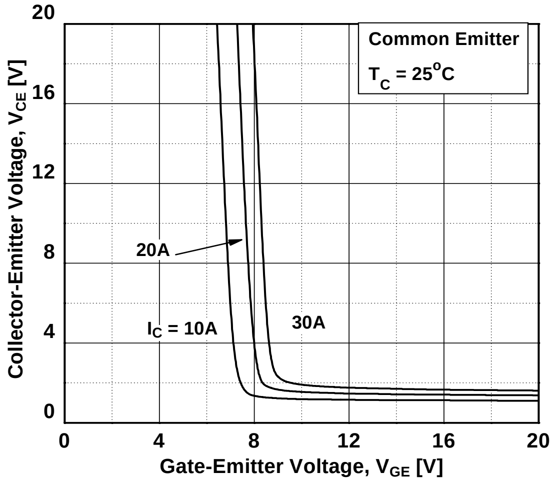

### Figure 4. Transfer Characteristics




### Figure 5. Saturation Voltage vs. Case Temperature at Variant Current Level

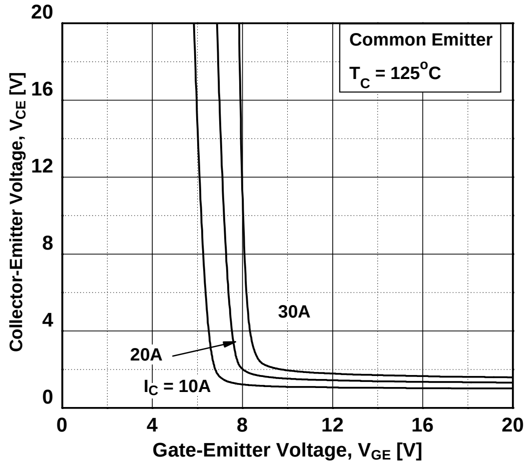



### Figure 6. Saturation Voltage vs. $V_{GE}$

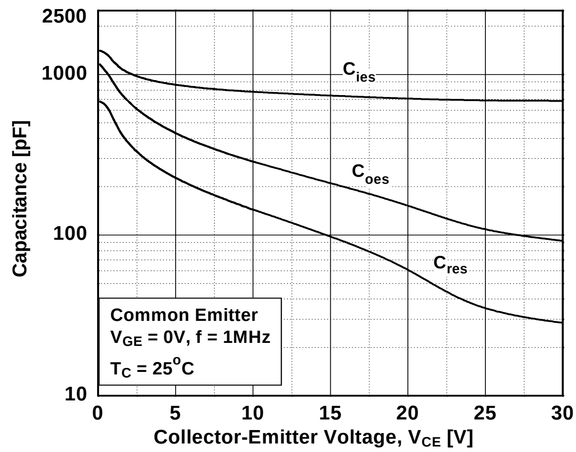


## Typical Performance Characteristics (Continued)

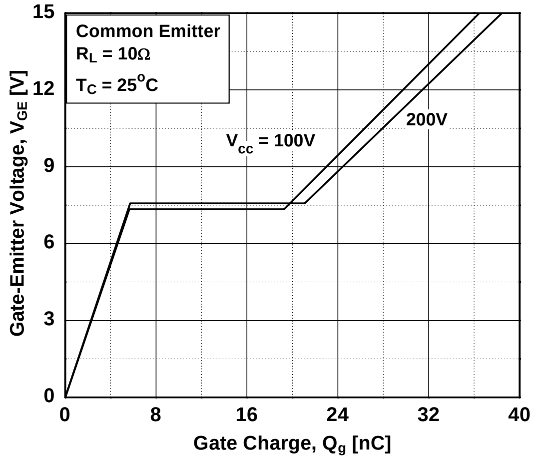
### Figure 7. Saturation Voltage vs.$V_{GE}$



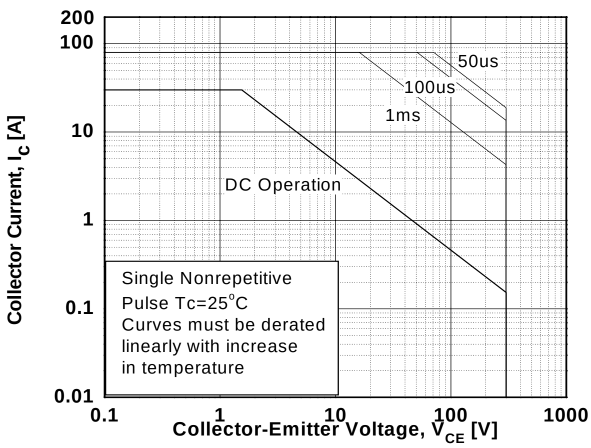

### Figure 8. Capacitance Characteristics



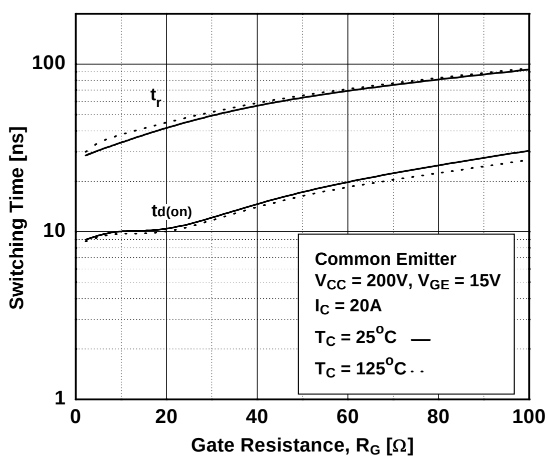

### Figure 9. Gate Charge Characteristics



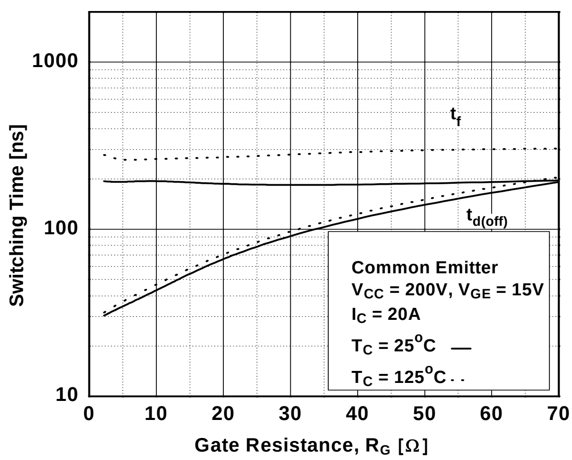

### Figure 10. SOA Characteristics




### Figure 11. Turn-On Characteristics vs. Gate Resistance




### Figure 12. Turn Off Characteristics vs. Gate Resistance



## Typical Performance Characteristics (Continued)

**Figure 13. Turn-On Characteristics vs. Collector Current**

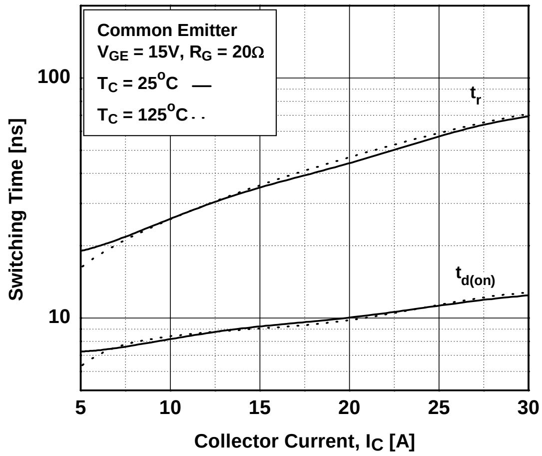



**Figure 14. Turn-Off Characteristics vs. Collector Current**

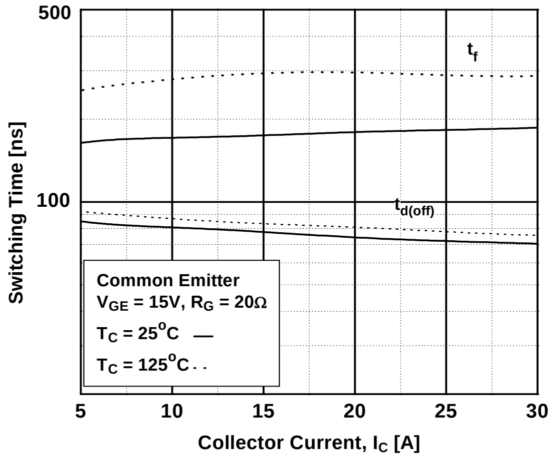



**Figure 15. Switching Loss vs Gate Resistance**

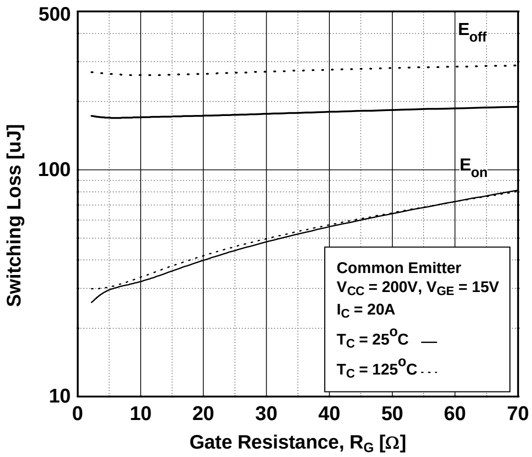



**Figure 16. Switching Loss vs Collector Current**

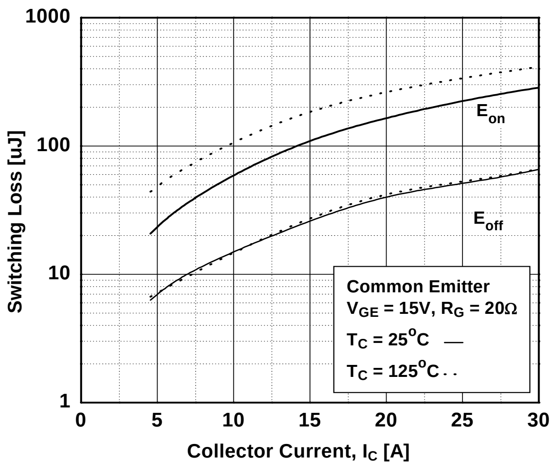
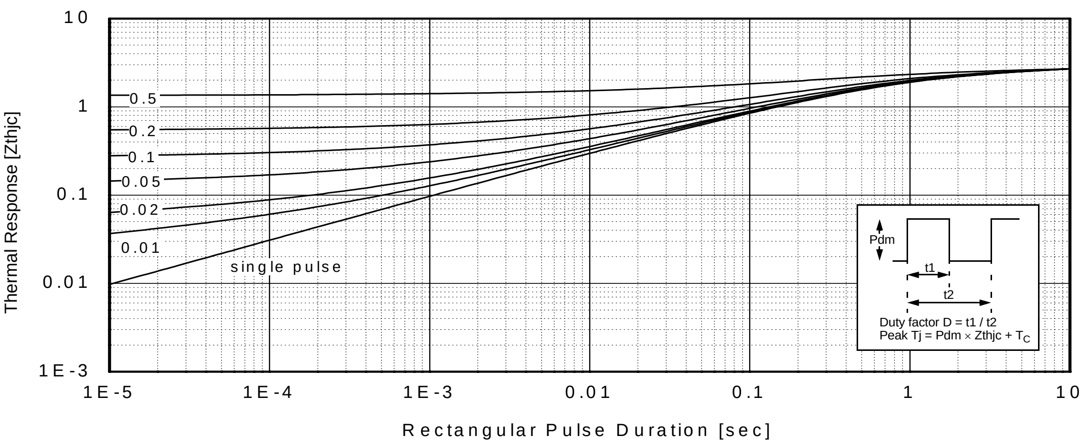
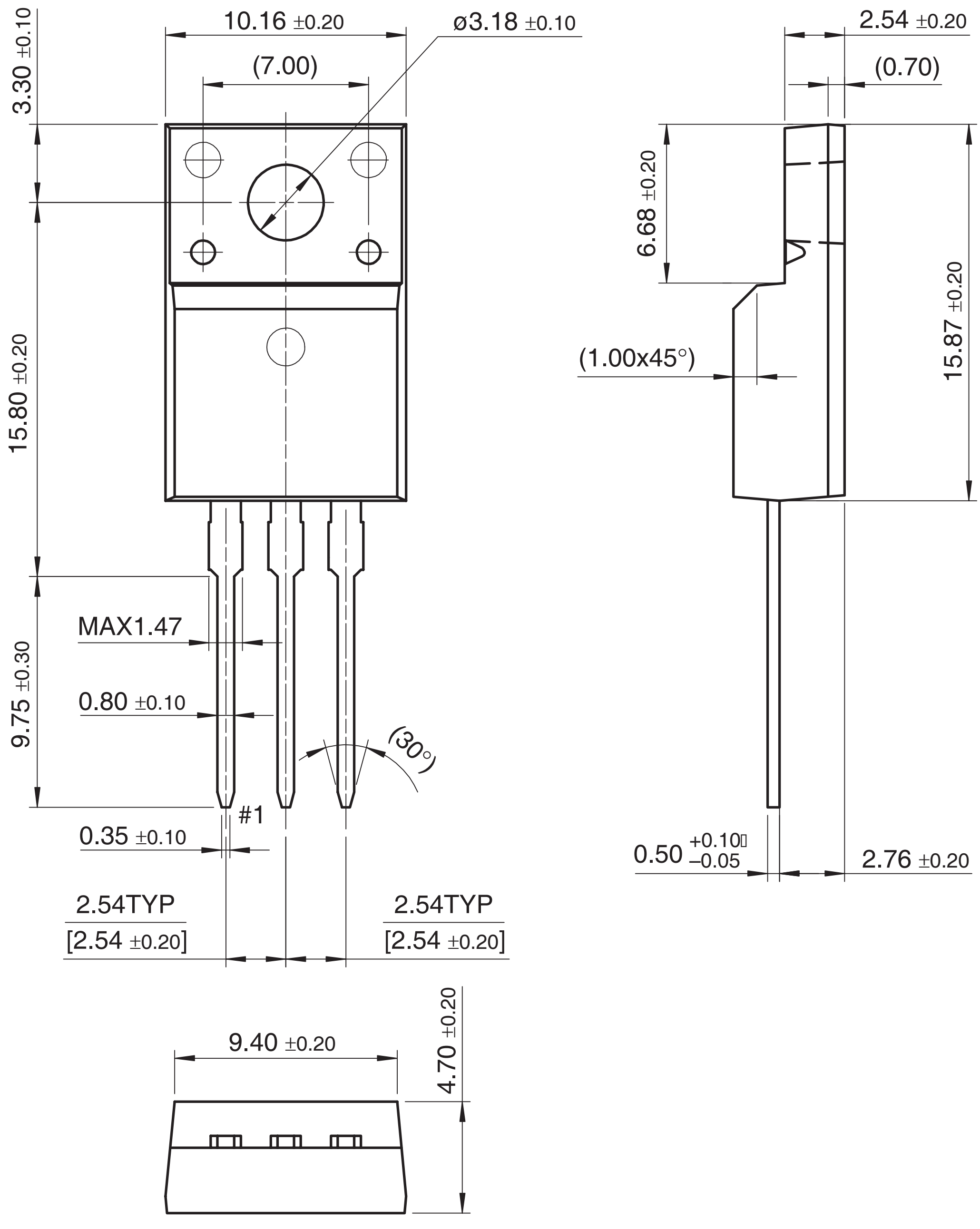



**Figure 17. Transient Thermal Impedance of IGBT**



# TO-220F


10.16 ±0.20
ø3.18 ±0.10
(7.00)
3.30 ±0.10
15.80 ±0.20
9.75 ±0.30
MAX1.47
0.80 ±0.10
(30°)
#1
0.35 ±0.10
2.54TYP
[2.54 ±0.20]
2.54TYP
[2.54 ±0.20]
2.54 ±0.20
(0.70)
6.68 ±0.20
15.87 ±0.20
(1.00x45°)
0.50 +0.10 −0.05
2.76 ±0.20
9.40 ±0.20
4.70 ±0.20

## TRADEMARKS

The following are registered and unregistered trademarks Fairchild Semiconductor owns or is authorized to use and is not intended to be an exhaustive list of all such trademarks.

ACEx™
ActiveArray™
Bottomless™
Build it Now™
CoolFET™
*CROSSVOLT*™
DOME™
EcoSPARK™
E$^2$CMOS™
EnSigna™
FACT™
FAST®
FASTr™
FPS™
FRFET™
FACT Quiet Series™
GlobalOptoisolator™
GTO™
HiSeC™
I$^2$C™
*i-Lo*™
ImpliedDisconnect™
IntelliMAX™
ISOPLANAR™
LittleFET™
MICROCOUPLER™
MicroFET™
MicroPak™
MICROWIRE™
MSX™
MSXPro™
Across the board. Around the world.™
The Power Franchise®
Programmable Active Droop™
OCX™
OCXPro™
OPTOLOGIC®
OPTOPLANAR™
PACMAN™
POP™
Power247™
PowerEdge™
PowerSaver™
PowerTrench®
QFET®
QS™
QT Optoelectronics™
Quiet Series™
RapidConfigure™
RapidConnect™
µSerDes™
ScalarPump™
SILENT SWITCHER®
SMART START™
SPM™
Stealth™
SuperFET™
SuperSOT™-3
SuperSOT™-6
SuperSOT™-8
SyncFET™
TCM™
TinyBoost™
TinyBuck™
TinyPWM™
TinyPower™
TinyLogic®
TINYOPTO™
TruTranslation™
UHC™
UniFET™
UltraFET®
VCX™
Wire™

**DISCLAIMER**
FAIRCHILD SEMICONDUCTOR RESERVES THE RIGHT TO MAKE CHANGES WITHOUT FURTHER NOTICE TO ANY PRODUCTS HEREIN TO IMPROVE RELIABILITY, FUNCTION OR DESIGN. FAIRCHILD DOES NOT ASSUME ANY LIABILITY ARISING OUT OF THE APPLICATION OR USE OF ANY PRODUCT OR CIRCUIT DESCRIBED HEREIN; NEITHER DOES IT CONVEY ANY LICENSE UNDER ITS PATENT RIGHTS, NOR THE RIGHTS OF OTHERS. THESE SPECIFICATIONS DO NOT EXPAND THE TERMS OF FAIRCHILD'S WORLDWIDE TERMS AND CONDITIONS, SPECIFICALLY THE WARRANTY THEREIN, WHICH COVERS THESE PRODUCTS.

**LIFE SUPPORT POLICY**
FAIRCHILD'S PRODUCTS ARE NOT AUTHORIZED FOR USE AS CRITICAL COMPONENTS IN LIFE SUPPORT DEVICES OR SYSTEMS WITHOUT THE EXPRESS WRITTEN APPROVAL OF FAIRCHILD SEMICONDUCTOR CORPORATION.

As used herein:
1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, or (c) whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in significant injury to the user.

2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

**PRODUCT STATUS DEFINITIONS**
**Definition of Terms**

| Datasheet Identification | Product Status | Definition |
|---|---|---|
| Advance Information | Formative or In Design | This datasheet contains the design specifications for product development. Specifications may change in any manner without notice. |
| Preliminary | First Production | This datasheet contains preliminary data, and supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design. |
| No Identification Needed | Full Production | This datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design. |
| Obsolete | Not In Production | This datasheet contains specifications on a product that has been discontinued by Fairchild semiconductor. The datasheet is printed for reference information only. |

Rev. I20

TOSHIBA PHOTOCOUPLER GaAℓAs IRED & PHOTO IC

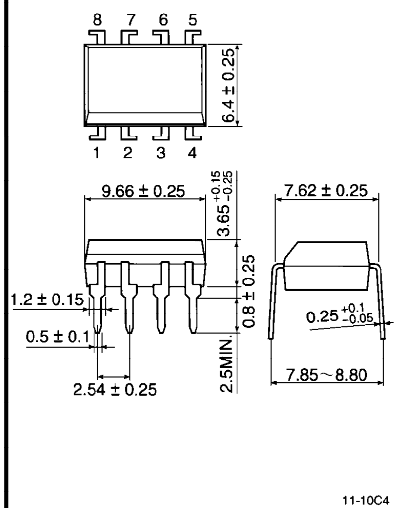
# 6N137

DEGITAL LOGIC ISOLATION

TELE-COMMUNICATION

ANALOG DATA EQUIPMENT CONTROL

Unit in mm




TOSHIBA 11-10C4

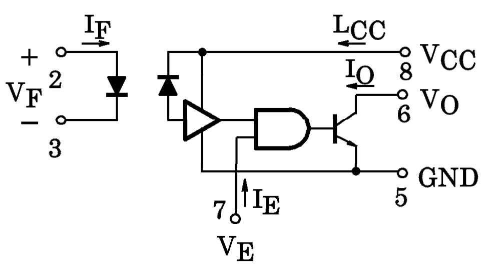
Weight : 0.54g

The TOSHIBA 6N137 consist of a high emitting diode and a one chip photo IC. This unit is 8-lead DIP package.

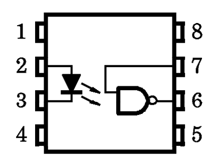
- LSTTL / TTL Compatible : 5V Supply
- Ultra High Speed : 10MBd
- Guaranteed Performance Over Temperature : 0°C to 70°C
- High Isolation Voltage : 2500Vrms Min.
- UL Recognized : UL1577, File No. E67349

TRUTH TABLE

| INPUT | ENABLE | OUTPUT |
|---|---|---|
| H | H | L |
| L | H | H |
| H | L | H |
| L | L | H |




PIN CONFIGURATIONS (Top view)




1 : N.C.
2 : ANODE
3 : CATHODE
4 : N.C.
5 : GND
6 : OUTPUT (OPEN COLLECTOR)
7 : ENABLE
8 : $V_{CC}$

## MAXIMUM RATINGS

| | CHARACTERISTIC | SYMBOL | RATING | UNIT |
|---|---|---|---|---|
| LED | Forward Current | $I_F$ | 20 | mA |
| | Pulse Forward Current (Note 1) | $I_{FP}$ | 40 | mA |
| | Reverse Voltage | $V_R$ | 5 | V |
| DETECTOR | Output Current | $I_O$ | 50 | mA |
| | Output Voltage | $V_O$ | 7 | V |
| | Supply Voltage (1 minute Maximum) | $V_{CC}$ | 7 | V |
| | Enable Input Voltage (Not to exceed $V_{CC}$ by More than 500mV) | $V_{EH}$ | 5.5 | V |
| | Output Collector Power Dissipation | $P_O$ | 85 | mW |
| Operating Temperature Range | | $T_{opr}$ | 0~70 | °C |
| Storage Temperature Range | | $T_{stg}$ | −55~125 | °C |
| Lead Solder Temperature (10s) (Note 2) | | $T_{sol}$ | 260 | °C |

(Note 1) 50% duty cycle, 1ms Pulse width.
(Note 2) Soldering portion of lead : up to 2mm from the body of the device.

## RECOMMENDED OPERATING CONDITIONS

| CHARACTERISTIC | SYMBOL | MIN. | MAX. | UNIT |
|---|---|---|---|---|
| Input Current, Low Level Each Channel | $I_{FL}$ | 0 | 250 | μA |
| Input Current, High Level Each Channel | $I_{FH}$ | 7 | 20 | mA |
| High Level Enable Voltage | $V_{EH}$ | 2.0 | $V_{CC}$ | V |
| Low Level Enable Voltage (Output High) | $V_{EL}$ | 0 | 0.8 | V |
| Supply Voltage, Output | $V_{CC}$ | 4.5 | 5.5 | V |
| Fan Out (TTL LOAD) | N | — | 8 | — |
| Operating Temperature | Ta | 0 | 70 | °C |

## PRECAUTION

Please be careful of the followings.

A ceramic capacitor (0.1μF) should be connected from pin 8 to pin 5 to stabilize the operation of the high gain linear amplifier. Failure to provide the bypassing may impair the switching property. The total lead length between capacitor and coupler should not exceed 1cm.

ELECTRICAL CHARACTERISTICS
OVER RECOMMENDED TEMPERATURE (Ta = 0~70°C unless otherwise noted)

| CHARACTERISTIC | SYMBOL | TEST CONDITION | MIN. | (**)TYP. | MAX. | UNIT |
|---|---|---|---|---|---|---|
| High Level Output Current | $I_{OH}$ | $V_{CC}=5.5V$, $V_O=5.5V$<br>$I_F=250\mu A$, $V_E=2.0V$ | — | 1 | 250 | μA |
| Low Level Output Voltage | $V_{OL}$ | $V_{CC}=5.5V$, $I_F=5mA$<br>$V_{EH}=2.0V$<br>$I_{OL}$ (Sinking) $=13mA$ | — | 0.4 | 0.6 | V |
| High Level Enable Current | $I_{EH}$ | $V_{CC}=5.5V$, $V_E=2.0V$ | — | −1.0 | — | mA |
| Low Level Enable Current | $I_{EL}$ | $V_{CC}=5.5V$, $V_E=0.5V$ | — | −1.6 | −2.0 | mA |
| High Level Supply Current | $I_{CCH}$ | $V_{CC}=5.5V$, $I_F=0$, $V_E=0.5V$ | — | 7 | 15 | mA |
| Low Level Supply Current | $I_{CCL}$ | $V_{CC}=5.5V$, $I_F=10mA$<br>$V_E=0.5V$ | — | 12 | 18 | mA |
| Resistance (Input-Output) (Note 3) | $R_{I-O}$ | $V_{I-O}=500V$, $Ta=25°C$<br>R.H.≦60% | — | $10^{12}$ | — | Ω |
| Capacitance (Input-Output) (Note 3) | $C_{I-O}$ | f=1MHz, Ta=25°C | — | 0.6 | — | pF |
| Input Forward Voltage | $V_F$ | $I_F=10mA$, $Ta=25°C$ | — | 1.65 | 1.75 | V |
| Input Reverse Breakdown Voltage | $BV_R$ | $I_R=10\mu A$, $Ta=25°C$ | 5 | — | — | V |
| Input Capacitance | $C_{IN}$ | $V_F=0$, f=1MHz | — | 45 | — | pF |
| Current Transfer Ratio | CTR | $I_F=5.0mA$, $R_L=100\Omega$ | — | 1000 | — | % |

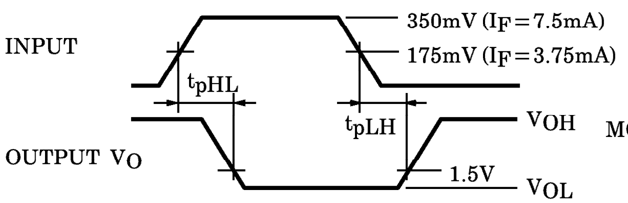
(**) All typical values are at $V_{CC}=5V$, $Ta=25°C$
(Note 3) Pins 1, 2, 3 and 4 shorted together and Pins 5, 6, 7 and 8 shorted together.

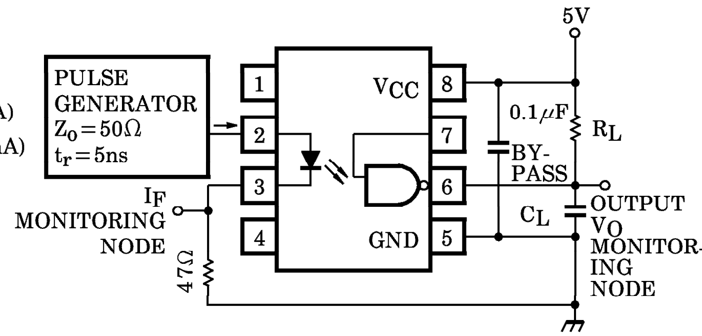
SWITCHING CHARACTERISTICS ($Ta = 25°C$, $V_{CC} = 5V$)

| CHARACTERISTIC | SYMBOL | TEST CIRCUIT | TEST CONDITION | MIN. | TYP. | MAX. | UNIT |
|---|---|---|---|---|---|---|---|
| Propagation Delay Time to High Output Level | $t_{pLH}$ | 1 | $R_L = 350\Omega$, $C_L = 15pF$<br>$I_F = 7.5mA$ | — | 60 | 75 | ns |
| Propagation Delay Time to Low Output Level | $t_{pHL}$ | 1 | $R_L = 350\Omega$, $C_L = 15pF$<br>$I_F = 7.5mA$ | — | 60 | 75 | ns |
| Output Rise-Fall Time (10-90%) | $t_r$, $t_f$ | — | $R_L = 350\Omega$, $C_L = 15pF$<br>$I_F = 7.5mA$ | — | 30 | — | ns |
| Propagation Delay Time of Enable from $V_{EH}$ to $V_{EL}$ | $t_{ELH}$ | 2 | $R_L = 350\Omega$, $C_L = 15pF$<br>$I_F = 7.5mA$<br>$V_{EH} = 3.0V$<br>$V_{EL} = 0.5V$ | — | 25 | — | ns |
| Propagation Delay Time of Enable from $V_{EL}$ to $V_{EH}$ | $t_{EHL}$ | 2 | $R_L = 350\Omega$, $C_L = 15pF$<br>$I_F = 7.5mA$<br>$V_{EH} = 3.0V$<br>$V_{EL} = 0.5V$ | — | 25 | — | ns |
| Common Mode Transient Immunity at Logic High Output Level | $CM_H$ | 3 | $V_{CM} = 10V$<br>$R_L = 350\Omega$<br>$V_{O\,(min.)} = 2V$<br>$I_F = 0mA$ | — | 200 | — | V / μs |
| Common Mode Transient Immunity at Logic Low Output Level | $CM_L$ | 3 | $V_{CM} = 10V$<br>$R_L = 350\Omega$<br>$V_{O\,(max.)} = 0.8V$<br>$I_F = 5mA$ | — | −500 | — | V / μs |

TEST CIRCUIT 1.

$t_{pHL}$ and $t_{pLH}$

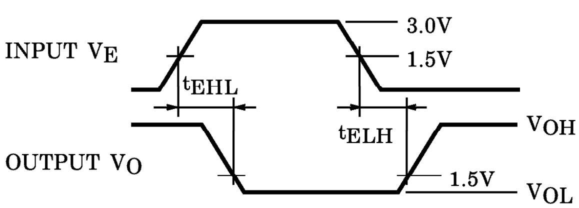


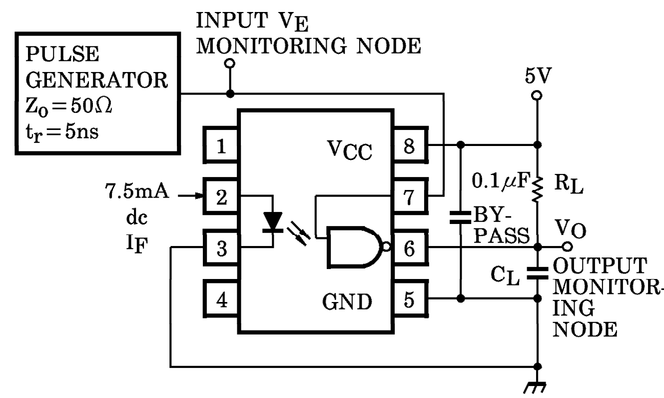




· $C_L$ is approximately 15pF which includes probe and stray wiring capacitance.

TEST CIRCUIT 2.

$t_{ELH}$ and $t_{EHL}$

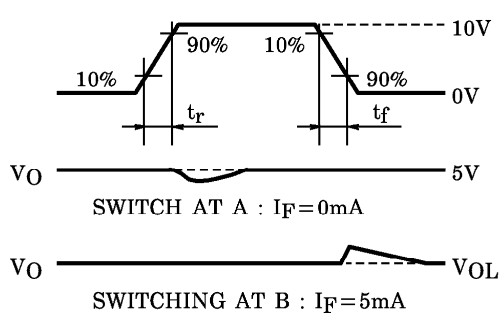


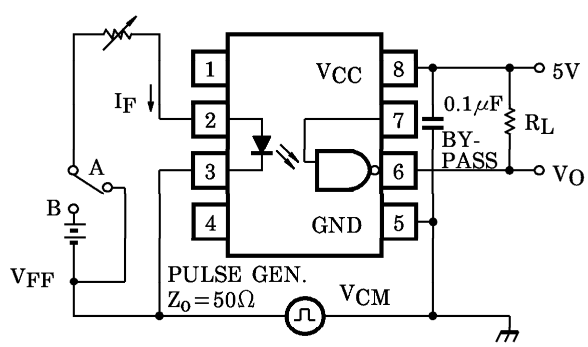




· $C_L$ is approximately 15pF which includes prove and stray wiring capacitance.

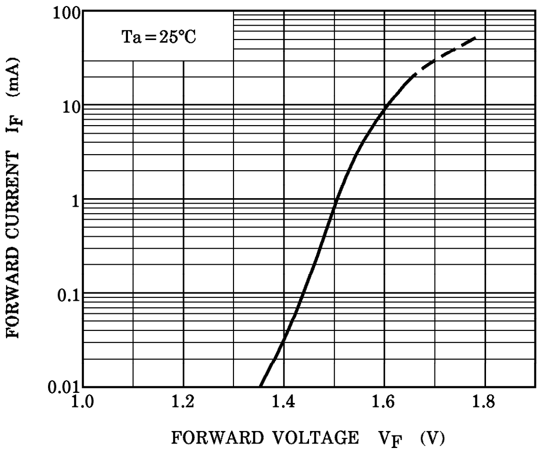
TEST CIRCUIT 3.

Transient Immunity and Typical Waveforms

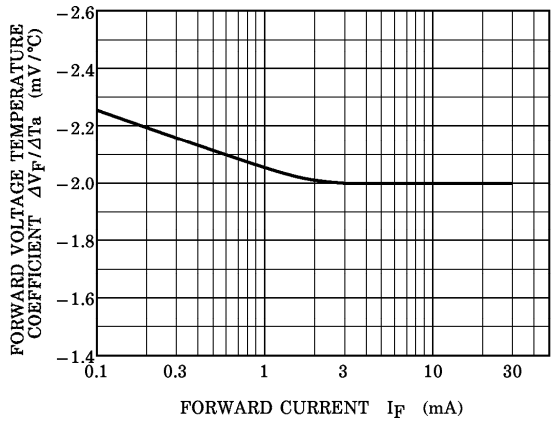


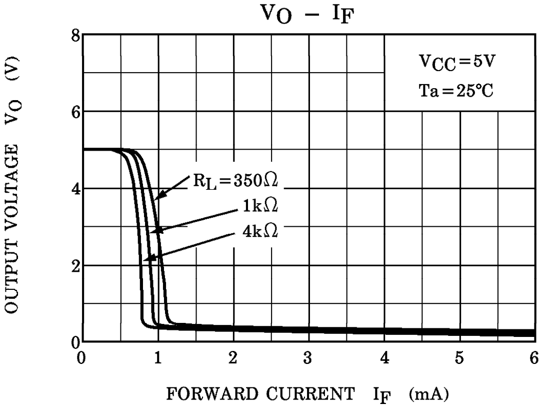
$I_F - V_F$



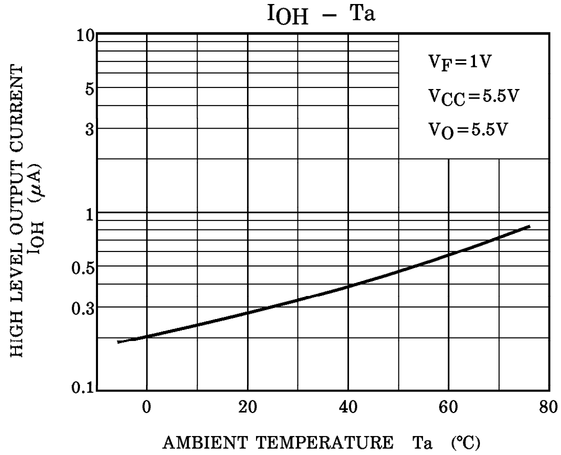

$\Delta V_F / \Delta Ta - I_F$



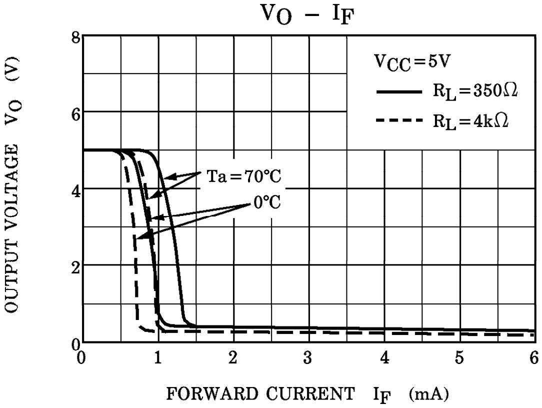

$V_O - I_F$



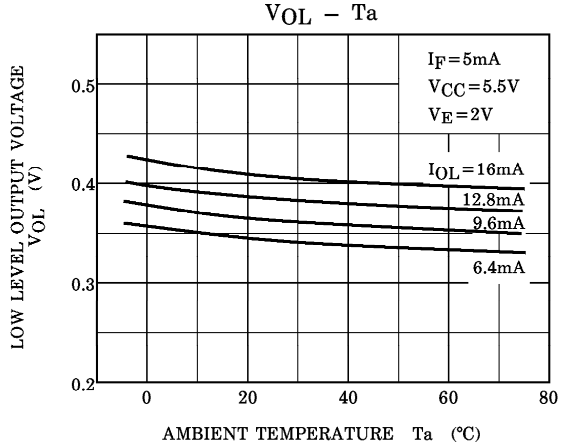

$I_{OH} - Ta$

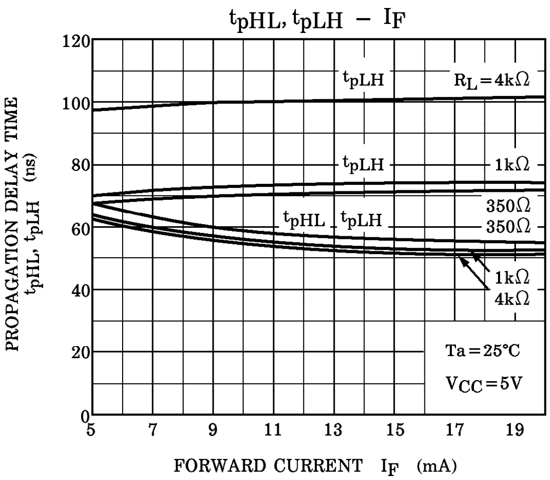


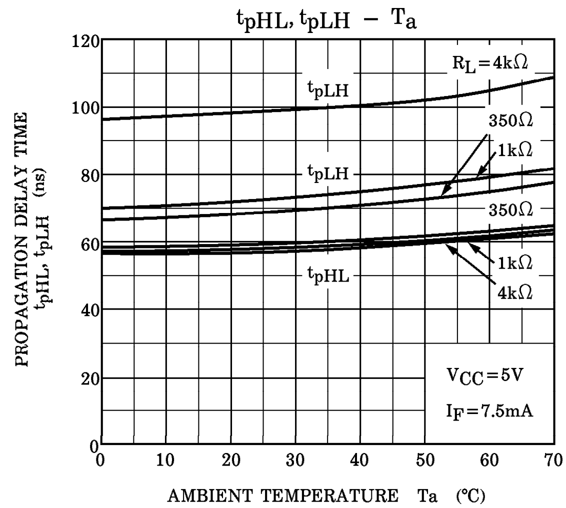

$V_O - I_F$

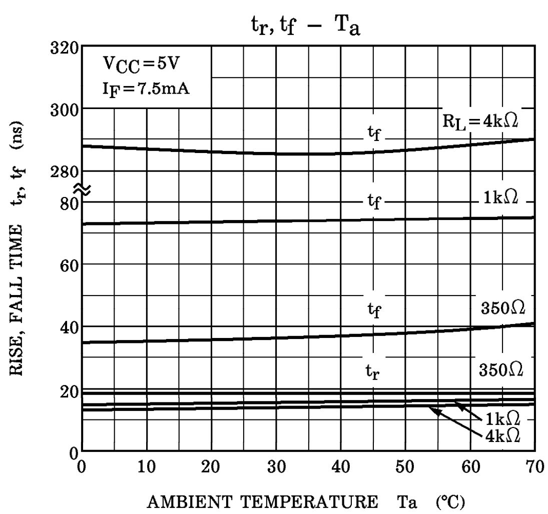


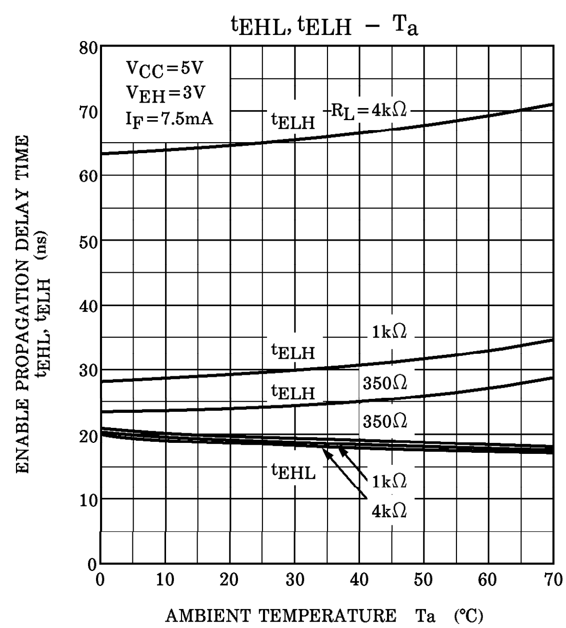

$V_{OL} - Ta$




tpHL, tpLH − IF
PROPAGATION DELAY TIME tpHL, tpLH (ns)
FORWARD CURRENT IF (mA)
Ta = 25°C
VCC = 5V
RL = 4kΩ
1kΩ
350Ω
tpLH
tpHL


tpHL, tpLH − Ta
PROPAGATION DELAY TIME tpHL, tpLH (ns)
AMBIENT TEMPERATURE Ta (°C)
VCC = 5V
IF = 7.5mA
RL = 4kΩ
350Ω
1kΩ
4kΩ
tpLH
tpHL


tr, tf − Ta
RISE, FALL TIME tr, tf (ns)
AMBIENT TEMPERATURE Ta (°C)
VCC = 5V
IF = 7.5mA
RL = 4kΩ
1kΩ
350Ω
4kΩ
tf
tr


tEHL, tELH − Ta
ENABLE PROPAGATION DELAY TIME tEHL, tELH (ns)
AMBIENT TEMPERATURE Ta (°C)
VCC = 5V
VEH = 3V
IF = 7.5mA
RL = 4kΩ
1kΩ
350Ω
4kΩ
tELH
tEHL