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Carbon Emission Reduction Methodologies

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Abstract: There are many sources of carbon emissions which includes industries, thermal powerplants, Vehicles etc. The goal of low carbon emission technologies is to cut down on or completely eradicate greenhouse gas emissions brought on by the production and use of energy. Some strategies to capture carbon emissions for low-carbon development in the energy sector, as well as in the steel and non-ferrous metals industries, include carbon sequestration and green energy. It meets the needs of averting global warming, cutting greenhouse gas emissions, and adjusting to a low-carbon economy. On the one hand, the development of a low-carbon economy depends on low-carbon technologies. However, it's also a major way to address the energy issue, climate change, and sustainable development. The development of low- carbon technologies requires a number of laws, regulations, and processes. Now that can also be applicable with AI technology

Keywords: *Carbon Footprint, Low-Carbon Emission Technologies, Green Energy, Carbon Sequestration, Greenhouse Gas Emissions, Low-Carbon Economy, Climate Warming, AI Technology.*

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I. INTRODUCTION

Global CO2 emissions have been increasing since the 1940s, but from the mid-1900s,they really took off, according to current statistics. About 38.5 billion metric tons of CO2 will be released by industry and fossil fuels combined in 2022. The primary source of CO2 emissions from the concrete industry is the manufacturing of Ordinary Portland Cement (OPC). While carbon capture and utilization (CCU) technologies, particularly the carbonation of waste cement powders (WCP), recycled concrete aggregates (RCA), and alternative binders, can assist lessen the environmental impact of the sector, their scalability and efficacy differ. When paired with alternate binders and SCMs, CCU technologies in concrete present viable avenues for mitigating CO2.They must, however, optimize carbonation processes, validate structural performance, and ensure net environmental benefits through thorough life cycle studies in order to reach their full potential [1]

In isolated Australian towns, reaching net zero energy is a technical difficulty as well as a national imperative. By combining solar (PV), wind, battery, and hydrogen storage technologies, hybrid renewable energy systems (HRES) pro- vide a sustainable and affordable option that dramatically lowers energy expenses and carbon emissions. For distant Australian settlements, optimized HRES—particularly those that incorporate hydrogen storage—are a viable and expand- able route to net zero energy. These solutions help Australia's sustainable energy transition, improve energy security, and reduce operating costs [2] Chemical absorption-based post- combustion carbon capture (PCC) is the most developed and extensively used technique for lowering CO emissions from power and industrial facilities. PCC is becoming increasingly feasible for widespread usage as a result of recent develop- ments in solvents, process integration, and digital optimization that drastically reduce energy consumption and expenses. With the help of new solvents, process designs, and digital tools, chemical absorption-based PCC is developing quickly and using less energy and money. For widespread, long- term implementation, interdisciplinary cooperation, encourag- ing legislation, and ongoing study are essential [3].

A major choice for large-scale CO storage is saline aquifers because of their enormous capacity and capacity to trap CO through solubilization in brine and subsequent mineralization. Long-term security and storage capacity can be improved by precisely predicting aquifer heterogeneity, optimizing brine chemistry, and utilizing cutting-edge technology like nano bubbles.The potential for safe, extensive CO storage in saline aquifers is strong. Aquifer heterogeneity and geochemical pro- cesses must be taken into account in models, brine chemistry must be optimized, and new technologies must be imple- mented to ensure long-term stability and capacity [4]. An increasingly popular and sustainable option for soil improve- ment, pollution removal, carbon neutrality, and environmental remediation is biochar, a carbon-rich substance made from biomass pyrolysis. Its physicochemical characteristics, which are influenced by the feedstock selection and production techniques, determine how effective it is. One very useful and sustainable solution for soil enhancement, pollution removal, carbon sequestration, and environmental management is bio char. It

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is a promising instrument for tackling global environ- mental issues because of its versatility and multi functionality [5].

Existing steel mills can drastically cut their CO_2 emissions by using post-combustion carbon capture and storage (CCS), but doing so comes with additional operational challenges and environmental effects. While life-cycle assessments (LCA) demonstrate that contemporary CCS supply chains, particularly those utilizing cutting-edge technologies such as DMXTM, can attain significant CO capture efficiencies with comparatively low life-cycle emissions, CCS by itself is unable to achieve net-zero steel production[5].

The complete life cycle of capture, transportation, and storage determines the full environmental impact of carbon capture and storage (CCS) supply chains, which are intended to lower greenhouse gas emissions from industrial sources. Although CCS has the potential to drastically reduce CO_2 emissions, it also comes with new environmental trade-offs and is highly dependent on the energy source used at every stage of the supply chain[6]. Carbon capture, utilization, and storage (CCUS) technologies must be widely implemented in order to achieve net-zero emissions by 2050, but there are substantial infrastructure, financial, and technical obstacles in the way. By offering a thorough framework for strategic CCUS planning and optimization, the National CCUS Assessment Framework (NCAF) aims to address these issues. CCUS is necessary for large-scale CO_2 mitigation, but it is cru- cial to overcome financial, policy, and infrastructure barriers. Advanced modeling and integrated planning frameworks are necessary to enable successful, cost-effective implementation and support the transition to a low-carbon future [6].

The efficient conversion of biomass into fuels and chem- icals is made possible by heterogeneous catalysis, which is essential to the development of clean, inexpensive energy. In order to make biomass conversion feasible at scale, recent research focuses on creating new catalytic materials, stream- lining procedures, and resolving environmental and financial issues. A key component of sustainable biomass conversion is heterogeneous catalysis, and continuous advancements are tackling the environmental, financial, and technical obstacles to aid in the world's shift to clean energy [7] .One possible tactic to increase the economic feasibility of green hydrogen and decrease wasteful clean energy use is to use reduced re- newable energy for hydrogen generation. The levelized cost of hydrogen (LCOH) can be considerably reduced by optimizing system design, grid integration, and storage, increasing the competitiveness of green hydrogen. Low LCOH and maximum use of renewable energy can be achieved by optimizing hydrogen production from reduced renewable power through system sizing, grid enhancements, flexible demand, and by- product usage. For both economic and environmental success, grid and storage infrastructure must be strategically integrated [7].

Selecting and evaluating the risk of CO_2 storage sites requires an understanding of the sealing or conduit capability of faulted marl-carbonate multilayers. These multilayers' capacity to function as barriers or conduits for fluid movement is directly impacted by the considerable variety in fault rock permeability caused by lithological heterogeneity. The lithology and deformation processes have a significant impact on the sealing behavior of faulted marl-carbonate multilayers. While carbonate-rich zones need careful consideration because of their increased permeability and propensity for leakage, marl-rich zones are advantageous for containment [8].

Because of the high deformability of the rock and the intri- cate interactions between mechanical, hydraulic, and thermal processes, extensive modeling is necessary for CO_2 injection into depleted chalk reservoirs. Reliable reservoir behavior pre- diction, risk assessment, and storage security depend on two-way coupled thermo-hydro-mechanical (THM) modeling.For accurate risk assessment and operational planning in CO_2 stor- age within chalk reservoirs, two-way coupled THM modeling is essential, guaranteeing long-term site integrity and storage security There are intricate relationships between fluid flow, heat transport, and rock deformation when injecting CO into chalk reservoirs. In these highly deformable strata, thermo- hydro-mechanical (THM) modeling with two-way coupling between reservoir and geomechanical models is crucial for accurately evaluating CO storage performance and dangers [9]. Combining enhanced coal bed methane (CO-ECBM) recovery with CO storage in coal seams has two advantages: it increases methane output while lowering greenhouse gas emissions. In order to guarantee storage integrity, operational safety, and economic sustainability in CO-ECBM operations, effective monitoring is crucial. Strong, multi-level monitoring systems are essential to CO-ECBM projects in order to guarantee secure and efficient storage. Monitoring is getting better thanks to developments in integrated remote sensing and customized site protocols, but long-term forecasting and cost issues still exist. For commercial-scale adoption, site-specifictactics and ongoing innovation are essential [10].

In general, oxygen-fuel circumstances change the produc- tion of aromatic compounds and increase the presence of short hydrocarbons, particularly because of the impacts of CO and higher flame temperatures. Compared to air combustion, oxygen-fuel combustion changes the production of aromatic compounds and enhances the formation of short unburned hydrocarbons, primarily because of the chemical and thermal impacts of CO. The creation of soot and tar, as well as the improvement of combustion and emission control tech- niques, are all significantly impacted by these changes [13]. Nanopore confinement dramatically changes the fluids' phase behavior and flow characteristics in shale reservoirs, which has an immediate effect on the efficiency of CO_2 injection and oil recovery. Recent studies have modeled and measured the intricate, coupled effects of nanopore confinement, such as molecule–wall interactions, going beyond isolated effects (capillarity or adsorption)[11].

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According to TCFD principles, companies with larger car- bon emissions typically reveal more information about the climate, particularly in carbon-intensive industries. The cate- gories of Strategy, Risk Management, and Metrics and Targets all exhibit this increasing openness, but Governance does not. The results indicate that companies with high emissions employ increased transparency to address corporate account- ability, perhaps in response to social and stakeholder pressures and to justify their environmental impact [12].

II. LITERATURE SURVEY

The results of life-cycle assessment (LCA) studies consis- tently demonstrate that, depending on the capture rate, energy source, and regional factors, post-combustion CCS can lower the global warming potential (GWP) of industrial processes by 47–91 percent. However, increased energy and material requirements for capture, solvent production, and plant modi- fications frequently result in an increase in other environmental impacts, such as acidification, toxicity, eutrophication, and resource use.

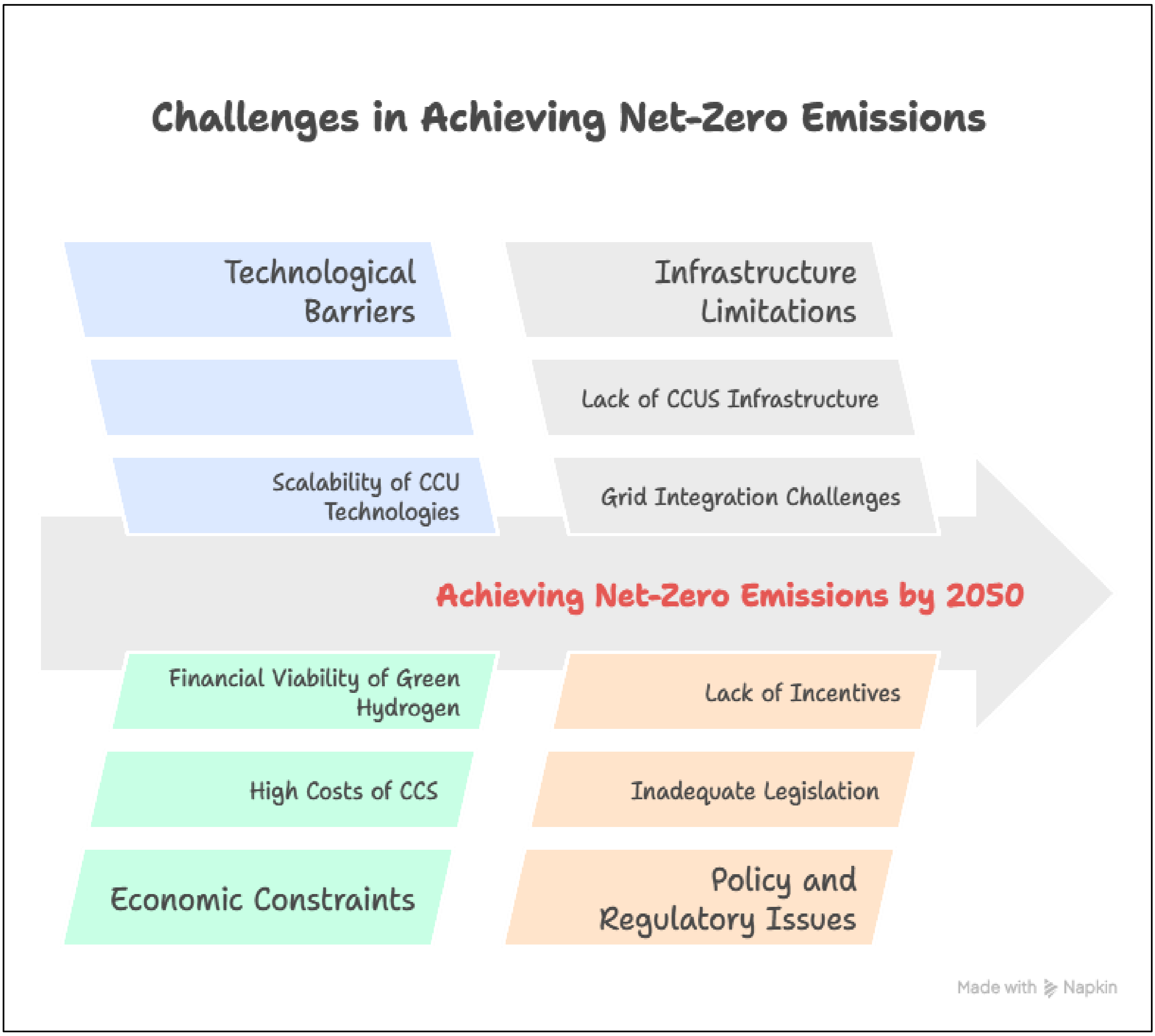

Fig 1 Net Zero Emission Challenges

Important Contributors: Especially when carbon-intensive electricity is used, the capture and conditioning phases are responsible for 70–80 percent of the overall environmental impact. Typically, storage and transportation account for less than 2 percent of overall impacts.

Technology Trends: The most developed and extensively used post-combustion capture technology is amine-based ab- sorption; however, studies into more stable, reasonably priced solvents and sophisticated adsorbents are still being conducted [6]

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Carbonation and CO2 Uptake: Although carbonation of RCA, WCP, and industrial wastes might improve some mate- rial qualities and absorb CO2, the overall mitigation of CO2 is frequently insignificant in comparison to the emissions of the sector. The materials' chemical and mineralogical properties as well as the particular carbonation method employed determine how effective the process is. Other Binders and Supplementary Materials: Using non-hydraulic cements or supplementary cementation materials (SCMs) such as slag, calcined clay, and limestone can further cut emissions, particularly when paired with CCU procedures [5]

In Environmental Remediation, Heavy metals, gasses, and pollutants can be removed due to the high surface area and functional groups. Performance is improved by adjusting the pyrolysis conditions and feedstock. Soil Amendment Carbon Sequestration enhances nitrogen cycling, water retention, and soil fertility; wood biochar works particularly well. Production characteristics determine stability and long-term advantages. In Wastewater Treatment, When compared to traditional sys- tems, biochar is an affordable adsorbent that produces high- quality water reclamation while lowering operating expenses.

Energy Biogas Production lowers greenhouse gas emissions, promotes renewable energy systems, and increases the produc- tion of biogas and anaerobic digestion. Advanced Materials Nano-Biochar is used in high-value like electrochemistry and bio catalysis; nano-biochar has exceptional catalytic and adsorptive qualities [1]

HRES Configurations With their high renewable integration, lower CO2 emissions, and affordable prices, PV-wind-battery and hydrogen storage systems are being researched extensively for net zero goals. Optimization Techniques Advanced algo- rithms (such as NSGA-II) enhance system sizing and perfor- mance, while multi-objective and multi-criteria optimization techniques are employed to balance cost, reliability, and grid interaction.

Storage Technologies Especially in isolated or off-grid envi- ronments, the combination of batteries, hydrogen, and hybrid storage improves dependability and permits greater penetra- tion of renewable energy sources. Economic Environmental Impact HRES can dramatically minimize operational costs, reduce grid strain, and reach near-zero or zero emissions, but economic feasibility is subject to local conditions and legislative incentives [2]

Chemical absorption, especially with solvents based on amines, is the predominant PCC technology because of its proven industrial application and retrofit possibilities. With alternatives like adsorption and membranes still needing to be developed for large-scale use, absorption is used in more than half of existing PCC projects.

Innovative Solvents: Alternative absorbents (carbonates, ammonia, ionic liquids, and nano fluids) and new solvent mixes (such MDEA/PZ) are being developed to increase efficiency and reduce regeneration energy in comparison to conventional Process Intensification: In order to enhance mass and heat transmission and lower operating and capital costs, technologies including improved heat exchangers and rotat- ing packed beds are being investigated. Digital Instruments: Significant efficiency gains have been demonstrated by the growing use of machine learning and advanced modeling for solvent screening, process optimization, and cutting down on experimental time [3]

Storage factors: Mineral, structural, residual, and solubility factors all contribute to the trapping of CO in saline aquifers. Long-term security depends on solubility and mineral entrap- ment, but mineralization is a gradual process that is heavily in- fluenced by the geochemistry and aquifer mineralogy. Aquifer Heterogeneity CO flow, dissolution rates, injectivity, and stor- age efficiency are all significantly impacted by permeability and geological heterogeneity. While high heterogeneity can improve residual trapping, it makes CO migration prediction and management more difficult.

Simulation Modeling: Predictions of CO2 trapping effi- ciency and migration are getting better thanks to sophisticated simulation tools and machine learning models, but it's still difficult to accurately depict heterogeneity and long-term be- havior.

Enhancement Technologies: Despite concerns about cost, toxicity, and pore size, methods including foam, nano particles, and possibly nano bubbles are being investigated to increase sweep efficiency and storage security [4]

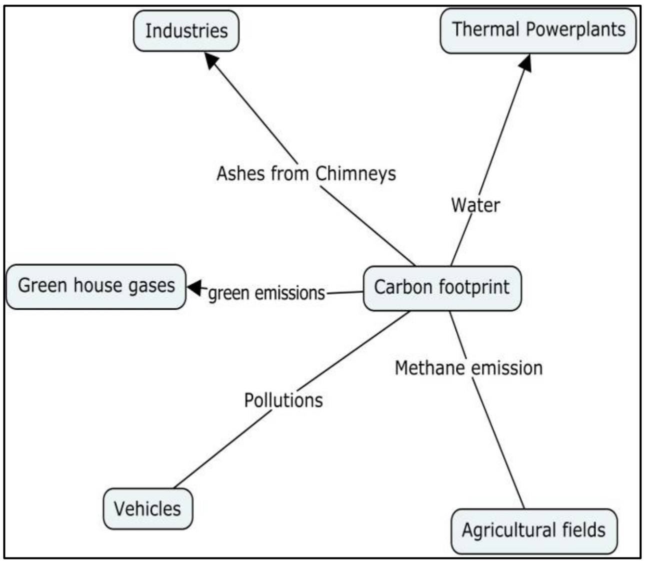

Fig 2 Carbon Foot Print Sources

Catalyst Design and Functionality: In recent years, multi- functional and nanostructured catalysts that improve activity and selectivity for biomass conversion have been developed. Examples of these catalysts include carbon materials, metal- organic frameworks, and porous metals and oxides. For com- plicated biomass feed stocks to change efficiently, porosity, acid-base, and redox characteristics must be tailored.

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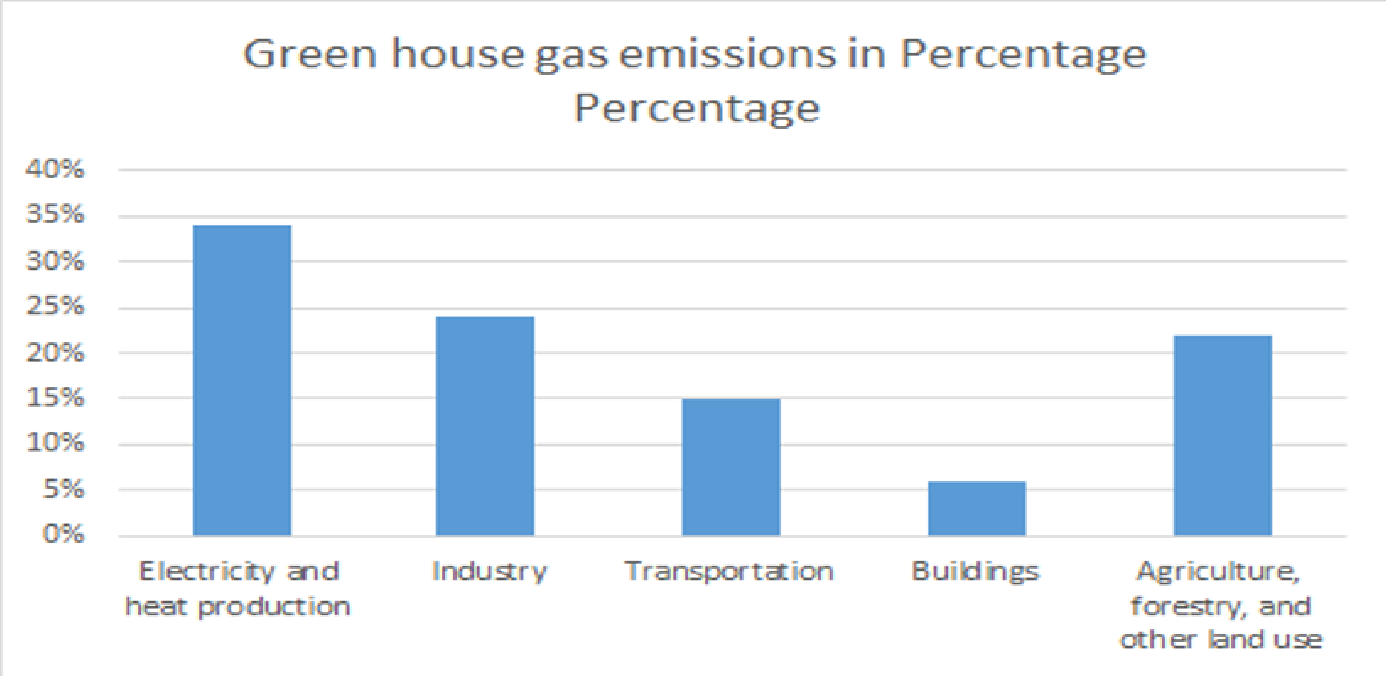

Fig 3 Graphical Representation of Green House Emission

Mechanistic Understanding: Although advancements in spectroscopic and computational technologies have enhanced our knowledge of active site activity and reaction processes, a comprehensive grasp of catalyst-substrate interactions and micro environments remains elusive. Process Integration: To increase yields and process efficiency, researchers are looking into integrating catalytic stages into bio refineries and com-bining heterogeneous and biochemical catalysis [5]

Research highlights the value of dynamic simulations, stan- dardized models, and open-source data in comparing various renewable-hydrogen systems at various scales and locales.

Techno-Economic Assessment: There is a strong focus on reducing the levelized cost of hydrogen (LCOH) through system optimization, including sizing of electrolyzers, storage, and grid connections. Studies emphasize the importance of open-source data, standardized models, and dynamic simula- tions to compare different renewable-hydrogen systems across locations and scales

Grid and Infrastructure Constraints: Research increasingly recognizes the need to model grid constraints, future renewable capacity, and weather variability to accurately assess hydrogen production potential and costs. Grid improvements and rapid deployment of offshore wind are identified as key enablers for low-cost hydrogen [6]

Two-Way Coupled Modeling: To describe the interaction of fluid flow, thermal impacts, and rock deformation during CO injection, sophisticated two-way coupled geomechanical- reservoir models are being utilized more and more. These models, particularly in highly ductile chalk and carbonate reservoirs, enhance estimates of subsidence, stress variations, and possible leakage pathways.

Validation and Calibration of the Model: Calibration against real-world data, such as production history, subsidence mea- surements, and seismic monitoring, is necessary to produce reliable model results. This method increases the accuracy of reservoir behavior predictions in both production and injection situations.

Mechanical and Thermal Effects: Research indicates that the injection of cold CO can cause considerable cooling, which can result in permeability changes, stress redistribution, and thermal fracture. When evaluating injectivity, caprock integrity, and long-term storage security, these impacts are essential [7]

Monitoring Domains: A variety of monitoring methods are used in atmospheric, near-surface, and subsurface domains by global CO-ECBM initiatives. Tracking CO migration and methane production requires subsurface monitoring (such as pressure, gas composition, and micro seismicity), while sur- face and atmospheric techniques (such as soil gas surveys and remote sensing) are being utilized more and more to confirm containment and find leaks.

Technological Advancement: Integrated ”space-air-ground- well” remote sensing systems were first developed in field testing, particularly in China. This allowed for high-resolution, multi-scale monitoring of CO plume migration and surface im- pacts. These developments enhance data for model calibration and improve early leak detection [8]

Drivers of Carbon Disclosure: Studies repeatedly show that companies with higher carbon emissions—particularly those in carbon-intensive industries—disclose more information on climate change, frequently in response to stakeholder expec- tations and pressures for legitimacy. Disclosure is utilized to control reputational risk and adhere

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to social standards, which is consistent with legitimacy theory. Features of the Firm and Industry: Market value, firm size, profitability, and industry all affect how much and how well information is disclosed. While emerging economies frequently fall behind in terms of both quantity and quality, carbon-intensive industries (such as energy, materials, and utilities) are more likely to make comprehensive disclosures [9]

III. PROPOSED MODEL IDEAS

A variety of creative and useful tactics from various in- dustries are highlighted by new study, which emphasizes the importance of reducing the global carbon footprint. The most successful strategies integrate systemic changes in energy, materials, and consumption with behavioral modification and technology.

Table 1 Carbon Emissions from Sources

S.No	Green House Gas Emitting Sources	Percent
1	Electricity and heat production	34
2	Industry	24
3	Transportation	15
4	Buildings	6
5	Agriculture, forestry and land use	22

IV. KEY IDEAS

- *Engaging Consumers:*

Developing options and rewards for low-carbon goods and ways of living.

- *Stakeholder Influence:*

Producers, merchants, and non- governmental organizations working together to modify prod- uct offers and advance sustainable choices.

- *Sector-Specific Innovations:*

CO use in wine production, green logistics at ports, and unique policies for high-income households.

- *Advanced Tracking:*

Real-time carbon monitoring and optimization through the use of IoT, AI, and open-source data.

V. HOW DE-CARBONIZATION IS BEING FUELED BY ARTIFICIAL INTELLIGENCE (AI)

Countries that account for more than 70 percent of the world economy have committed to achieving zero net emissions by 2050 in order to keep the planet’s temperature below 1.5°C. Although the precise methods for accomplishing this objective are still to be decided, digital technology will surely be essential.’

VI. AI TECHNOLOGY

Digital technology have the ability to cut global CO2 emissions by 20 percent by 2030, per new analysis from Digital Europe. Practically speaking, they can assist companies in determining the most economical and significant method of decarbonizing their activities.

Artificial Intelligence (AI) is a field of computer science that describes a machine’s capacity to carry out tasks that are typically performed by human minds. AI-driven solutions can help businesses minimize their energy expenses by 10–20 per- cent and their CO2 emissions by up to 10 percent, according to a recent McKinsey analysis. Additionally, it could result in 15 percent energy savings for transportation systems and up to 20 percent energy savings for buildings.

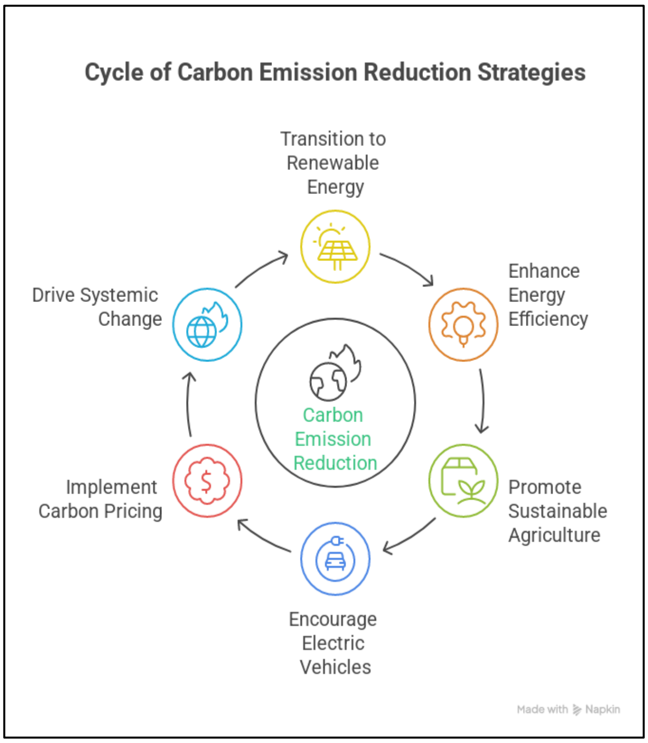

Fig 4 Carbon Foot Prints Obtained from the Sources

VII. DECARBONIZATION

The process of lowering or getting rid of carbon dioxide (CO2) emissions from a variety of sources, such as energy generation, transportation, and industry, is known as decar- bonization. It entails moving away from the use of fossil fuels and toward clean, renewable energy sources with a significantly smaller carbon footprint, such as geothermal, hydroelectric, wind, and solar power. By lowering greenhouse gas emissions, switching to cleaner energy sources and al- ternative fuels not only helps fight climate change but also promotes sustainability and energy security.

VIII. THE CLIMATE'S COMPATIBILITY WITH AI

Although there are worries about how AI could affect employment and the possibility of abuse, the technology is also viewed as a valuable weapon in the fight against climate change. People who have the authority to make decisions about AI and climate change think that the technology is a crucial instrument for halting global warming.

AI has the ability to forecast severe weather and offer tools for decision-making that will assist us in determining and putting into practice the best course of action. Additionally, it can assist in the identification of different climatic risk factors and the development of useful solutions to reduce them.

Strategy/Idea	Sector/Scope	Impact/Details
Integration of Renewable Energy	Industry, Mining	High-emission industries can be transformed by doubling renewable capacity and having a mix of more than 50% RE by 2050.
Auditing and Energy Efficiency	Industry, Buildings	Emissions and operating expenses are decreased via methodical energy audits and efficiency improvements.
Zero-Waste & Circular Economy Projects	Cities, Industry	Emissions are reduced by waste reduction, recycling, and reuse (such as in China's "Zero-waste City").
Low-Carbon Ways of Living	Consumers	Frameworks for housing, food, and mobility decisions; changes in behavior have a significant influence.
Green Jobs & Green Supply Chains	SMEs, Business	Green jobs are produced via eco-friendly waste reduction, circular processes, and green buying.
Digital Management and Optimization Algorithms for Material Innovation in Construction	Buildings	Building emissions can be reduced by 25–90% by the use of low-carbon materials, prefabrication, and recycling.
Capturing, Utilizing, and Offsetting Carbon in Aquaculture and Sustainable Agriculture Algorithms	All Sectors	Planning for emission reduction and tracking using big data, AI, and optimization
Capturing, Using, and Offsetting Carbon	Industry, Agriculture	Reuse and capture of CO2(e.g., synthesis of sodium carbonate, fermentation of wine)
Aquaculture and Sustainable Agriculture	Food Systems	Supply chain emissions are decreased via precise technology, agroforestry, renewable energy, and organic farming.

Fig 5 Carbon Emission Reduction Techniques

IX. CONCLUSION

AI has the potential to revolutionize carbon emissions reduc- tion and climate mitigation efforts in a variety of industries. Its success hinges on sustained innovation, ethical and transparent implementation, and robust industry and policy cooperation to provide equitable and sustainable climate solutions.

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