INTRODUCTION

• Access to energy has become a fundamental necessity, serving as the backbone of economic development, technological progress, and improved quality of life.

• Reliable electricity is essential not only for the commercial and industrial (C&I) sectors but also for meeting the daily needs of households in both urban and rural regions. Although the Government of India officially declared in 2019 that all villages had been electrified, the ground reality in 2025 reveals that a significant portion of rural households still lack dependable and quality access to electricity.

• In many parts of the country—particularly in remote, hilly, and northeastern regions—the power supply is often irregular, characterized by low voltage and limited availability, sometimes restricted to just 8–10 hours per day.

• Recent national surveys and independent research studies estimate that nearly 40–50 million people in rural India continue to face unreliable electricity supply. This persistent challenge underscores the urgent need for alternative, sustainable, and decentralized energy solutions.

• So, the focus has increasingly shifted toward renewable energy sources such as solar, wind biogas, geothermal, hydro and ocean-based power generation. These technologies promote environmental sustainability.

OVERVIEW AND PRESENT SCENARIO OF POWER SYSTEM IN INDIA

India's power system is undergoing a major transformation aimed at providing clean, reliable, and affordable electricity to all. With over 420 GW of installed capacity (as of early 2025), India is the third-largest producer and consumer of electricity in the world.

Installed Capacity Overview

As of 2025, India's installed power generation capacity is approximately 420 GW, with the following distribution:

Source	Capacity (GW)	Share (%)
Coal (Thermal)	**~202**	**48%**
Renewable Energy (Solar, Wind)	**~125**	**30%**
Hydro (Large + Small)	**~47**	**11%**
Nuclear	**~13**	**3%**
Natural Gas, Diesel	**~33**	**8%**

India aims to reach 500 GW of non-fossil fuel capacity by 2030 as part of its climate goals.

Electricity Consumption and Demand Trends

Peak Demand (2024–25): Exceeded 250 GW, driven by increased air-conditioning, industry, and electric vehicles.

Per Capita Electricity Consumption: ~1,200 kWh/year (still below the global average of ~3,500 kWh).

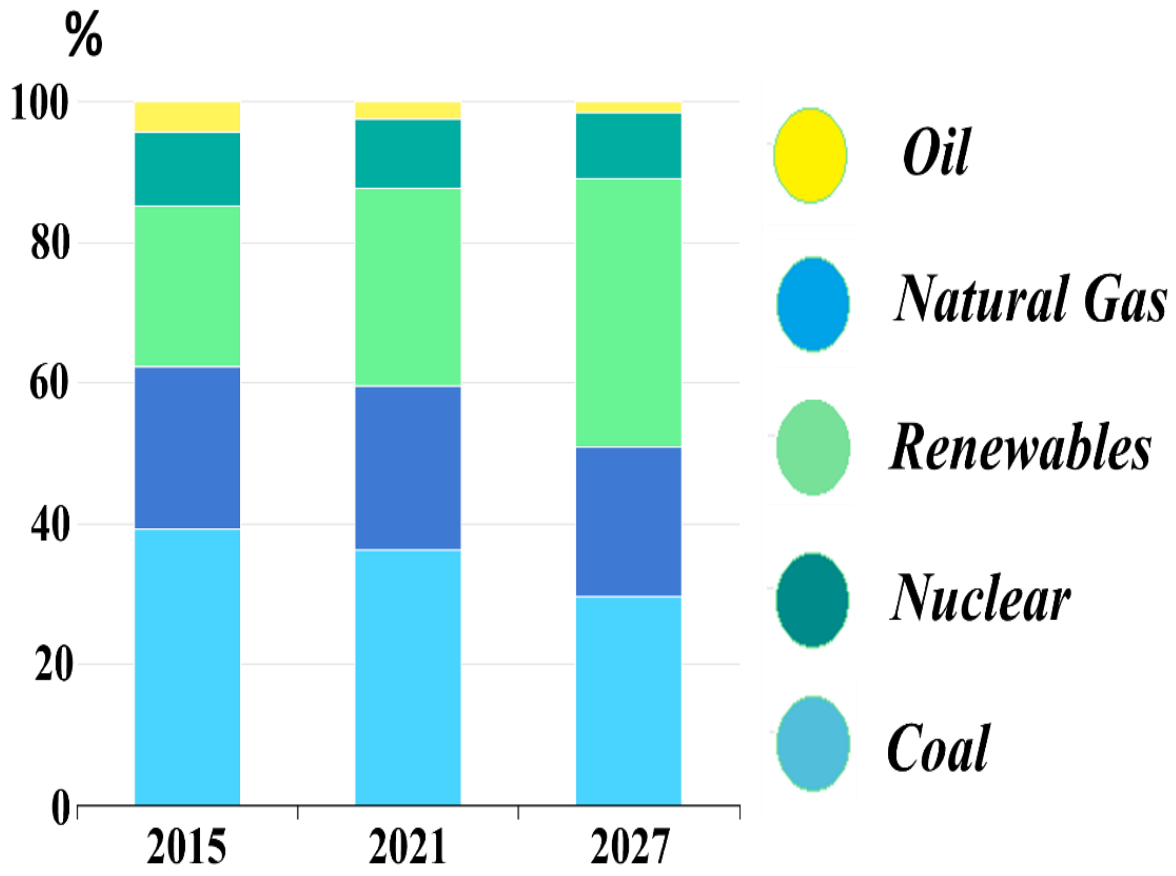
- **Demand-Side Distribution:**
  - Industrial: ~40%
  - Residential: ~25%
  - Agriculture: ~18%
  - Commercial and others: ~17%

Renewable Energy Progress

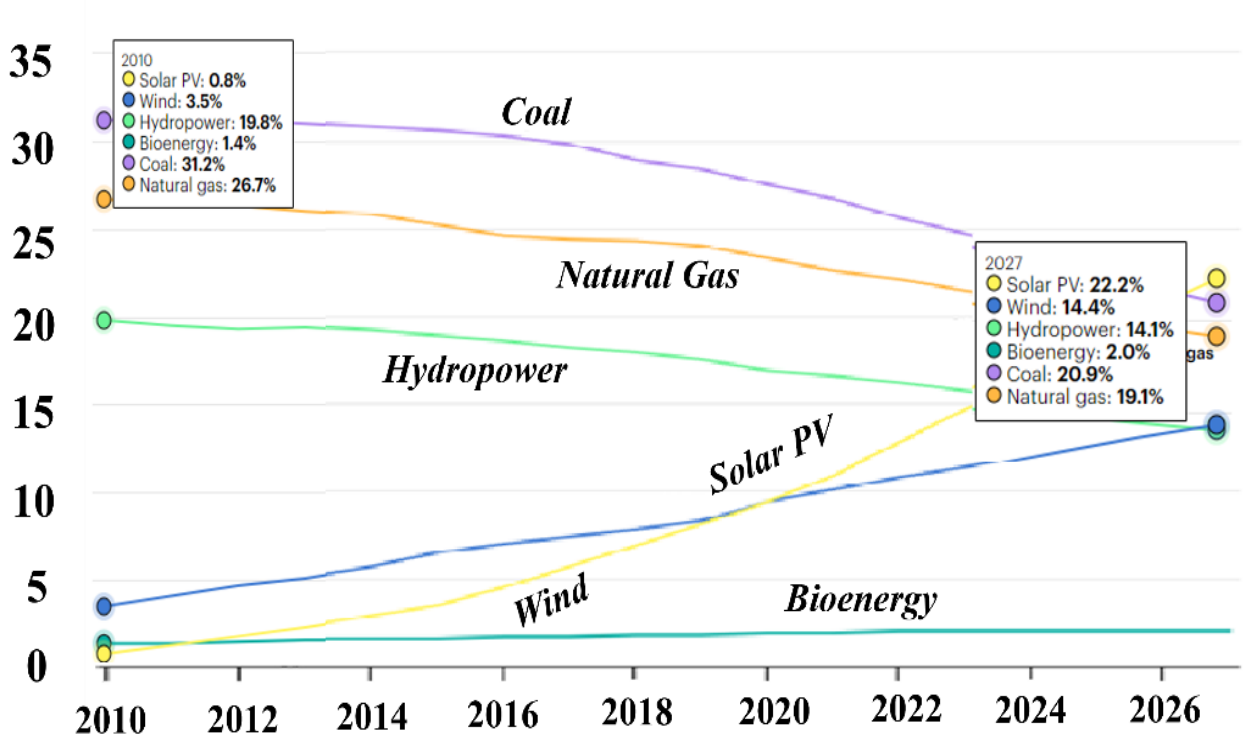
- Solar Power: Installed capacity crossed 75 GW.
- Wind Energy: Installed capacity around 45 GW.
- **Targets for 2030:**
  - 280 GW Solar,
  - 140 GW Wind,
  - 10 GW Biomass,
  - 15 GW Hydro.

Large-scale projects include floating solar plants, offshore wind farms, and solar parks under MNRE (Ministry of New and Renewable Energy).

Global trend of electricity generation using different technology



✓ Global trend of electricity generation trend from 2015 to 2027 predicts electricity generation by renewable energy (22.8% to 38.1%) is increasing and using coal (39.4% to 29.7%) and oil (4.2% to 1.5%) it is decreasing.

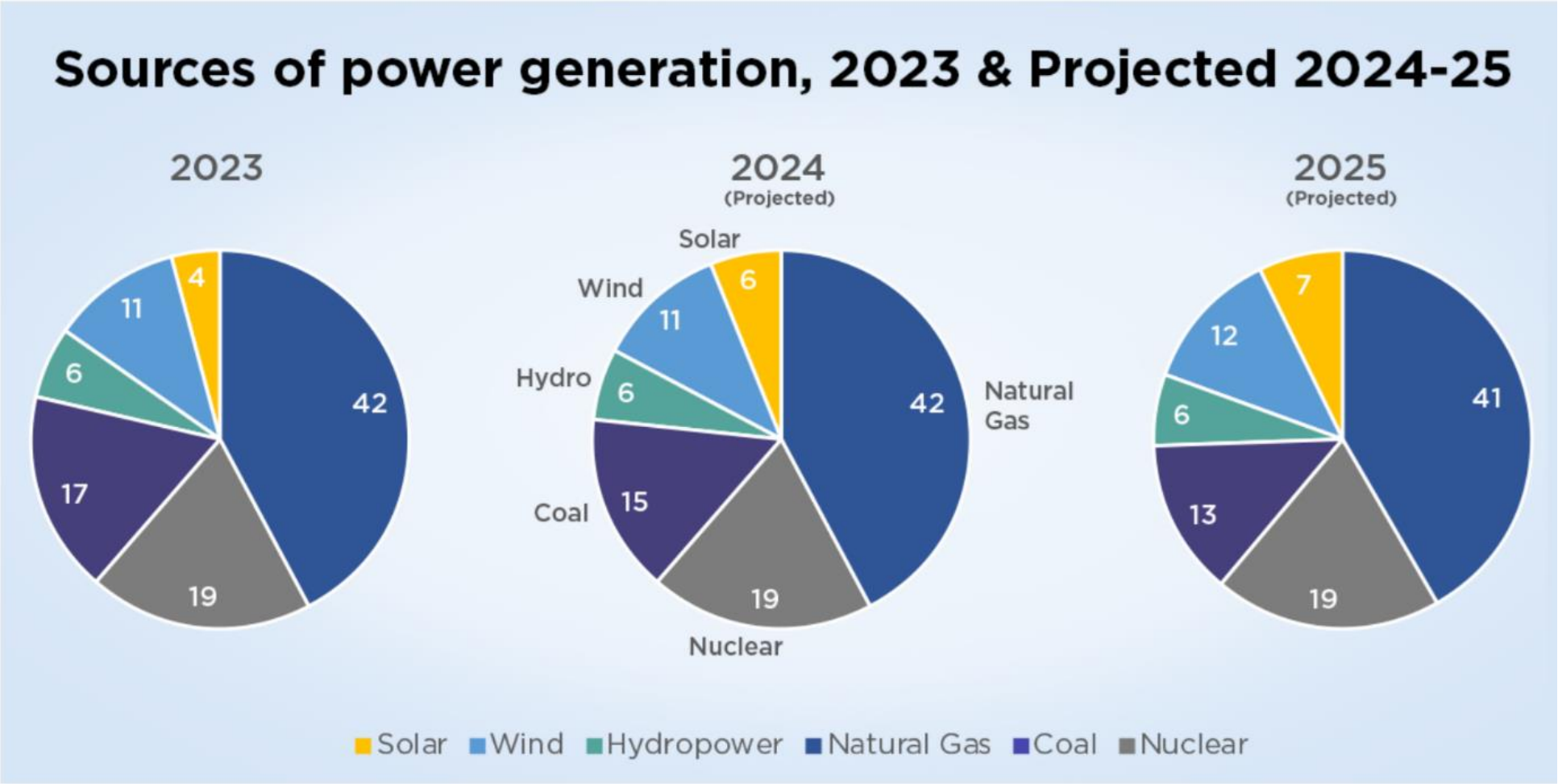


✓ Global trend of the cumulative power capacity by different technology from 2010 to 2027 predicts the energy generation by solar PV technology is increasing rapidly from 0.8 % to 22.2%

Global trend of cumulative power capacity using different technology

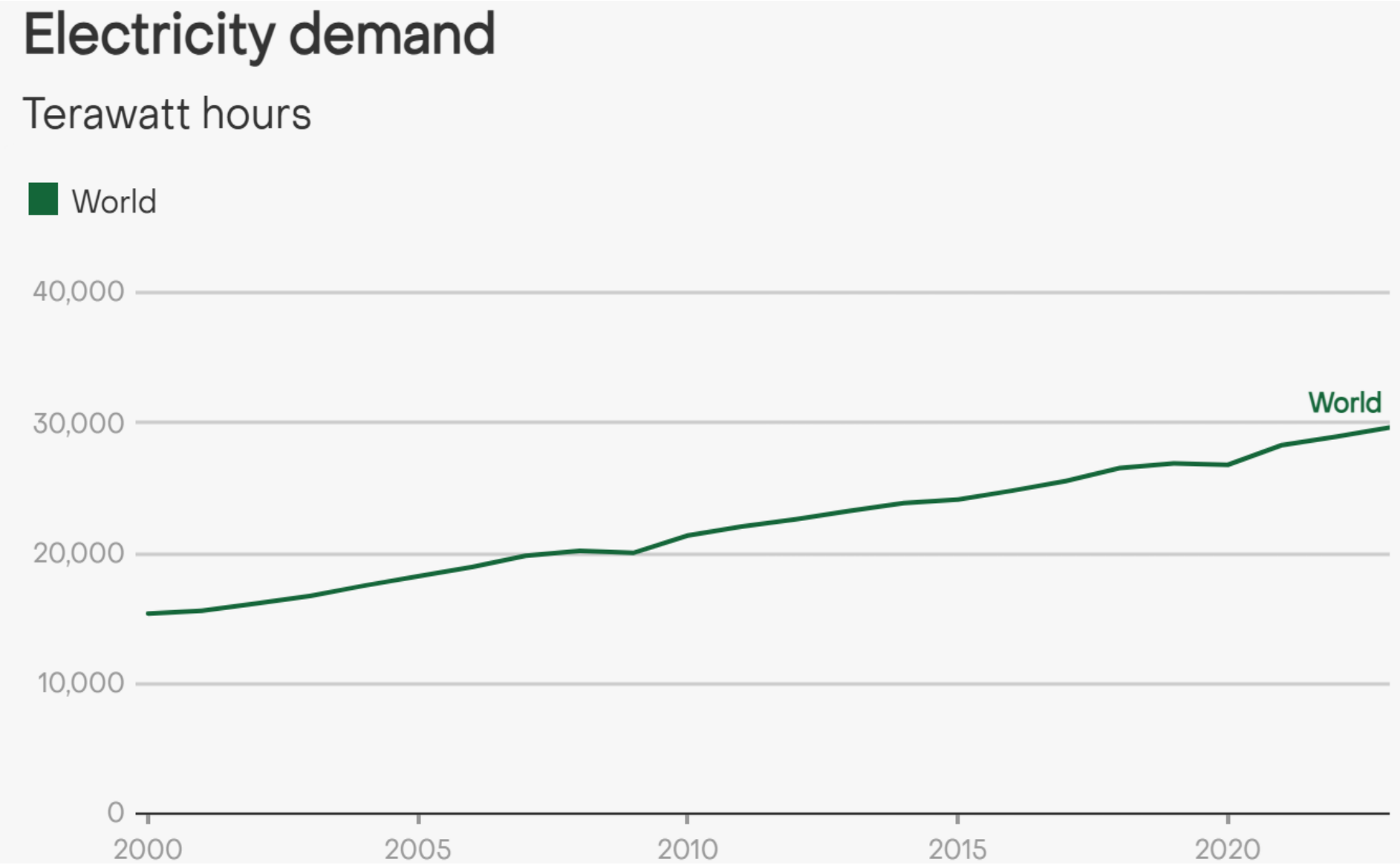
[1] IEA, Global electricity generation by technology, 2015, 2021 and 2027, IEA, Paris https://www.iea.org/data and statistics/charts/global electricity-generation-by-technology-2015- 2021-and-2027

[2] IEA, Share of cumulative power capacity by technology, 2010-2027, IEA, Paris https://www.iea.org/data-and statistics/charts/share-of-cumulative-power-capacity-by-technology- 2010-2027



Contribution of differer sources of power generation.

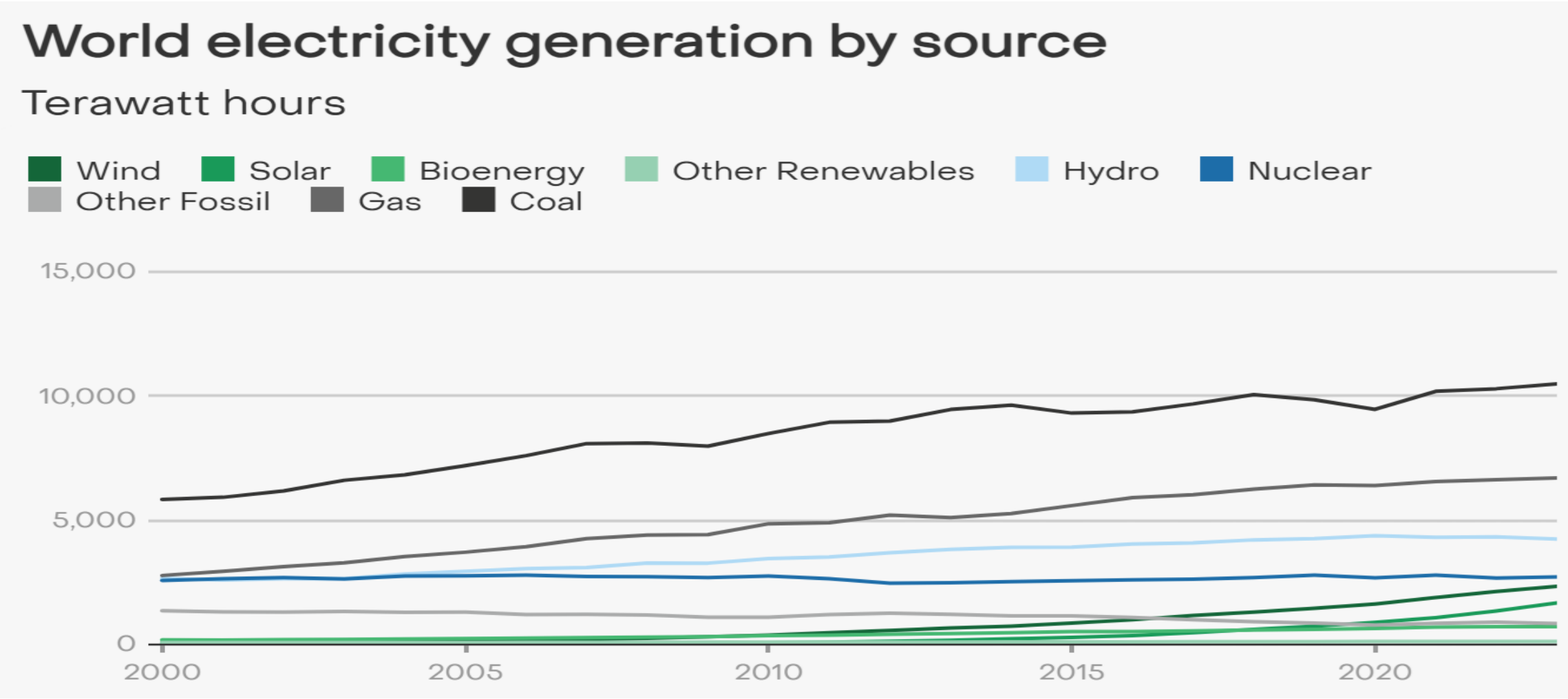
• Fossil fuel-based energy sources hold the top position regarding the deployed power-generating units. The rapid and consistent extraction of fossil fuels is responsible for the deterioration of its reserve capacity.
• Using fossil fuels as energy sources increases the carbon footprint, which is undoubtedly a well-recognized and well-talked challenge of the 21st century.
• Renewable energy sources such as solar, wind, geothermal, hydro (on small and large scales), ocean energy, fuel cells, and green hydrogen may pave the way to perceiving low carbon emissions worldwide without compromising the growing living standard.



Electricity demand worldwide (Source: Ember Electricity Data Explorer, ember-energy.org)

• A continuous improvement in the standard of living demands high energy consumption, especially electrical energy consumption, the most convenient form of energy used to cater to day-to-day activities.

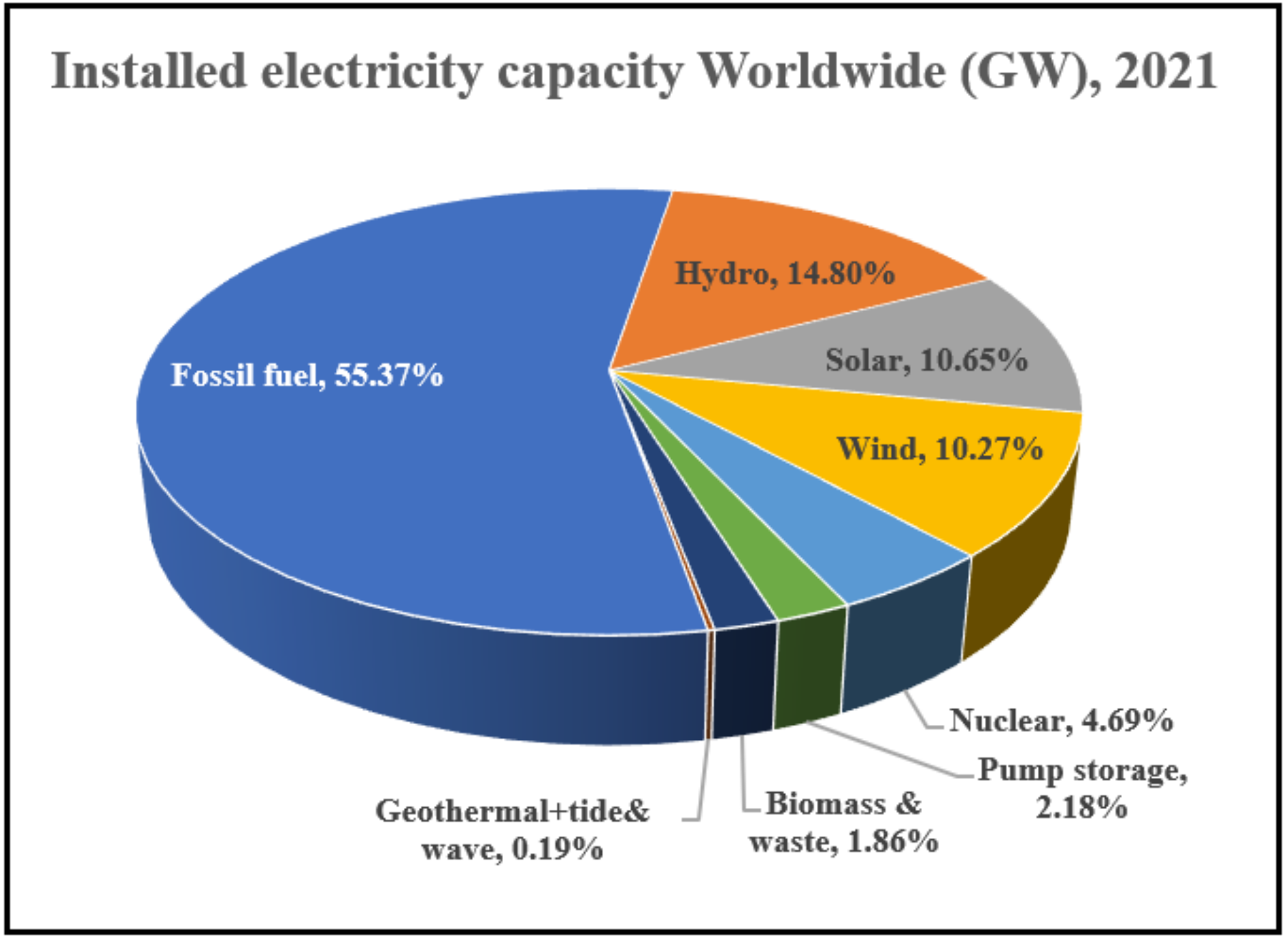
•According to the report, in 2023, the global electricity demand of the whole world climbed to 29,471 TWh



(Source: Ember Electricity Data Explorer, ember-energy.org)

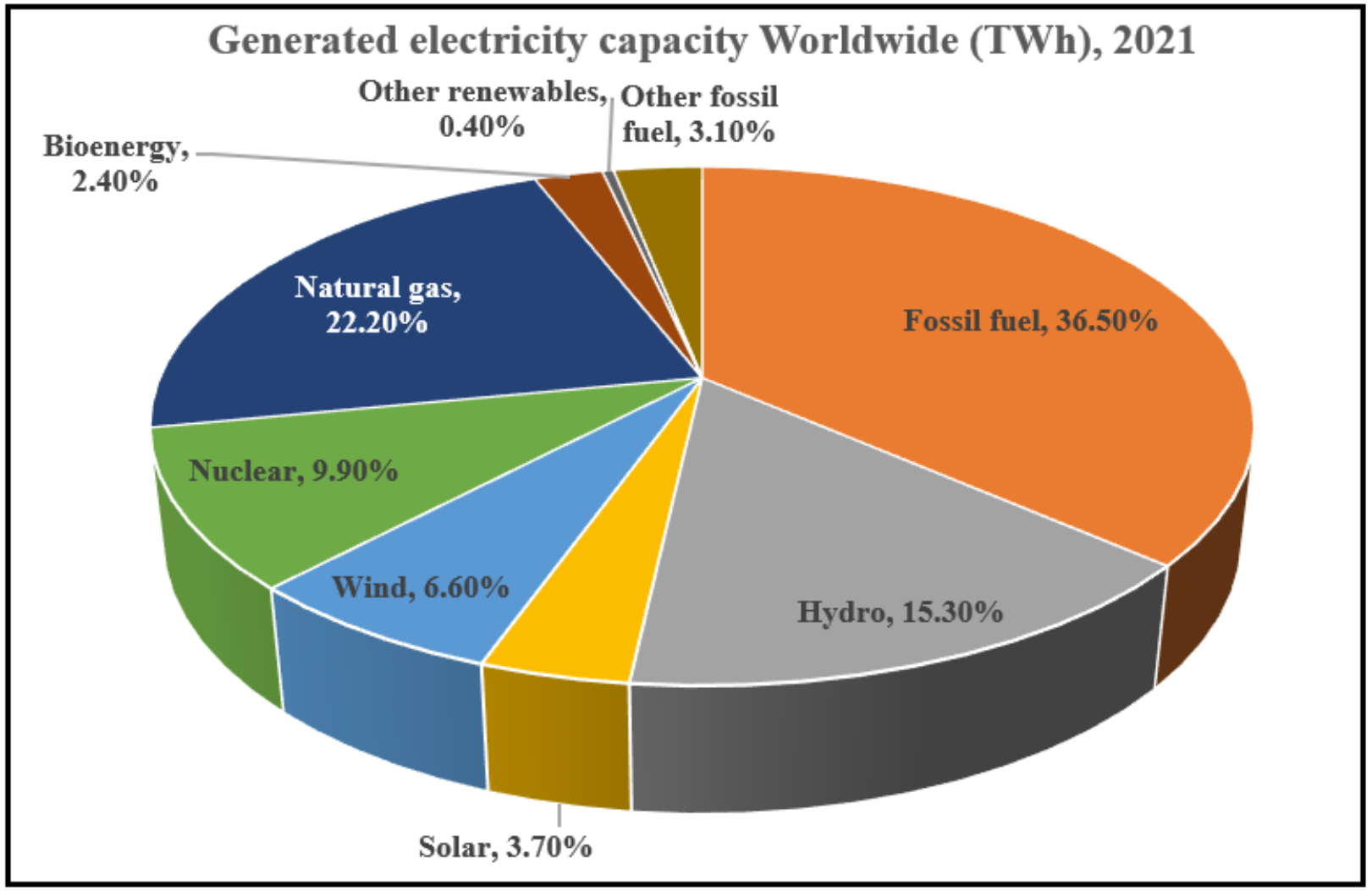
• Steady uptrend is observed and predicted in the production of electricity by the renewable energy sources.

• Among the numerous renewable energy sources, solar energy is considered as one of the most effective energy sources as it can provide adequate power output without damaging the environment in a significant way. The energy incident from the Sun, the most predominant source of energy, on the earth crust in one hour is higher than the worldwide annual energy consumption



- Figure shows the global installed electricity capacity of different types of sources as on 2021 which is 8012.98 GW. Out of that, 10.65% is from solar photovoltaics.

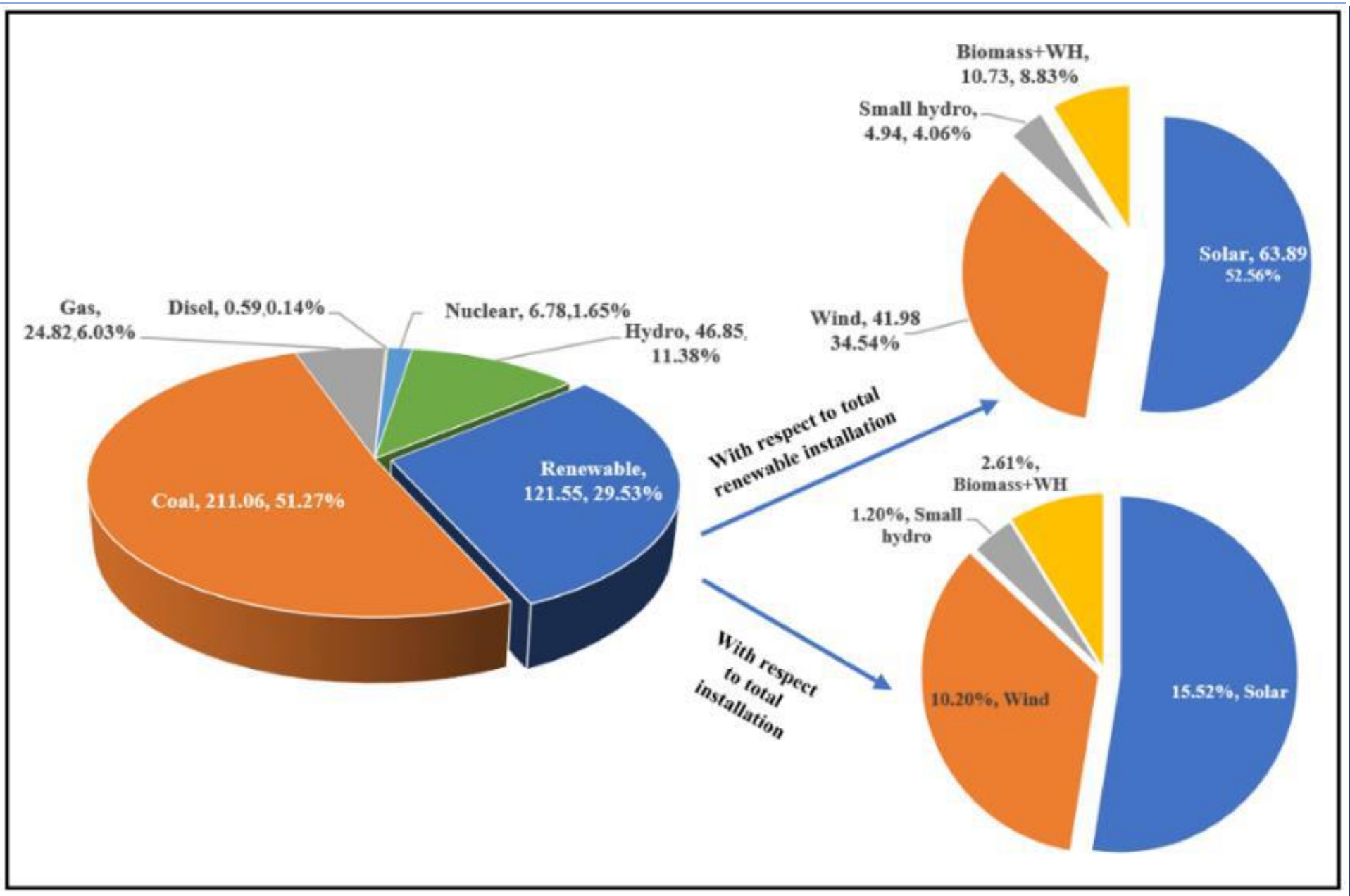
[1] https://www.statista.com/statistics/267358/world-installed-power-capacity/



• The global generated energy share for 2021 and shows that solar PV contributed just 3.7% of the overall energy generated. Thus, for 2021, the global situation is that solar PV is 10.65% (853 GW) of the total installed capacity (including fossil fuel) of electricity, 8010.42 GW. But the PV generation share is only 3.7% of total energy generation of 28003 TWh (from all the sources) [1]. PV capacity grows upto 12.3% and its contribution in energy generation increases upto 4.5% in 2022 in world market [2], [3].

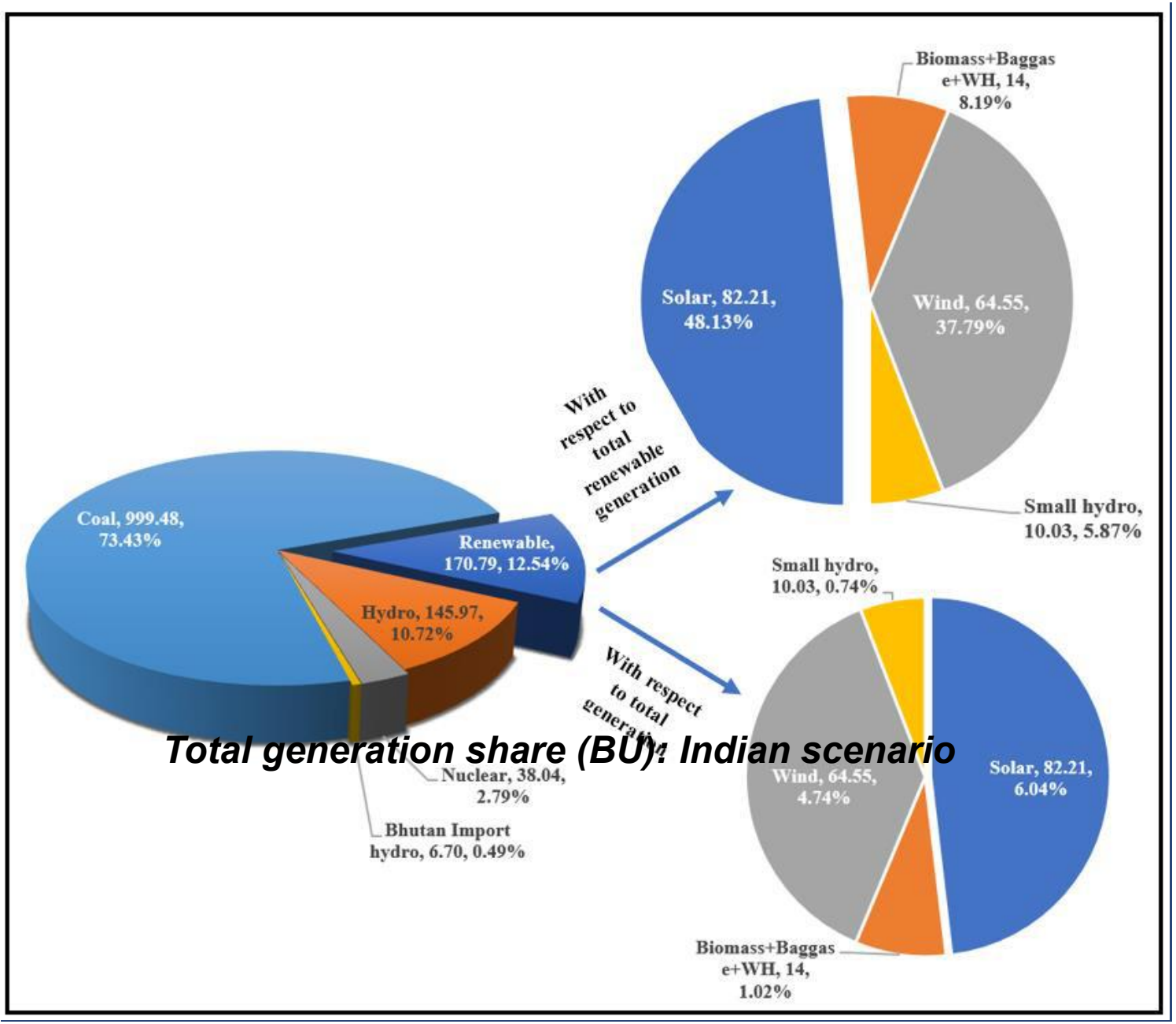
[1] https://ember-climate.org/data-catalogue/yearly-electricity-data/
[2] https://www.statista.com/statistics/1302055/global-solar-energy-share-electricity-mix/
[3] https://www.iea.org/energy-system/renewables/solar-pv

Total installed capacity (GW): Indian scenario



- In the Indian scenario, the installation of renewable resources amounts to be 29.53% (as on January 2023) [Ref] in which more than 50% comes from solar PV applications. Figure illustrates that it is just 15.52% of the entire capacity that is installed.

[Ref] Broad Overview of Monthly Renewable Energy Generation, Central Electricity Authority (CEA), January 2023, https://cea.nic.in/renewable-generation-report/?lang=en



Total generation share (BU): Indian scenario

One Billion Units is equivalent to one terawatt-hour (TWh)

• From the energy generation point of view, according to the figure fossil fuel sources share 73.43% whereas, that from solar PV sources it is 48.13% of renewable generation and only 6.04% of as a whole energy output from all sources.

• Considering the installed Photovoltaic capacity in India (63.89 GW as on 31.01.2023), the expected generation comes out to be 117 BU per year taking an average generation of 5kWh/kW/day. But the actual generation is seen to be only 82 BU which is 70% of the expected generation. The worldwide situation has likewise shown a similar outcome. It should be noted that Indian cities have extraordinarily high pollution levels, according to the World Air Quality Report issued by the Swiss company IQAir [ref].

[ref] https://www.iqair.com/world-air-quality-report

In the beginning of the **twenty-first century**, our society is faced with an **energy challenge**: as **highly populous**, developing countries become more affluent and as the developed nations continue to increase their energy consumption, the energy demand in the entire world has reached levels that cannot be sustained in the future.

At the same time, **fossil fuels**, which are currently providing **more than 85% of the total global energy supply**, are limited and, in addition, their widespread use has significant **adverse environmental consequences**. The combustion of fossil fuels produces **carbon dioxide**, which is one of the causes of **global warming** as well as of other environmental effects, such as **acid rain; higher ozone concentration** in urban areas; **particulates**; and **aerosols** that are detrimental to air quality.

The limited supply of the fossil fuels and their effects on the global environment indicate the only **long-term solution** of the energy challenge: a significant increase in the use of **alternative energy sources** for the **production of electricity** as well as for meeting other energy needs of the industrial and post-industrial human society.

- Energy is one of the major inputs for the economic development of the country.
- Energy can be classified into several types based on the following criteria.
  - ✓ Primary and secondary energy
  - ✓ Commercial and Non commercial energy
  - ✓ Renewable and Non-Renewable energy

- **Primary energy sources** are those that are either found or stored in nature e.g. Coal, oil, natural gas, biomass (such as wood). Primary energy sources are mostly converted in industrial utilities into **secondary energy sources** e.g. Coal, oil or gas converted into steam and electricity.
- **Commercial Energy sources** are available in the market for a definite price e.g. electricity, coal, oil, natural gas etc.

Non-commercial energy sources are not available in the commercial market for a price e.g. firewood, agro waste in rural areas; solar energy for water heating, electricity generation for drying grain, fish and fruits; animal power for transport; lifting water for irrigation; crushing sugarcane; wind energy for lifting water and electricity generation.

- **Renewable energy** is obtained from sources that are essential inexhaustible on a **human time scale** e.g. wind power, solar power, geothermal energy, tidal power and hydroelectric power. This type of energy can be harnessed without the release of harmful pollutants. **Non-renewable energy** is the conventional fossil fuels e.g. coal, oil and natural gas. These energy sources deplete with time.

Energy distribution between developed and developing countries

- Everything we do depends on energy. Energy resources of a country are a key input in economic growth and the availability of energy resources is very closely linked to the future growth of our nation.
- India is the world's third largest energy consumer, and its energy use is projected to grow at a rapid pace supported by economic development, urbanisation, improved electricity access and an expanding manufacturing base.

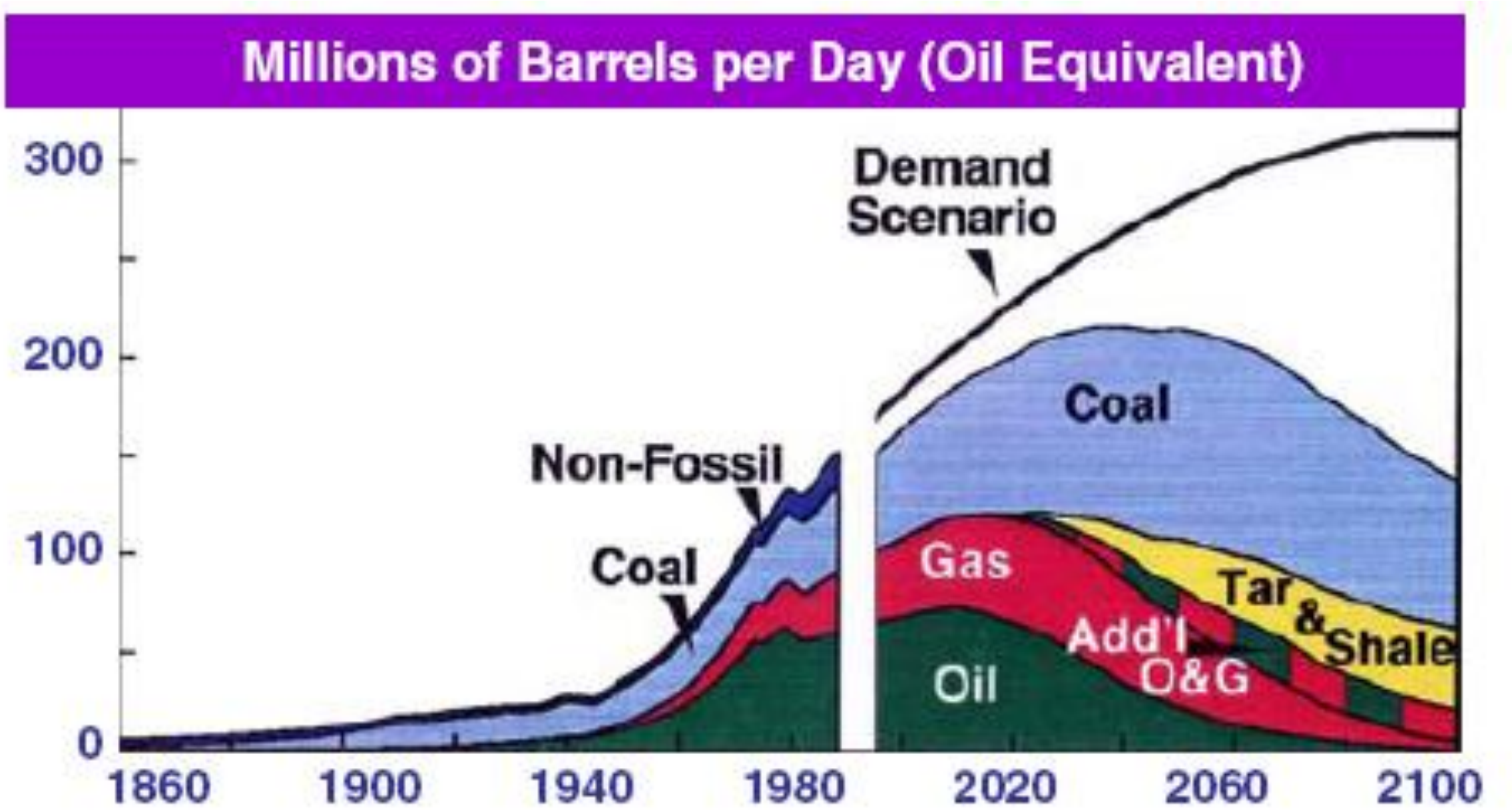
- High standards of living in the developed countries are attributable to high energy consumption levels.
- The rapid population growth in the developing countries kept the per capita energy consumption low compared with that of highly industrialized developed countries.

- The world average energy consumption per person is equivalent to 2.2 tonnes of coal.

- In industrialized countries, people use four to five times more energy than the world average energy consumption and nine time more than the average for the developing countries.

- An American uses 32 times more commercial energy than an Indian.

Historical and projected World Energy Supply and Demand



1 million barrel of oil equivalent (boe) = 2×10^9 kWh

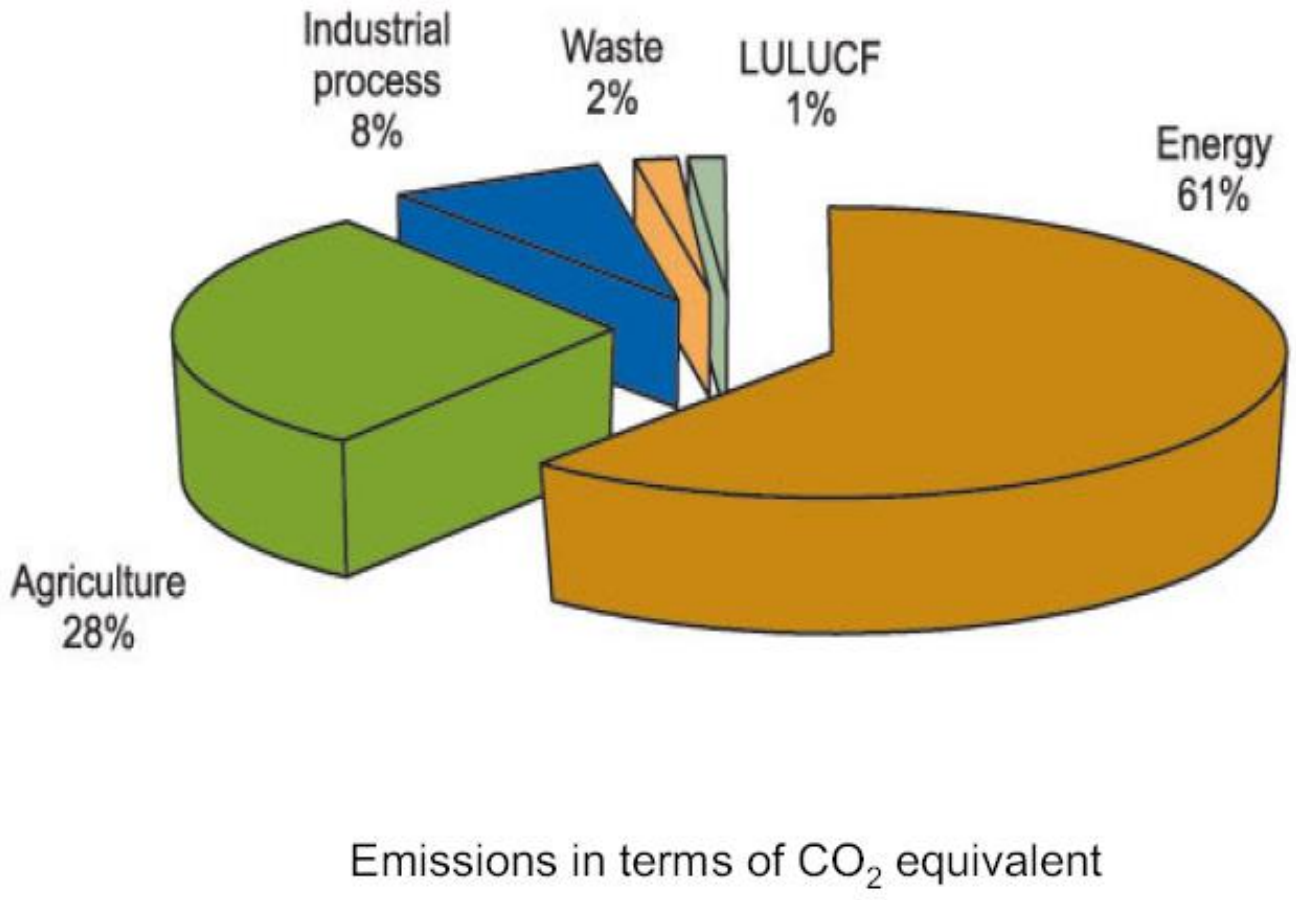
Demand for Clean and Affordable Energy

- **Traditional energy sources:**
  - **Coal:** polluting air with acid rain - Serious pollution to environment; Detrimental to ecology; Costly and danger in mining.
  - **Natural gas:** Limited supply; High shipping costs; Hazard in handling.
  - **Petroleum:** Limited supply; Costly refinery; Growing demand by economically emerging countries; Air pollution; National security concerns.
  - **Nuclear power**: Heavy capital costs; Safety; Waste fuel treatments.
  - **Hydro power:** Very heavy cost in construction; Limited to few sites; Ecological damage.

All forms of traditional energy cause environmental and ecological damages.

All natural sources are fast depleting and they are also the largest polluter of the environment

Sectoral Distribution of GHG emissions



The carbon stored in fossil fuels is released as carbon dioxide when they are burnt

– **leads to the green house effect and global warming**

– Land use, land-use change, and forestry (**LULUCF**)

List of major countries by carbon dioxide emissions

Country	CO_2 emissions (killoton)	Emission per capita (ton)
World	35,669,000	5.0
China	10,540,000	7.6
United States	5,334,000	16.5
European Union	3,415,000	6.7
India	2,341,000	1.8
Russia	1,766,000	12.4
Japan	1,278,000	10.1
Germany	767,000	9.3

Nuclear Resources

• India has modest reserves of Uranium, mostly located at Jadugoda, Jharkhand.
• Other locations are Narora (UP), Rawatbhatta (Rajasthan), Kakrapar (Gujrat), Kaiga (Karnataka), Kalpakkam, Kudanulam and Tombay.

• Thorium is abundance in India in the form of Monazite (ore) in sand in the beaches of Kerala.

• Outside India in United States, UK, France, Japan, Germany and Russia.

• In 2009 there were 439 operating nuclear power plants in the world, 103 of which operated in the USA.

Nuclear Waste

- The transportation and storage of the waste materials produced in the nuclear power plants around the world is a significant global environmental threat because the uncontrolled release of radioactive compounds is harmful to all living animals on the planet.

- Heat in a nuclear power plant is typically produced by the fission of the nuclear fuel, primarily uranium-235 and plutonium-239. The fission of the radioactive materials produces other isotopes, some of which are radioactive.

- Nuclear wastes are sometimes radioactive and causes health threat to the human population. For this reason permanent storage facilities must be constructed that will be capable to store the radioactive waste.

- There is not a proven and reliable method for the storage of such materials during the thousands or tens of thousands of years required for remediation of the nuclear waste materials.

• The safe and permanent storage of nuclear waste is an environmental issue for the nuclear industry. However, the populations and governments of several countries, including the USA, have not prepared permanent storage facilities for the nuclear waste that has been produced since the 1950s.

• At present, the nuclear waste is typically stored in temporary facilities in the vicinity of the power plant that produced the waste. A typical temporary storage facility is a water pool, where the nuclear waste is immersed. These storage arrangements are temporary, mostly unsecured .

• At present, there is no known storage material of the nuclear waste for long periods of time. For this reason, the nuclear waste management processes is still a challenge.

Renewable Energy

- **SOLAR ENERGY**
- **WIND ENERGY**
- **BIOMASS ENERGY**
- **GEOTHERMAL, TIDAL etc**

Jawaharlal Nehru National Solar Mission

- **Jawaharlal Nehru National Solar Mission is one of the major global initiatives in promotion of solar energy technologies, announced by the Government of India under National Action Plan on Climate Change.**

- **Mission aims to achieve grid tariff parity by 2022 through**

- **Large scale utilization and rapid diffusion and deployment of solar technologies across the country at a scale which leads to cost reduction**

- **R&D**

- **Local manufacturing and support infrastructure**

Design of Microgrid

As a part of these motivations, a microgrid system has been set up within the IIEST Shibpur campus consisting of,

- 35 cubic meter biogas digester with 15kVA biogas generator,
- 10kWp solar PV,
- 1kW wind generator,
- 1kW 6hr vanadium redox flow battery (VRFB) storage
-
- 500 m underground LT distribution line connected to the IIESTS loads
- communication system between the Renewable Energy Sources by connecting the specific nodes to National Instrument's LabVIEW platform.

Selection of Sub Systems of Microgrid

Bio energy based power plant:

a. Biomass gasification based plant – The fuel (e.g. Wood chips, rice husk etc.) is difficult to collect in regular basis.
b. Bio methanization based plant **-** By creating biogas reactors on campus, kitchen waste (food waste, vegetable waste etc.) is to be collected from different block of the Institute and will be used to produce methane gas for heat as well as power generation.

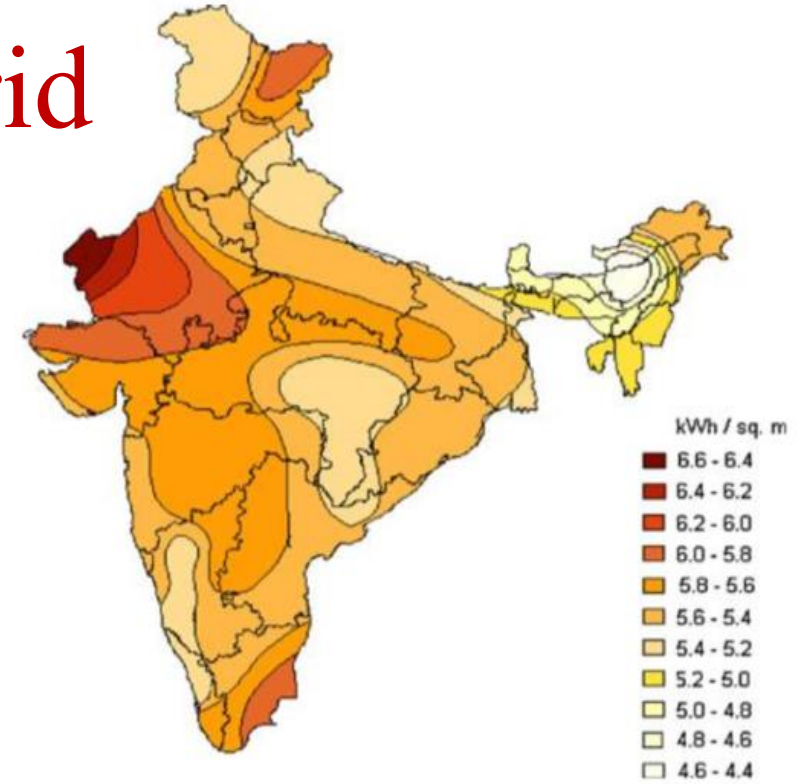
Calculation:

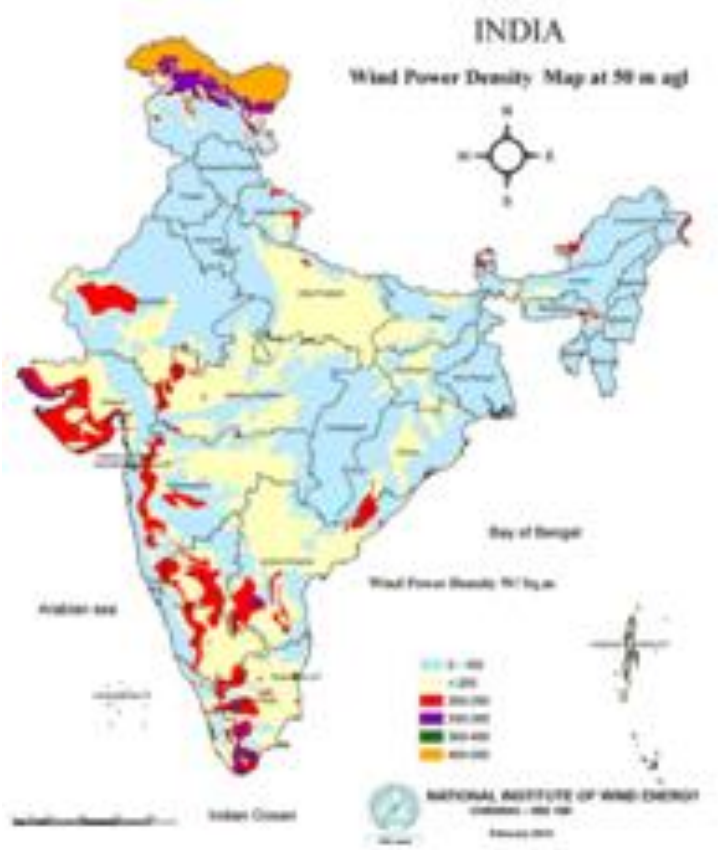
1. 1 cubic meter gas = 25kg of food waste
2. Total waste collected/day = 700kg
3. Size of bio digester = 36 cubic meter

Selection of Sub Systems of Microgrid

The solar radiation incident over the site is equal to average 4kWh per square meter per day with an annual radiation ranging from 1500-1600 kWh per square meter.

Based on the irradiance level and matching with the biogas system a 10 kWp solar PV plant has been installed.





The wind resource for power generation in this eastern region of the country does not show significant potential. **To study the wind pattern in this region a 1kW wind generator has been installed as part of the microgrid system though power generated from this wind generator does not impact significantly**

Selection of Sub Systems of Microgrid

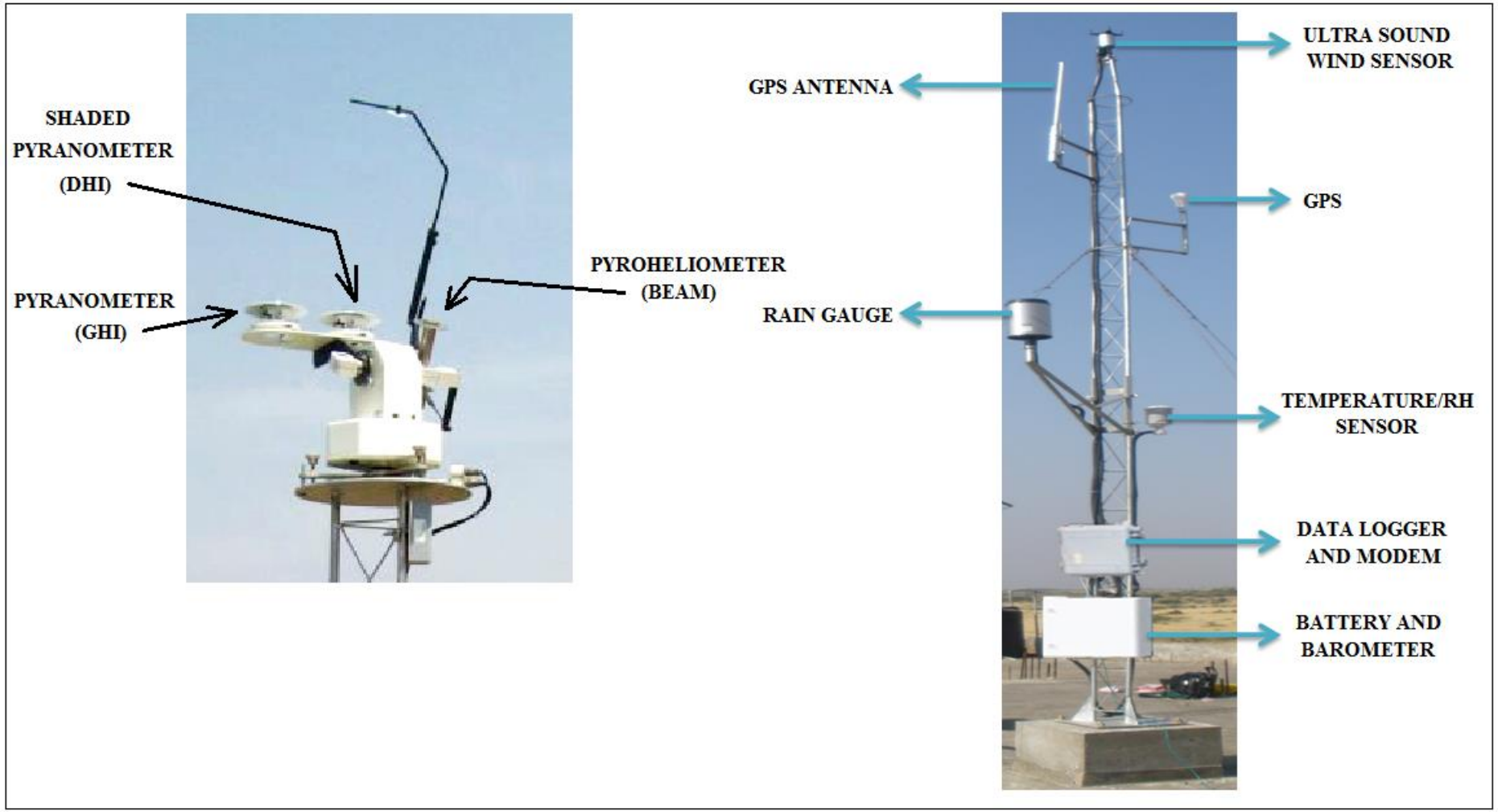
A battery bank is also connected with the microgrid system in addition to the aforesaid system. A special type of battery technology is the redox flow battery (RFB) storage. In our case vanadium redox flow battery was selected as it exhibits some commendable merits over other type of battery available in the market such as independent scalability of power and energy capacity, very long life cycle (7500+ which is equivalent to 20 years), deep discharge capacity, reliability for long term discharging capacity and also cost effectiveness.

Selection of Sub Systems of Microgrid

Solar Radiation Resource Assessment (SRRA)

SRRA

The meteorological data such as solar irradiance, wind speed etc. are collected from the **Solar Radiation Resource Assessment (SRRA)** station located in IIEST campus.



SRRA station at IIEST campus

Solar Power Plant and Wind Generator

10 KWp Solar PV Array on IIEST rooftop , ACDB and String Inveter

Solar Power Plant and Wind Generator

Installation of 1kW Wind Generator on IIEST Rooftop

Biogas Generator

The size of the Biogas Generator was selected on the basis of the capacity of the Biogas Digester needed for utilizing the total kitchen wastes, table food wastes and other Biodegradable wastes inside the IIESTS Campus which is approx 800 kg to 1 ton per day. The capacity of the Biogas Digester needed was 35 Cubic meter and the corresponding size of the Biogas Generator was 15 kVA. Fig shows the installed Biogas Digester along with the accessories for processing the daily kitchen wastes inputs and also shows the Biogas Generator installed in IIESTS.

The Integrated ac output of the Solar and Wind Generator from the Roof top Control room is brought via underground cable tray to the Master Control panel of the Microgrid System located near the Biogas Generator.

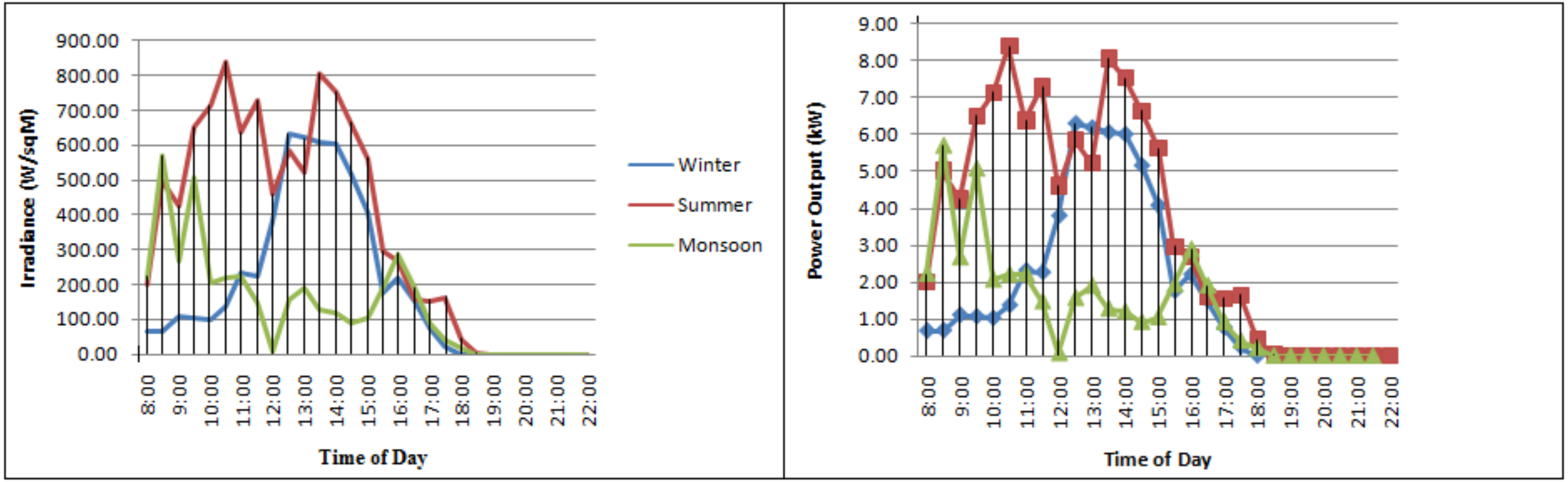
Biogas Generator

35Cum Biogas Digester with Vibrators, Shredders
And 15 KVA Biogas Engine housed in MicroGrid Centre at IIEST

Vanadium Redox Flow Battery Storage

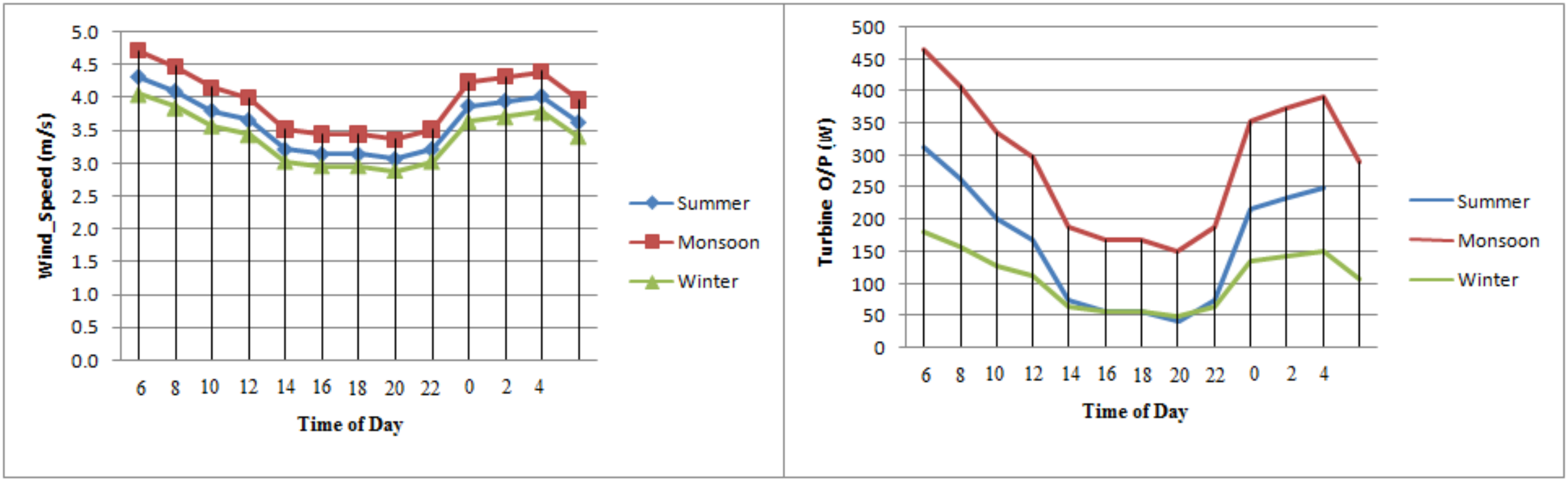
Vanadium Redox Flow Battery

Figure below shows the irradiance profile of three seasons e.g. winter, summer and monsoon. The generation from 10kWp solar plant also indicated. The maximum instantaneous power received from the plant in summer which is nearly 8.5kWp and the minimum is in monsoon which is nearly 0kWp.



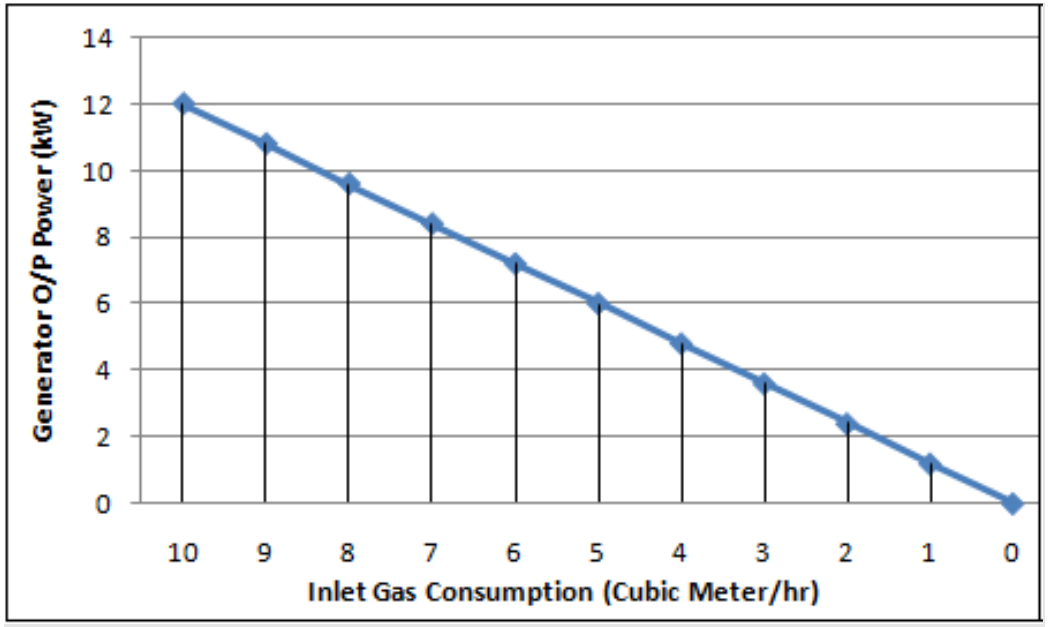
Seasonal average irradiance profile at Kolkata, West Bengal and power output from 10kW inverter

The wind profile obtained from SRRA station and figure indicates the power output from 1kW wind generator. The yearly average data shows that the maximum power which can be obtained from the wind generator is nearly 300W and it is also noticed that the maximum power is obtained mainly before and after sunset.



Yearly average wind profile at Kolkata, West Bengal and power output from 1kW wind turbine

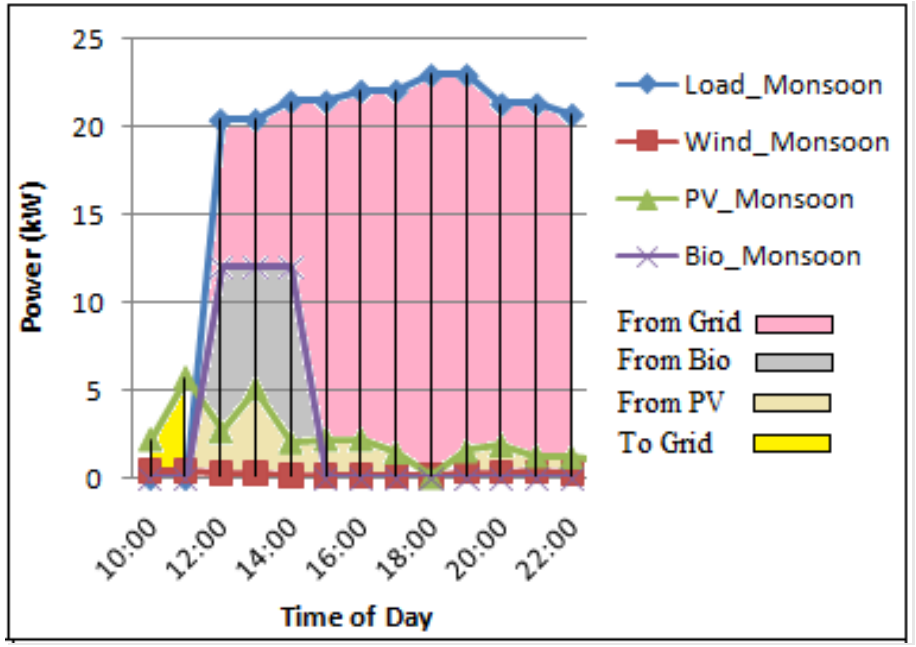
Figure below indicates the biogas engine I/P – O/P relationship i.e. inlet gas consumption Vs generator output power and table indicates the relationship between seasonal yield of biodegradable waste and gas generation.



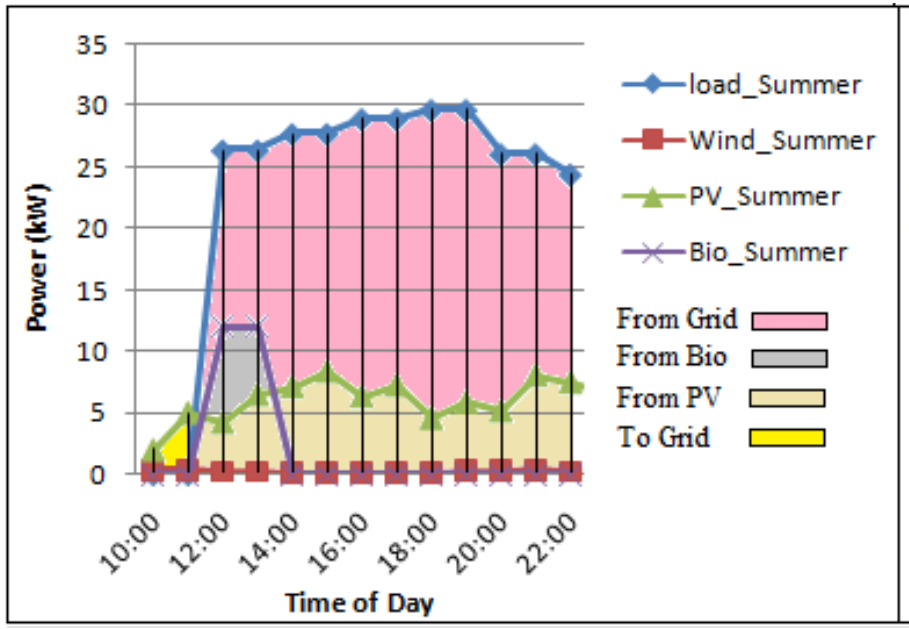
Biogas engine I/P – O/P

Seasonal Average Yeild of Bio Degradable Waste (kg/Day)		Gas Generation (Cubic Meter/Day)	Operation Hour At Full Load(hr/Day)
Winter	900	36	3.6
Summer	610	24	2.4
Monsoon	750	30	3.0

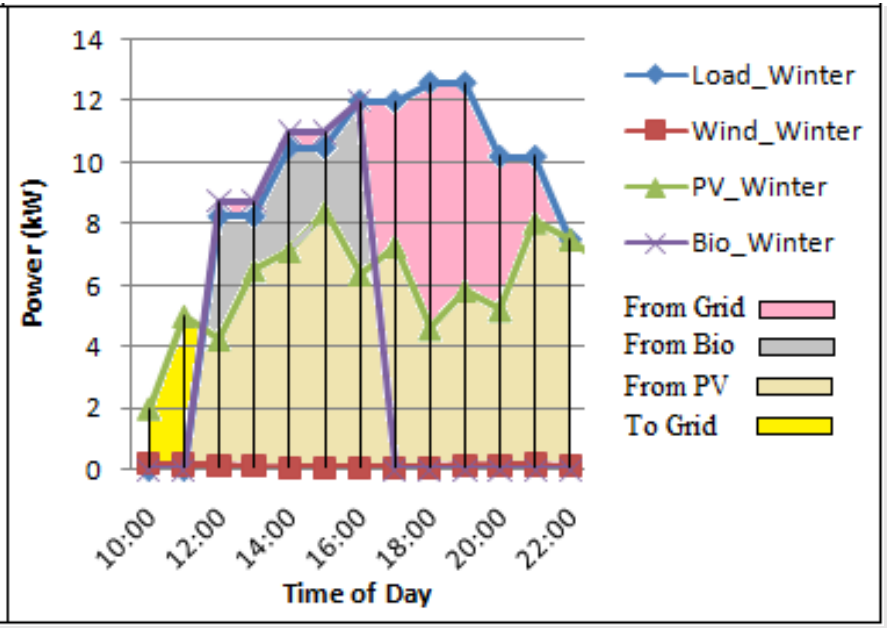
Biogas Engine I/P-O/P data



.a Combined PV-wind generation in monsoon season



b. Combined PV-wind generation against load for summer



.c.Combined PV-wind generation against load for winter

Item	Capacity	Capital Cost (INR)	Replacement Cost (INR)	O&M Cost (INR/Yr)	Life Time
Solar PV module including system	1kW	80000	35000	1000	25 years
Wind generator including system	1kW	150000	90000	2500	15 years
Biogas digester	1 Cubic Meter	11500	8050	1500	15 years
Gas generator	1kW	25000	20000	2500	10000 hrs
VRF battery	1kW/6kWh	120000	120000	5000	15 years

Microgrid Sources	Generation (kWh/Yr)	% Sharing
Solar PV	15409.57	47.54
Wind Generator	811.03	2.50
Biogas Generator	11687.3	36.06
Battery Storage	817.6	2.52
Grid	3686.5	11.37

Capacity Estimation

Solar PV – 10.6kWp
Wind – 1.2kW
Biogas – 12kW
Battery – 1kW/6kWh

What is Sustainable Energy and Why Do We Need It?

•Fossil fuels (e.g. coal, natural gas and oil) are not only harmful when burned for energy and causes global warming. These are not sustainable as resources are finite. One day the world will run out of fossil fuels. Sustainability refers to the concept that all people can meet their basic needs infinitely, without compromising future generations.

• **What is sustainable energy?**

Sustainable energy includes any energy source that cannot be depleted. It does not need to be renewed or replenished. Sustainable energy meets our demand for energy. Sustainable energy doesn't harm the environment. The energy sources themselves are free but there is a cost associated for capturing sustainable energy.

• Examples of sustainable energy sources are wind, solar and water (hydropower). All these are inexhaustible and widely available to almost everyone. Geothermal energy can also be included as a sustainable alternative energy source. Geothermal energy creates usable energy from the planet's internal energy sources, such as geysers.

What is the difference between sustainable and renewable energy?

• People often use the terms “sustainable” and “renewable” interchangeably. However, there is a difference between the two: the possibility of replenishment.

• Sustainable energies are theoretically inexhaustible. It cannot be depleted because sustainable energy sources don’t need to be replenished. For example, think of the sun or wind. Neither resource needs to be created or replaced. On the other hand, renewable energy is theoretically exhaustible — it uses resources from the earth that can naturally be replenished, such as crops and biomatter. A renewable energy source like bioenergy uses biological masses (e.g. agricultural byproducts like straw and manure) to create energy. Another example of bioenergy is ethanol, which is made from sugarcane and corn. Since these crops can be planted and farmed to generate more energy, it’s a type of renewable energy.