A Review of Global Warming, Mitigating Climate Change and India's Road Map for Energy Sustainability

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Abstract- Exponentially rising energy demands, excessive use of fossil fuel resources, ever rising level of greenhouse gases are causing global warming and climate change and are posing a big threat to human population, animals and plant species. The use of fossil fuels during the last 150 years has exceeded several times more than their use prior to this period. Excessive release of carbon emissions into the environment due to burning of fossil fuels for energy production and for other purpose is responsible for climate change and atmospheric pollution. These environmental concerns are compelling nations to reduce use of energy by increasing energy efficiency and by making use of alternative sources of energy which are renewable and sustainable and also keep the environment clean and healthy along with capture of carbon di-oxide and sequestration of flue gas to mitigate and reverse climate change. The global efforts on stopping and reversing climate change and the environmental commitments made by India at Paris and Glasgow Summits to reduce emissions intensity by 45% by 2030 from 2005 levels and its road map for energy sustainability are reviewed in the paper.

Keywords– Global warming, Climate change, Carbon capture, Renewable energy sources, Energy storage systems, Sustainable development.

1. INTRODUCTION

Global warming, climate change and sustainability are the burning problems of the current century. Unrestricted use of fossil fuels since industrial revolution has led to increased discharge of greenhouse gases in the environment which has resulted in the rise of global average temperature of about 1.41^0C causing climate change. This is a global problem and hence its solution requires the cooperation of all the nations to mitigate the ill effort of global warming. Reversing climate change not only requires shifting of use of fossil fuels to renewable resources of energy mainly solar and wind for production of electricity but also requires the world to extract CO_2 from the atmosphere. To achieve net zero carbon emissions by 2050 will require a rapid and massive shift in the electricity generating infrastructures which contribute almost 80% of greenhouse gases. To achieve this goal, the International Energy Agency has given an estimate that would require the addition, every year, of 630 GW of solar photovoltaic and 390 GW of wind energy systems starting no later than 2030. This massive addition of renewable sources of energy into the existing grid will pose several challenges due to variable nature of solar and wind energy systems and lack of intertia due to absence of conventional synchronous generators. This will necessitate installation of appropriate Grid Forming Inverters (GFM) and evaluation of their performance by their proper simulation and modeling5.

India is a fast growing economy and is planning to become self relient and join the list of developed nations by 2047. The energy needs will rise exponentially to fulfill the aspirations of its citizens. India has already fixed a goal of setting up of 500 GW of electricity by 2030 by using renewable sources of energy mainly solar and wind. India is also planning to tap other sources of green energy by establishing nuclear power plants, hydro-electric power plants including pumped storage & mini and micro hydro plants. Currently the total generating capacity as on August 31, 2024 is 450.760 GW out of which 207.763 GW is using sources such as solar, wind, hydro and nuclear.

As per Central Electricity Authority6 the projected figures for creating total generating capacity at the end of 2030 is 777.144 GW out of which 542.287 GW will be from sources other than coal and gas. These figures indicate that India's focus is now clearly and rapidly shifting towards energy generation using renewable sources of energy. India has always shown its intention to support global concern to fight climate change. During Paris summit India has given its commitment to reduce carbon emissions until 2030 by a billion tons.

In this paper the problem of rising energy demand, depleting fossil fuel resources, rising level of carbon emissions, global warming and climate change which are posing serious challenges to human population are reviewed and effort to overcome these challenges at global level in general and at India level in particular are presented in the subsequent sections.

2. GLOBAL WARMING

Energy is the basic need for each and every activity that humans perform. From the beginning of the civilization to pre-industrial revolution the use of energy was minimal and was only for cooking food and heating. The release of carbon dioxide in the environment due to burning of wood was very little. At the beginning of the nineteenth century before industrial revolution took place the global emissions of carbon di-oxide from burning of fossil fuel was nearly 10 million tonnes a year which rose to 8.1 billion tonnes 8, 9 a year in 2024. The concentration of carbon di-oxide in 2024 is around 440 ppm whereas the safe concentration of carbon di-oxide is 350 ppm which has already been crossed in 1988. If it continues at the current rate, it may reach upto 450 ppm by 2050.

Currently about 85% of electricity is generated world over using fossil fuels such as coal, oil and natural gas. Apart from it various other activities such as industrial, agricultural, transportation, construction, forest fires, savanna fires and volcanic also release considerable carbon di-oxide into atmosphere. Several other harmful gases such as methane and nitrous oxide which are produced during chemical processes and also due to decay of organic matters are released into the atmosphere. Tiny particles of the size 10 micro metre or less are also released into atmosphere due to incomplete burning of fossil fuels. These gases and tiny carbon particles trap heat energy reaching the earth from the sun and prevent it from radiating back into space. Due to trapped heat the temperature of the earth is going up. The global average rise in temperature due to heat trap by these gases and tiny carbon particles is about 1.2˚C since 1940 till 2024. This global warming causes climate change which is defined as gradual change in all the interconnected weather parameters over fifty year period.

3. CLIMATE CHANGE IMPACT

Global warming results in climate change which affects adversely the entire global population. The important effects are summarized below:

3.1 Torrential Downpour and Land Slides [16]

Global warming evaporates more sea water and produce heavy downpours instead of moderate showers, causing floods and land-slides in hilly areas.

In India also particularly in Himachal Pradesh, Uttrakhand and north-western part of Himalayas, landslides have become common due to climate change, disrupting schools, blocking roads, making higher reaches inaccessible for days, damage to infrastructures and killing people. India accounts for about 8% of global fatalities due to land-slides. Between 2001 and 2021, land-slides caused 847 deaths and displaced thousands. In India about 13.17 % of the land mass is susceptible to land-slides and out of this 4.75% is highly susceptible.

3.2 Cyclonic Storms [17]

Due to global warming several countries including India suffer badly due to cyclonic storms. These cyclones have become more frequent and intense causing lot of damage to power and other infrastructure, uproot trees and displace people. India with a total coastal line of about 7516 km is exposed to around 8% of the global tropical cyclones, Every year nearly two to four cyclones impact 9 states and some union territories along eastern and western coasts of India affecting 32 crore people. As per WHO report cyclones killed 233000 people world over between 1998 and 2017 and affected 726 million people.

3.3 Heat Waves and Draughts [28]

Global warming is causing uneven distribution of rainfall resulting in droughts and prolonged heat waves in some parts and heavy rains in other parts of the world. In 2023, according to a report published by World Meteorological Organization (WMO) the global average temperature reached 1.450C higher than pre-industrial levels. As global carbon emissions are still growing the hot dry places will become much hotter and drier. The temperate region which had regular rainfall will also become hotter and drier. Due to climate change a huge heat wave and unexpected extremely high temperatures occurred in India in 2022 from March to end of April and again in 2024 from April to May. Temperature in Delhi and some other parts of the country went more than 500C. Scientists predict that in future temperatures may even go higher and heat waves may sweep over a longer period during summer in some parts of India.

In metros and big crowded cities, the problem may even become worst due to the phenomenon called Urban Heat Island (WHI) effect [28]. Temperatures in such cities can reach several degrees higher due to retention of heat by concrete structures, tarmac roads and waste heat released from air conditioners.

3.4 Changing Ecosystem [30]

Complete ecological change may occur throughout the globe due to rise in temperature. It may transform forests into deserts and as a result hundreds of plant species may disappear and some of the animals may change their natural habitats or may become extinct. It has been reported that due to rise in temperature at the equator has pushed rice crop into northern cooler areas. Also several fish species have migrated to stay in waters that have proper temperatures for their survival. If the temperature continue to rise at the present rate, a large fraction. of plant and animal species may become extinct altogether.

3.4 Reduced Food Security [30]

One of the most striking impact which has been observed due to climate change is in the domain of agriculture. Different crops grow best in particular seasons when temperatures and humidity conditions are favourable. When these conditions change, their productivity declines significantly. It is predicted that production of rice which is the staple food for most people in Asian countries will decline by 10% with every 1^0C increase in temperature due to global warming. If the global average surface temperatures rise at the current rate then the productivity of rice will decline by 25% by 2050. Other impacts due to global warning in temperate regions may lead to changes in various seasonal processes such as earlier leaf production by trees, earlier greening of vegetation, altering time of egg laying and hatching and shifts in the seasonal migration patterns of birds, fishes and other migratory animals. Rising temperatures favour increase in agricultural pests, plant diseases and support spread of human diseases such as malaria, dengue in much wider zones.

3.5 Melting of Glaciers and Rise in Sea Water Level [8], [9]

The effect of global warming is more on land mass as compared to sea water. As a consequence, glaciers located in Himalyan region of India are slowly melting. Also land mass in northern hemisphere is more compared to southern hemisphere causing sea ice to melt slowly at the north pole. It is claimed that with an average rise of surface temperature by 2^0C will cause sea water level to rise by one metre and may submerge several coastal cities, sea resorts and islands world over. If the climate change is not reversed the rise in temperature by the end of 2100 will be around 5^0C which will melt all the glaciers, ice cap at the poles including Antarctica causing the sea level to rise by 6.0 metres. In such a situation most of the land mass will get submerged under water and the remaining land mass will be so hot making it very difficult for the mankind to survive.

4. GLOBAL EFFORTS TO MITIGATE CLIMATE CHANGE

Global warming, climate change and sustainable development are the most important problems of the current century and are attracting the attention of innovators and scientists all over the world. Urgency for mitigating and revering the climate change and depleting natural resources have triggered research into area of use of renewal sources of energy generation and development of advanced technology to make processes, systems and domestic appliances more energy efficient. Researchers and scientists are putting serious efforts in making processes continuous, less poluting and less carbon intensive.

Climate change affects the entire global population and hence it was recognized that to solve this global problem efforts are needed at the global level. The first global effort[10] to mitigate climate charge was organized through 'UN frame work connection on climate change' (UNFCCC) in 1992 at the Rio Earth Summit and it was resolved that the nations will voluntarily make efforts to reduce greenhouse gases which cause global warming. With the failure of Rio Earth Summit it was decided to meet in Kyoto in 1997. Under Kyoto Protocol the participating nations agreed to create a global trading system for carbon credits and voluntarily reduce greenhouse gases. Following Kyoto Protocol Conferences of Parties (COPs) were held annually at places such as Hague, Cancum and Doha without much progress. Following the failure of the 2012 Doha meeting the Kyoto carbon trading system was not renewed and died its natural death in 2020.

In 2015 renewed efforts to mitigate climate change were made and a summit of UN member nations was held at Paris. Under Paris Protocol it was resolved that all the nations will reduce carbon emissions by 33 to 35 per cent by 2030 from 2005 level by installing 40 per cent of total installed capacity from non- fossil fuel energy resources. The agreement binds the countries to pursue efforts to keep the rise in the global average temperature below 2˚C above pre-industrial levels. Several Countries including U.S. and China have ratified the agreement. India has also ratified it on October 2, 2016.

To give further boost to control climate change a conference of the Heads of States was organized at Glasgow from 31 October to 12 November 2021. The participating nations were called upon to phase down unabated coal power and inefficient subsidies for fossil fuels and collective efforts be put in by the nations to limit global temperature rise to 1.5^0C. Speaking at this 26th Conference of Parties (COP 26) in Glasgow Prime Minister of India announced that India will achieve net-zero emissions by 2070. The Prime Minister also announced that India will raise its non-fossil energy capacity to 500 GW by 2030 while meeting 50 per cent of its energy demand through renewables.

Followed by Glasgow conference the COP28 UN Climate Change Conference was held in Dubai from 30 November to 13 December 2023 in which 150 Heads of the states and governments participated. In Dubai, Prince Minister of India launched a "Green Credit Initiative" focused on creating carbon sinks of 2.5 to 3.0 billion tonnes of carbon dioxide by creating additional forest and tree cover by 2030 through people's participation. India is doing well to fulfil its targets promised at all the international forums.

5. RENEWABLE ENERGY SCENARIO IN INDIA [11]

To realise the goal to become developed country by 2047 India needs to make all out efforts to meet the exponentially growing demand of electricity and at

the same time honour its commitments made at the Paris and Glasgow Summits to achieve net zero carbon emissions by 2070. To achieve its committed target of generating 50% of its required electricity by using renewable resources of energy by 2030, India is setting up large solar parks and wind farms both in private and public sectors. It has already sanctioned 50 solar parks in 12 states with aggregate generating capacity of 37.99 GW. Out of 50 solar parks, 11 solar parks with aggregate capacity of 8.521 GW have already been completed and 7 solar parks with aggregate capacity of 3.985 GW have been partially completed.

The solar park at Bhadla in Phalodi tehsil of Jodhpur district is the World's largest solar park. It covers an area of 56 square kilometres and has a total installed capacity of 2.245 GW as of 2023.

Apart from solar power generation, India is also focusing on wind power generation by setting up wind farms. These wind farms can be set up on shore and off shore. India has a strong manufacturing base in wind power and has already set up a large number of on shore wind farms[12] at various locations mainly across southern, western and north-western regions. The total installed capacity of wind projects in India as on February 29, 2024 is 45.15 GW. To meet its commitment made by India at Paris summit to set up 500 GW of energy by 2030 using renewable sources of energy, it was decided to generate 140 GW of energy using wind. India's largest[12] wind farm Muppandal is located at Kanyakumari in Tamilnadu having a capacity of 1.5 GW and the second largest wind farm is located at Jaisalmer in Rajasthan with a capacity of 1.064 GW. The problems which India is facing in the installation of wind farm projects are in acquiring the land and transporting wind turbines due to which only 6% of India's wind potential could be exploited till now.

In order to boost wind power generation, India has also identified 54 off shore locations[2] for Installation of wind turbines. Due to higher wind speed and longer wind duration the utilization factor of these off shore wind turbine is almost double that of on shore wind turbines. Currently no off shore wind project is in operation in India. According to MNRE the first off shore wind project is expected to come up by 2030.

6. IMPROVED ENERGY EFFICIENCY

Energy efficiency means to make use of energy efficiently to perform the same task with same perfection. It means that by making use of advanced technology or production process in such a manner that losses are reduced and the task can be completed with energy as little as possible. Energy efficiency has been named as the ‘first fuel’ as it provides quickest and most cost effective means to reduce carbon emission and release of GH gases into the atmosphere by reducing energy production. It will also help in lowering the energy bill, enhancing energy security and promote sustainable options. It is claimed by International Energy Agency (IEA) that it is possible to reduce greenhouse gases by 40%, just by increasing energy efficiency. Countries all over the globe including India are promoting energy efficiency to reduce GH gas emissions and to fight climate charge. During G20 summit, member nations committed to double the energy efficiency change to 7.3% globally by 2030. The decade ending 2020 saw energy efficiency change of 0.4%, that is, from 6.1% to 6.5%. The target of doubling the energy efficiency change means an improvement of 0.8%, over the previous value of 6.5% to 7.3% by 2030.

Transportation of men and material from one place to another is an important economic activity. Globally in this sector which includes light and heavy road vehicles, planes and ships accounts for about 19% of energy consumption. It is expected to reach to 21% by 2040. The conventional IC engine driven vehicles cause lot of pollution particularly in urban area. To address this problem use of electric vehicles is encouraged globally. It is claimed that by adopting EVs using fuel cells the air pollution in the certain metropolitan cities can be cut by about 24%.

Several countries including India have implemented numerous initiatives to enhance energy efficiency by introducing standards and labelling scheme for the appliance sector. Efforts have also been made in reducing the use of energy in the construction sector by introducing energy conservation building codes.

Other energy efficiency actions include reduction in transmission and distribution losses in the grid, reduction in commercial losses by installation of smart meters, implementing energy tariff as a function of time thereby reducing peak demand and filling the low load periods.

In India transmission and distribution losses are quite high compared to other developed nations. Recently by strengthening the distribution system the distribution sector has been successful in cutting down the energy losses from 17% in 2021-22 to 15.41% in 2022-23 which is still high compared to world average of 7.53%. For further reduction in energy losses the sector must strengthen its network, adopt advanced techniques of load forecasting, better load planning, carryout load balancing in phases, replace inefficient distribution transformers and replace heavily loaded distributors by larger diameter conductors or by introducing distributed generation wherever possible. Similarly, transmission losses can be reduced by replacing 110 kV and 220kV lines by 400kV lines.

According to International Energy Agency improved energy efficiency in construction, industrial processes and transportation could reduce the world's energy needs in 2050 by one third and help control emissions of green house gases.

6.1 Use of Hybrid Ac/Dc Infrastructure

The use of DC power has increased many fold due to large scale application of electronic devices. In

business electronics, data servers, variable frequency drives in industries require tremendous amount of energy conversion from AC to DC. Today nearly 30% of power generated pass through power electronics converters before it is utilized. It may go even upto 80% in near future due to solar and wind power generation. These frequent conversion from AC to DC and back involve losses and bring inefficiency, Energy losses due to all these conversions can be avoided by developing hybrid AC/DC infrastructure and operations.

7. FOCUS ON RENEWABLE SOURCES OF ENERGY AND SUSTAINABLE DEVELOPMENT [29]

Extensive use of natural resources since industrial revolution has exceeded for more than their use prior to it. As a consequence, these natural energy resources started depleting at an alarming rate and it was felt that very soon these resources may get exhausted and nothing would remain for future generations. Sustainability began to be felt in the scientific world as a force in research and development by the early years of the current century. Extensive use of fossil fuels caused global warming. Recent estimates suggest that the world is currently heading for temperature rise of about 2.4^0C to 2.7^0C by the end of current century. This will cause devastating effects all round the globe. Feeling the importance, the U.N. convened the Sustainable Development Goals Summit (SDG Summit) on 18-19 September 2023 in New York during the General Assembly high level week in which world leaders deliberated and identified 17 sustainable development goals and the actions required to achieve these goals by the target year 2030. Among the identified sustainable goals, the goal no. 7 is about ensuring access to clean, reliable, sustainable and affordable energy to all which is the key to development of agriculture, business, communication, education, healthcare, transportation, construction etc. In other words energy is an important requirement for development in every domain which integrates Social, Cultural, Economic and Political values of all human beings. With the increased focus on sustainable development goals and to mitigate climate change efforts are being intensified by all the nations to reduce carbon emissions in the atmosphere by making use of renewable energy resources for generation of electricity.

7. HYDROELECTRIC POWER PLANTS INCLUDING PUMPED STORAGE PLANTS [1]

Hydroelectric power plants and pumped storage plants (PSP) play an important role for intermittent stainable and reliable operation of grid which is integrated with renewable sources of energy. These plants can store energy and can be started, synchronized and loaded within minutes and hence can mitigate the ill effect of intermittent nature of solar and wind based power plants. Due to unique flexible characteristics these plants can be efficiently used for voltage control, reactive power control and frequency regulation. These can operate efficiently on part load and suitable for multiple start-stop and black start operation.

Pumped storage power plants (PSP) were developed on a large scale world over in the twentieth century to be used as energy storage systems. According to International Hydro Power Association (IHA) the pumped Storage capacity globally rose from 142 GW in 2014 to 175 GW in 2022.

To meet its commitment made at Paris and Glasgow Summits India plans to raise power generation using renewable sources of energy upto fifty per cent of total generation by 2030. At the same time to make grid flexible India plans to increase[13] hydro power generation to 53.86 GW, PSP to 5.35 GW. It also plans to import hydro power from neighbouring countries including Bhutan upto 5.856 GW.

As per Central Electricity Authority (CEA) India is having 4.75 GW of PSP as on June 15, 2024 out of which 3.3 GW are in pumping mode and apart from it 44.5 GW projects are at various stages of development. CEA has also identified 63 sites across India for location of PSP with a capacity of 96 GW. According to National Electricity Plan 2023 (NEP 2023) the capacity of energy storage by 2032 is estimated as 73.93 GW, Considering 2.78 GW of PSPs under construction to achieve the above target of 73.93 GW by 2032 will require capacity addition of about 7.9 GW per year which is difficult but not an impossible task.

One of the most significantly PSP currently under construction is Sillahalla Plant in Nilgiris district of Tamil Nadu State having a capacity of 2 GW. Another PSP having capacity of 1.44 GW is under construction at Khemla Block of Neemach in Madhya Pradesh. A recent MoU has been signed between the Telangana State Government and JSW Energy to setup a PSP with a generating capacity of 1.5 GW. Although PSPs have several advantages for energy storage point of view but unfortunately they are location dependent and can't be easily expanded. Also these projects involve high initial cost and long gestation period.

8. NUCLEAR POWER [8], [9]

Currently India is the fifth largest economy in the world economy ranking. Looking to high GDP growth of about 7% it is predicted that India may become the third largest economy by 2030. This will require exponential growth in energy production. To meet climate goals India will have to carry forward aggressively its nuclear power generation programme. Apart from small fuel mass and zero carbon emissions it adds diversity to energy mix and reduce dependency on fossil fuels. The problem with nuclear power generation is the

safe disposal of radio active waste generated in the nuclear reactors. India possesses this technology to store such radioactive waste safely for the required period. Currently 23 pressurized heavy water reactors[18] are in operation in seven nuclear power plants and another six are under construction. They use uranium as fuel but unfortunately India has very little reserve of uranium. Currently contribution of nuclear power in the India's energy mix as of March 31, 2024 is only 8.18 GW which is only 1.85 per cent. France generates more than 70 per cent energy from nuclear power. In spite of resistance from social activists India has the plans[18] to increase the nuclear power capacity to 63 GW by 2032.

To make nuclear power production sustainable and independent of import of uranium India is aggressively pursuing development of reactors based on thorium cycle. India has world's largest reserve of thorium which can meet country's needs for 400 years. Another advantage of thorium cycle is that the radio active waste generated lasts only for 300 years.

India is also developing small modular reactors[19] (SMRS) which are much smaller in size compared to conventional nuclear fission reactors. These reactors can be transported easily to plant locations and have reduced chances of adverse impacts. It is claimed that SMRs can overcome the usual objections raised by anti-nuclear social activists regarding accidental release of massive amount of radioactivity in the environment.

9. CARBON CAPTURE, UTILIZATION AND STORAGE (CCUS) [3], [4]

If the rise in global average temperature is to be restricted below 2^0C above pre-industrial levels the role of carbon capture, utilization and storage (CCUs) cannot be underestimated. It involves capture of CO_2 generally from large point source such as fossil fueled power plant or large steel or cement industry which uses fossil fuel not only as a source of energy but within the process itself. The captured CO_2 can be converted into useful products of commercial value such as green urea, building materials (concrete and aggregates), chemicals (methanol and ethanol), polymers (including bio-plastics), carbonated drinks, dry ice etc. If CO_2 is not being used on site, it can be compressed and transported by pipe line, ship or truck to a suitable site where it can be converted into useful commercial product. In case conversion facilities are not available captured CO_2 can be injected into deep geological formations such as depleted oil and gas reservoirs or saline aquifers.

CCUS in the past could not pick up on a large scale as expected because of some technical but mostly economic barriers. It required large capital investment which made it unprofitable activity for the industries. In recent years CCUS gained momentum substantially. Currently 45 commercial facilities are already in operation and 700 projects are in various stages of development world over.

India is a fast growing economy. It will have to depend on fossil fueled power plants for many years in future to meet its energy requirement even if it is able to substantially green the power grid and meet the target of 500 GW installed capacity by 2030 using renewable sources of energy. India will have to promote CCUS technology to capture carbon emissions from the existing power plants and heavy industries which use fossil fuel. Till today (2024) there is not a single CCUS plant operating in India. Some public sector undertakings such as NALCO, ONGC, BHEL etc. and some private sector players such as Dalmia Cement are exploring the adoption of CCS technology by setting up of pilot plants. The future plan of ONGC is to set up a CCU plant which will have the sequestration capacity of around 5-8 MMT of CO_2.

The Government of India also has the plan to set up CCU plant[3] which will be operational in 2026 and has the sequestration capacity of 0.7 Mt of CO_2 per year. It also has the plan to set up CCU plants which will be operational in 2028 and 2030 with a similar capacity of 0.7 Mt of CO_2 per year.

10. PROBLEMS IN GRID OPERATION DUE TO DEEPER PENETRATION OF RE RESOURCES

After Paris Summit of 2015 and Glasgow of 2021 countries world over are vigorously chasing the policy of increasing share of renewable energy sources mainly wind and solar to control carbon footprint and arrest climate change by curtailing the use of fossil fuel. India also submitted its intended Nationally Determined Contribution (INDC) to the UNFCCC outlining the country's post 2020 climate actions. It has a target of increasing the share of renewable energy to 500 GW by 2030.

Large scale penetration of wind and solar power into the power grid creates several difficulties. Sudden fluctuation in the output of solar panels due to cloud passing over them and also during sun rise and sun set times it is impossible for the grid operator to predict precisely the additional power generation required during the next hour of the day. The impact of cloud cover can be reduced to some extent if solar power projects are spread over a large area as it is done in case of solar parks. Similar problem also arise during solar eclipse.

Wind energy as compared to solar energy is less predictable. Wind generation during wind storm particularly during light or peak load conditions can create considerable problems in maintaining balance between generation and demand. The renewable energy sources particularly solar are connected through inverters which do not have rotating masses and hence inertia. Thus with deeper penetration of these renewable energy resources the grid will lack the inertia to maintain stable operation in the event of large disturbance.

11. ENERGY STORAGE SYSTEMS [14]

For stable operation of grid it is necessary to balance generation and load at every instant. Power grid having deep penetration of renewable energy resources it is necessary to convert infirm power generation by solar and wind power plants into firm power within a short period by energy storage systems. These Systems should be capable of absorbing energy during low demand and supply energy during peak demand. They should also be capable of handling the effects of high ramp up or ramp down situations caused at the time of sun rise, sun set and during solar eclipse.

As no single energy storage system is adequate for a large grid, it is desirable to create hybrid storage system comprise pumped storage system, battery storage system, compressed air, super capacitors, fly wheels etc. These systems can provide back up ranging from a few hours to a few minutes and can be effectively used for load balancing, frequency regulation, reducing peak load by shifting it to low load period and integration of renewable energy resources.

Electrical energy generated in excess of demand due to renewable energy resources can't be stored as such but can be used for the production of green hydrogen which can be stored, transported and can be used in fuel cells for converting it again in electrical energy.

To mitigate the ill effects of deeper penetration of renewable energy resources into grid the Central Electricity Authority prepared a road map under National Electricity Plan[25] (NEP) 2023 for creating energy storage capacity. According to the plan the projected storage capacity requirement would be 83.37 GWh (47.65 GWh from PSP and 34.72 GWh from BESS) in 2026-27 and 411.4 GWh (175.18 GWh from PSP and 236.22 GWh from BESS) in 2031-32. Further CEA has also projected that by the year 2047 the requirement of energy storage is expected to be 2380 GWh (540 GWh from PSP and 1840 GWh from BESS) due to large amount of renewable energy penetration in the light of net zero emission target set for 2070.

12.1 Battery Energy Storage System (BESS)

Currently Battery Energy Storage System (BESS) is the most popular and convenient dispatchable source of power on electric grids. Due to recent developments in battery technology and corresponding reduction in cost has played an important role in the deployment of battery energy storage system world over[15]. These systems mostly use lithium-ion batteries. These batteries have a long life without maintenance. They generally have high energy density and low self-discharge. Other types of batteries namely sodium-sulphur battery, vanadium flow batteries, solid state batteries etc. are in the development stage. The advantages of battery storage system are location independent, low initial cost, requires less time to install and its mode of operation can be changed from standby to full power in about 10 milliseconds. BESS is compact and can be located if necessary within urban areas close to customer load. BESS is composed of large number of smaller batteries and hence provide greater redundancy.

BESS in addition requires additional components that allow the system to be connected to the power grid. A bidirectional inverter[5] usually grid forming inverter (GFM) or grid following inverter (GFL) is the main device that allows power to flow both ways to charge and discharge the battery. The other components are battery management system, energy management system and safety system.

The Solar Energy Corporation of India Limited has installed country's largest BESS[14] with a capacity of 40 MW/120 MWh at Rajnandgaon in Chattisgarh to provide backup for solar photovoltaic plant having installed capacity of 152.325 MWh and dispatchable capacity of 100 MW A.C. (155.02 MW peak d.c). The project was dedicated to the nation on February 24, 2024.

12.2 Green Hydrogen [24]

Many scientists consider hydrogen as the most promising and versatile alternative source of energy for the future. Its utilization for energy generation produces water only which does not pollute environment. Hydrogen is the most abundent element available in the form of water on the globe and therefore it can be considered as a sustainable source of energy. Hydrogen can be produced from diverse resources such as fossil fuels, biomass and water electrolysis using electricity. Hydrogen production processes other than electrolysis of water releases carbon dioxide which pollutes the environment and therefore are unsuitable for production of hydrogen. The electrolysis of water using renewable sources of energy produces green hydrogen but it requires fresh water which is a scarce commodity. Also the electrodes of electrolysers are made from specialized materials such as nickel or platinum which makes the process very expansive. Researchers are trying to make electrolysers cost effective and sustainable by developing less expensive catalysts such as combination of stainless steel and nickel instead of expansive platinum and iridium based catalysts. Research is in progress to develop a process known as photo-electro-chemistry or photo-electro-analysis in which a catalyst harness sunlight to initiate the splitting of water, eliminating the need of electricity. This process requires lower input of electricity compared to conventional electrolysis for generating green hydrogen. Research is also in progress to develop technology to obtain green hydrogen at a much lower cost from waste or brakish water.

In spite of difficulties in the storage and transportation of hydrogen, it is now considered as the energy source of the future for road

transportation, shipping, aviation and for industrial production of steel, cement, glass, chemicals etc.
India is also focusing development of technologies for production and storage of green hydrogen. The National Green Hydrogen Mission (NGHM) and Harnessing Green Hydrogen (HGH) are some of the policies of the Indian Government which promote green hydrogen. Under NGHM the government aims to produce 5 MMT of green hydrogen annually. India has designated Kandla (West Coast) and Tuticorin (East Coast) ports as green hydrogen refuelling hubs. However, there are challenges to overcome, including the economics of green hydrogen production, the availability of affordable and uninterrupted renewable energy and pure water resources.

12.3 Transportation Sector and Fuel Cell Technology

Globally transportation sector which includes light and heavy road vehicles, railways, aeroplanes, and ships accounts for about 19% of energy consumption. It is expected to reach upto 21% by 2040. The conventional IC engine driven vehicles emit a lot of pollution carbon emissions particularly in areas where traffic density is very high. To address this problem countries all over the world are encouraging the adoption of electric vehicles. To curb pollution due to carbon emissions it is necessary that the batteries used in EVs must be charged from renewable energy resources otherwise it will only shift air pollution from one place to another. Instead of using batteries one good option is to make use of green hydrogen in fuel cells for driving vehicles. Hydrogen fuel cells can be used in place of batteries in all types of vehicles ranging from small cars to commercial aeroplanes. Hydrogen fuel cells have several advantages over battery driven vehicles. They do not run down as long as the constant supply of hydrogen and oxygen is there. Energy density of hydrogen is much more than batteries and due to low density it can be easily stored in tanks and can be easily placed on board of heavy vehicles and can be refilled or replaced in a short time. This technology has improved in recent years, it is still relatively expensive due to high cost of production of green hydrogen.

12.4 Linear Generators [20]

The technology of linear generators has been developed at Stanford University's Advanced Energy Systems Laboratory. It is claimed that they can be switched on quickly and can replace battery energy supply system in distributed generation system. These linear generators can be run on green hydrogen or other not-so-green gaseous fuel such as biogas, ammonia, grey hydrogen etc. It has the capability to make the distributed generation system free from the variability of renewable energy resources. Since 2020 linear generators having capacities ranging from 230 to 460 kW have been installed at different locations in the U.S. and are operating efficiently and successfully. Linear generators operate on the principle that when a mixture of carbon free ammonia and air is compressed in the reaction chamber to the extent that molecules of both ammonia and oxygen fall apart and rearrange, energy is released. The force produced during rearrangement of molecules is larger than the force applied during compression. This force can be used for driving conventional generators for electricity production. Research is continuing at Stanford University to scale up the size of linear generators.

12.5 Renewable Iron Fuel (RIF) Technology [21]

Renewable Iron Fuel technology is under development at Eindhoven University of Technology, Netherlands and McGill University, Canada. In this technology iron is first converted into fine powder and then burnt in the combustion chamber to generate power. Iron metal is available in abundance in earth crust, recyclable and possess higher energy density and hence it can be an ideal alternative fuel to store energy as compared to hydrogen. Iron metal can be converted into fine powder using renewable energy and can be transported from the place of production to location of power plants where it can be burnt to produce electricity by a steam turbine. Iron powder on burning will produce iron oxide which can be converted into iron powder by removing the oxygen away by using green hydrogen. A demonstration plant of 1 MW capacity has already been setup and running successfully in Budel near Eindhoven, Netherlands.
Although iron fuel has energy density of about 11.3 kWh per litre which is better than gasoline and does not release greenhouse gases but can't be switched on quickly. There are other problems such as its safe transportation from the place of manufacture to place of use without getting rusted, proper burning in the furnace and separation of iron oxide from air. However it can be considered as one of the promising solution for replacement of fossil fuel as it can be easily and safely transported and stored in bulk quantities.

12. CONCLUSION

India is figuring on the rising graph on the economic front. Today it is the fifth largest economy and if the current GDP growth continues it will soon become the third largest economy of the world only after US, and China. To achieve this target India will have to provide access of uninterrupted quality power supply to all its citizens in a sustainable manner and simultaneously uphold its commitments made at Paris and Glasgow summits to reduce carbon emissions and contribute in mitigating and reversing the climate charge. In order to meet this challenge with restriction on carbon emission India will have to focus on generating electricity using a combination of

dispatchable and variable generation, centralized and distributed generation using variety of resources which are renewable in nature and at the same time do not contribute to carbon emissions. India should focus on nuclear power technology based on thorium fuel cycle and also expand the capacity of nuclear power generation using thermal and fast breeder reactors. India should also go in a big way to install battery energy storage devices and other energy storage devices such as pumped storage systems to offset the effect of variable nature of solar and wind energy systems. Deeper penitration of solar and wind energy systems make grid unstable due to lack of intertia provided by conventional synchronous machines. Smart inverters[5] such as grid forming inverters (GFM) will have to be installed to support grid to maintain stability during disturbance. These GFM inverters also called Virtual Synchronous machines are provided with software which allows during disturbance the output voltage waveform to change over time to synchronize with other nearby sources such as generators and other GFM inverters.

It is also necessary to strengthen the existing transmission network by expanding transmission capacity by more than 100 GW to connect renewable energy rich locations such as Rajasthan and Gujarat for solar energy and Tamil Nadu for wind energy with demand centres. Proper planning and coordination is necessary for expansion of transmission network as it takes much longer time due to legal problems in obtaining the right of way as compared to installation of solar or wind energy generation system. India should also focus on energy efficiency by making it medatory for manufacturers to manufacture energy efficient domestic appliances and force industries to adopt energy efficient processes for manufacturing their products. Efforts are required particularly at the distribution level to reduce losses from 15% to world average of 7.53%

Transport sector emits a lot of carbon emissions particularly in metro and other big cities. It can be controlled by changing over to electrical vehicle using fuel cell technology which is efficient and do not emit carbon emissions. The green hydrogen required as fuel can be produced using renewable energy. Extensive research is required to reduce the cost of production of green hydrogen and that too from impure or brakish water.

The technology required for extraction of green--house gases from the atmosphere or capturing them at the source of generator and store them is expansive and also there are no suitable geological formations available in India where these gases can be stored.

India is progressing well in fulfilling its commitments made at all the international forums to achieve net zero carbon emissions by the target date 2070.

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