Systematic Literature Analysis of Carbon Neutrality Implementation Methods in Major Carbon-Intensive Industries in Thailand

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***Abstract*—The rising impact of climate change from greenhouse gas emissions urges industries worldwide to implement strategies to achieve carbon neutrality. Various implementation plans may be utilized to achieve carbon neutrality. This study performs a systematic review to identify key carbon neutrality methods in various industries. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement and the frequency analysis are used to extract key carbon neutrality methods. The results reveal four carbon-intensive industries: electricity, chemical, construction, and transportation. Four implementation methods commonly used include renewable energy, carbon sequestration, carbon capture and storage, and clean energy vehicles. Solar, wind, and biomass are renewable energy sources increasingly used in various industries. Biomass is increasingly used in the chemical and transportation industries. Carbon sequestration can be applied in all industries as soil, oceans, and forests absorb CO_2. Carbon capture and storage is used in industries with high CO_2 generation, like power plants and cement manufacturing. This technology can capture CO_2 during the production processes, especially heating and boiling, thus stopping the emissions from being released into the atmosphere. Clean energy vehicles, such as battery and fuel cell electric vehicles, are becoming popular in the transportation sector, specifically in Europe, America, and China. The study results provide insights into methods to achieve carbon neutrality in different industries. Related stakeholders may use the results to plan for the implementation effectively.**

***Keywords*—carbon capture and storage, carbon neutrality, carbon sequestration, CO_2 emission, electric vehicle, renewable energy, systematic review**

I. Introduction

Carbon neutrality is a balance between emitting CO_2 and absorbing or offsetting it from the atmosphere [1]. Implementing carbon neutrality plans is crucial to mitigating climate change and Greenhouse Gas (GHG) emissions. Various initiatives have been launched worldwide for a more resilient, low-carbon future. In Thailand, the Thai government has pledged to achieve carbon neutrality by 2050 and net zero by 2065. Countries like the United Kingdom, the European Union, the United States, and China have committed to achieving carbon neutrality by 2060. Many major economies have set mid-century carbon neutrality targets (e.g., the EU, UK, and US by 2050 and China by 2060) [2–5]. Strategies, such as energy transition, technical innovation, and renewable energy sources, are initiated to achieve the neutrality target [6–8].

Implementing the carbon neutrality concept varies by country, industry, and method. Different industries adopt different approaches. For example, solar panels support the concept of green buildings in the construction industry. Carbon sequestration can convert CO_2 to the mineral form, which is thereafter permanently sequestered within the concrete to enhance its compressive strength. In the cement industry, the primary source of CO_2 emissions in cement clinker manufacturing arises from the high-temperature heating of limestone and other materials in a kiln [9]. Pelissari *et al.* [10] stated that CO_2 emissions in electricity generation are mostly from coal combustion and fossil fuels. Biomass has been increasingly explored as a renewable and clean alternative to fossil fuels to minimize GHG emissions [11].

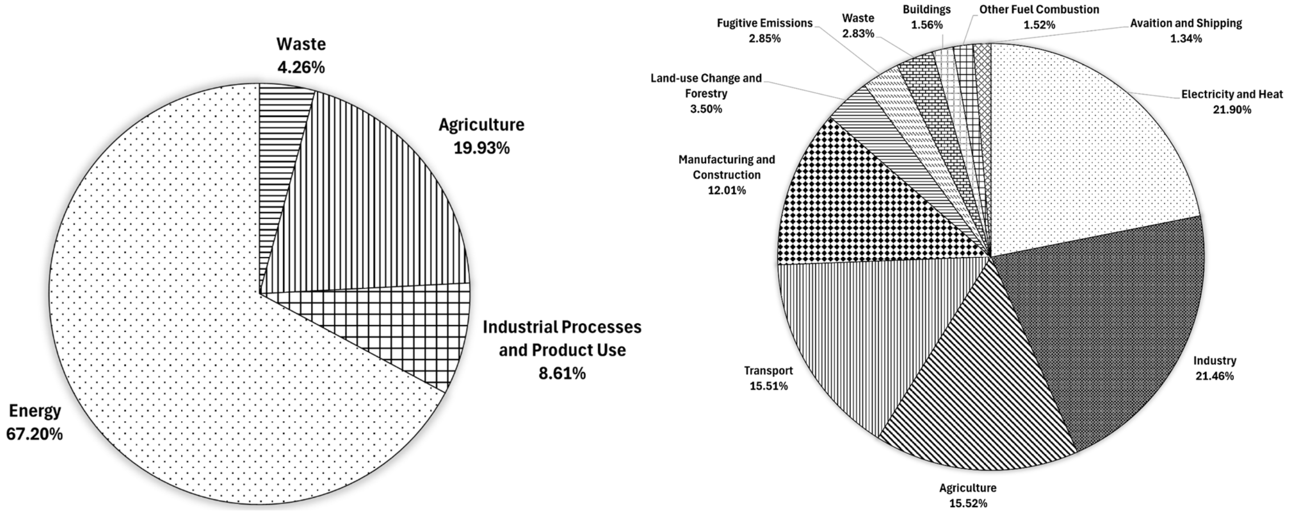
To effectively plan for carbon neutrality implementation, selecting suitable methodologies for the industries is crucial. Different industries depict different characteristics and work nature, so carbon neutrality implementation varies in time and strategies. For example, Vitharana and Chinda [12] stated that the construction industry has a unique nature and involves several phases in a project, such as designing, planning, executing, decommissioning, and demolishing. This sector accounts for 40% of global energy use and contributes 40% of GHG emissions. Carbon neutral construction materials, such as low-carbon concrete, cross-laminated timber, bio-composite bricks, and algae panels, are introduced to lower CO_2 emissions [13]. The chemical industry incorporates different products based on heavy uses of chemicals, such as olefins, ethylene, propylene, benzene, and methanol [14]. For instance, a traditional ethylene production, as a composition of olefins, uses electrified furnaces for steam cracking to accomplish optimal ethylene production. The furnaces require high temperatures and consume energy from fossil fuels, emitting large amounts of CO_2. Using solar energy to operate the furnaces may help reduce emissions [14]. The transportation industry is the basic industry of the national economy. It can be divided into public, private, and cargo transportation [15]. Gao and Zhu [15] stated that energy consumption and GHG emissions are the most pressing issues in this industry. Pollutants, such as CO_2, PM2.5, sulfur dioxide, nitrogen oxides, and ammonia, are released from conventional vehicles, harming human health. Electric Vehicles (EVs) may be encouraged to minimize those emissions. Nevertheless, achieving the level of CO_2 emission reduction with continuous reliance on fossil-fuel-based electricity is not feasible. Using renewable energy and biomass may have short and medium-term decarbonization potential [15].

This study utilizes a systematic review to identify industrial sectors with high carbon emission potential. Key carbon neutrality implementation methods for each industry are discussed to achieve recommendations and strategies for achieving carbon neutrality in the long term.

II. Literature Review

A. Industrial Sectors with High Carbon Emission Potential

Stock Exchange of Thailand [16] classified industries into eight groups with a total of 28 business sectors: agro and food (two sectors), consumer products (three sectors), financial (three sectors), industrials (six sectors), properties and construction (four sectors), resources (two sectors), services (six sectors), and technology (two sectors). In contrast, the Federation of Thai Industries [17] considered 47 industrial sectors, such as gas, printing and packaging, chemical, machinery, automotive parts, digital, cement, electricity, renewable energy, and electronics. UNDP [18] commented that the energy sector ranked the first and contributed 69% of GHG emissions in Thailand in 2020, followed by the agriculture, industrial processes and product use, and waste, respectively (see Fig. 1). Similarly, Ritchie and Roser [19] ranked the electricity and heat sector as the most GHG emissions sector in Thailand in 2021, followed by industry, agriculture, transport, and manufacturing and construction, see Fig. 1. Leenoi [20] commented that the carbon-intensive businesses in Thailand in 2023 include energy and utilities, construction materials, transportation and logistics, and petrochemicals and chemicals, see Fig. 1. In this study, the electricity, chemical, construction, and transportation sectors are examined with the carbon neutrality implementation methods to minimize the emissions in the long term. They are carbon-intensive sectors with high intentions and potentials to achieve carbon neutrality in Thailand.



(a) (b)

Fig. 1. GHG emissions in Thailand: (a). GHG emissions in Thailand in 2020 [18]; (b). GHG emissions in Thailand in 2021 [19].

B. Carbon Neutrality Implementation Methods

Literature has proposed numerous methods to achieve carbon neutrality in the past decade, ranging from renewable energy and EVs to carbon pricing and digital technologies. However, not all are equally emphasized across industries. In this study, the initial literature survey identified 20 distinct methods; among these, four stood out as most prevalent: renewables, carbon sequestration, CCS, and EVs.

1) Renewable energy

Renewable energy is utilized in several industries. For instance, Chayutthanabun *et al.* [21] recommended using renewable energy, such as hydroelectric, wind, and solar, in the transportation sector, specifically EVs. They commented that at least half of the energy used in electricity generation should be renewable to minimize the environmental impacts of EV battery production. UNIDO [22] stated that renewable energy has received great attention in the power generation and manufacturing sectors. Solar thermal systems may be used in the washing and pre-heating of boilers and space heating in industrial buildings.

There are several types of renewable energy. Solar, wind, and biomass are among the top choices as they are clean and, unlike fossil fuels, are not depleted.

a) Solar power

Several solar technologies, such as Photovoltaic (PV) and Concentrating Solar Power (CSP) systems, have been developed to support the transition toward carbon neutrality. PV directly converts sunlight into electricity, while CSP plants employ advanced technology to concentrate sunlight to generate heat that is converted to electricity [23, 24]. The life cycle of these solar power technologies depends on materials like glass, steel, and concrete. Other issues like costs, complicated grid integration, and environmental consequences require a thorough life cycle evaluation to gain wider adoption [23, 24].

b) Wind power

Ye *et al.* [25] stated that improving wind and solar energy systems is essential for accelerating the transition to carbon neutrality. The wind energy conversion system includes the electrical, transmission, and wind turbine systems. Though wind farms are a great potential source of renewable energy, several concerns are raised. The unpredictable wind dynamics make it hard to integrate wind farms into networks. Turbines may generate noise pollution. Improper turbine placement may impact bird lives [26, 27].

c) Biomass

Biomass has become a growing renewable energy source with high growth potential. Biofuels achieved from biomass may be in the form of wood and charcoal (solid state), bioethanol and biodiesel (liquid state), and biogas (gaseous state) [28]. The conversion of biomass is carried out using different techniques. Combustion is a traditional process that produces electricity, direct heat, and residual ashes [29]. The gasification technique creates a gas mixture called syngas when biomass is partially oxidized in controlled conditions, producing chemicals and fuels. The liquefaction method converts solid biomass into liquid bio-oil [11]. The pyrolysis process releases syngas, biochar, and bio-oil [30]. Millinger *et al.* [31] stated that biomass is one of the most crucial energy types in the renewable energy pursuit for carbon neutrality. It is environmentally friendly and made of organic materials that are converted to biogas for electricity generation [32]. Nevertheless, biomass faces challenges regarding feedstock availability, cost, and environmental impact [33].

2) Carbon sequestration

Carbon sequestration focuses on absorbing CO_2 from the atmosphere and storing it in terrestrial or oceanic systems. Land-based methods, particularly those involving forest ecosystems, are included in terrestrial sequestration. On the other hand, oceanic sequestration refers to oceans absorbing CO_2 through biological and physical processes [34, 35]. The atmospheric carbon that is absorbed by seas and coastal wetland ecosystems is called blue carbon. Hao *et al.* [36] stated that forests play a key role in carbon sequestration on land and that trees account for over 80% of China's terrestrial ecosystem's carbon sequestration. Fig. 2 shows an example of a carbon sequestration area in Chiang Mai, Thailand. It revealed an average rate of above-ground carbon sequestration in the dense forest areas of 10.2 kg/m^2 [37].

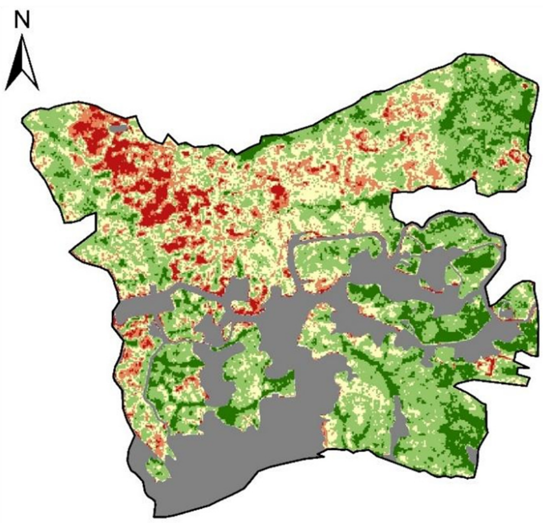


Fig. 2. Example of carbon sequestration area in Chiang Mai, Thailand [39].

On the other hand, oceans offer biological sequestration through phytoplankton, algae, and coral reefs. This may offer a long-term solution for sequestering carbon [38]. Nevertheless, data uncertainty and changes in land use require targeted research and effective regulations to maximize the effectiveness of carbon sequestration.

3) CCS

CCS systems are increasingly used to lower CO_2 emissions. IEA [39] stated that 19% of CO_2 emissions must be captured and stored to prevent the global temperature from rising above 2°C by 2050. The system involves several processes: CO_2 separation, conversion, transportation, and underground storage, see Fig. 3 [40]. Various capturing technologies exist, such as pre-combustion, post-combustion, and oxyfuel combustion [40]. The pre-combustion process involves reacting fuel with oxygen, air, or steam to produce syngas or fuel gas. Post-combustion separates CO_2 from flue gases produced by primary fuel (coal, natural gas, or oil) combustion in the air. Oxyfuel combustion uses pure oxygen, resulting in flue gas, which is mainly CO_2 and H_2O [41]. Once CO_2 is captured, it must be compressed into a supercritical fluid to facilitate its transportation via pipelines to designated storage sites [42].

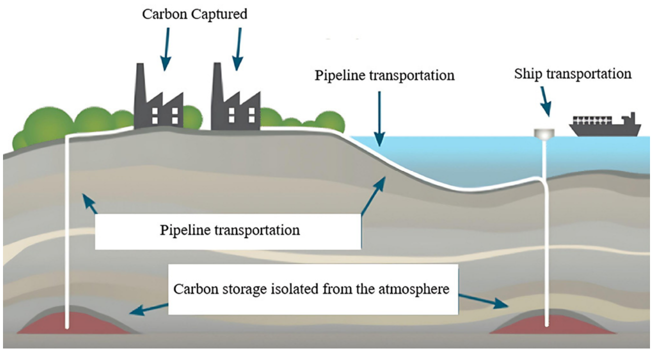


Fig. 3. Basic principle of CCS system [39].

4) EVs

EVs are a solution to achieve carbon neutrality in the transportation sector. Chinda [43] mentioned that the transportation sector is responsible for CO_2 emissions and PM2.5 problems, and the Thai government has implemented several policies to support alternative energy used in transportation, including EVs. The number of EVs in Thailand is expected to be over 2 million in the next 20 years, see Fig. 4 [43, 44].

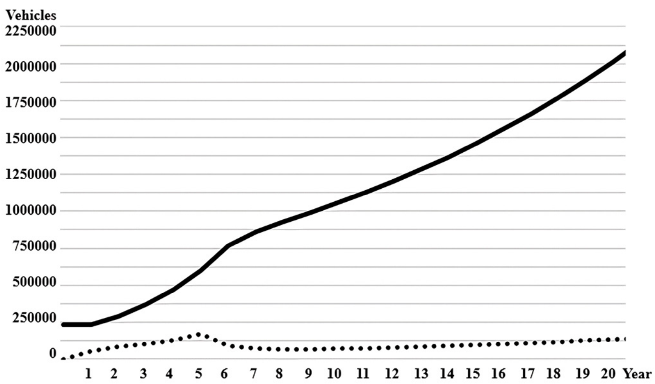


Fig. 4. EV trend in Thailand [43].

There are four types of EVs: battery EVs (BEVs), plug-in hybrid EVs (PHEVs), hybrid EVs (HEVs), and fuel-cell EVs (FCEVs). BEVs run entirely on batteries, while PHEVs run on battery and gasoline. HEVs have two complementary driving systems: a gasoline engine with a fuel tank and an electric motor with a battery. FCEVs create electricity from hydrogen and oxygen [44].

III. Materials and Methods

This study uses systematic literature and thematic analysis to identify key carbon neutrality methods for carbon-intensive industries. It examines themes that can reveal what lies underneath the viewpoints of data sets. A comprehensive theme analysis technique may result in dependable and perceptive results. However, this method lacks clear instructions on how academics should conduct in-depth thematic analysis [45].

This study follows the PRISMA statement to identify key carbon neutrality focusing on topics, such as eligibility criteria, information sources, search strategy, selection process, data collection, data items, risk of bias, synthesis methods, and study selection [46]. The Scopus and Thai Journal Citation Index Center (TCI) databases are used as major sources of data. Scopus is a large database used by many authors to conduct the literature review to retrieve relevant articles based on a search query related to the research objectives. On the other hand, TCI is Thailand's database for Thai and English publications. The process involves three steps: identifying relevant search keywords and creating search queries within the database, screening search results using filters, such as languages, document types, and publication dates, and downloading the identified articles [47]. The search has been conducted during August–December 2023. The initial search by inputting keywords, namely carbon neutrality, implementation, method in the "article title, abstract, keywords" section yielded 4907 articles in the Scopus database and 29 articles in the TCI database (i.e., 4936 articles in total). After that, additional keywords, including electricity, chemical, construction, and transportation are input into the databases, resulting in 2594 articles extracted. The search is further limited to English and Thai articles and the publication dates from 2013–2023. Only full-paper publications were selected and did not include the reports, conference proceedings, book chapters, and extended abstracts. It is noted that the extracted articles include the studies from Thailand and other countries.

A total of 1962 articles were extracted. They are further screened using manual screening to facilitate keyword searches within the downloaded articles and help screen out irrelevant ones. In this study, 130 articles were randomly selected from the recent publications and manually skimmed to identify the carbon neutrality methods mentioned in each. Duplicated or similar terms, such as solar power, solar energy, and solar farm, are grouped manually into a single term (e.g., solar power). The groupings of the duplicated terms were discussed with colleagues working in this field prior to confirming the groupings and avoiding possible bias. The results yield 15 comprehensive methods to achieve carbon neutrality, namely renewable energy (solar power, wind power, and biomass), carbon sequestration (tree planning and ocean absorbing), CCS, EVs, carbon trading, hydrogen energy, nuclear energy, geothermal energy, carbon tax, carbon market, digital technology, hydropower, carbon offset, recycled materials, tidal energy, and synthetic fuel (see Fig. 5).

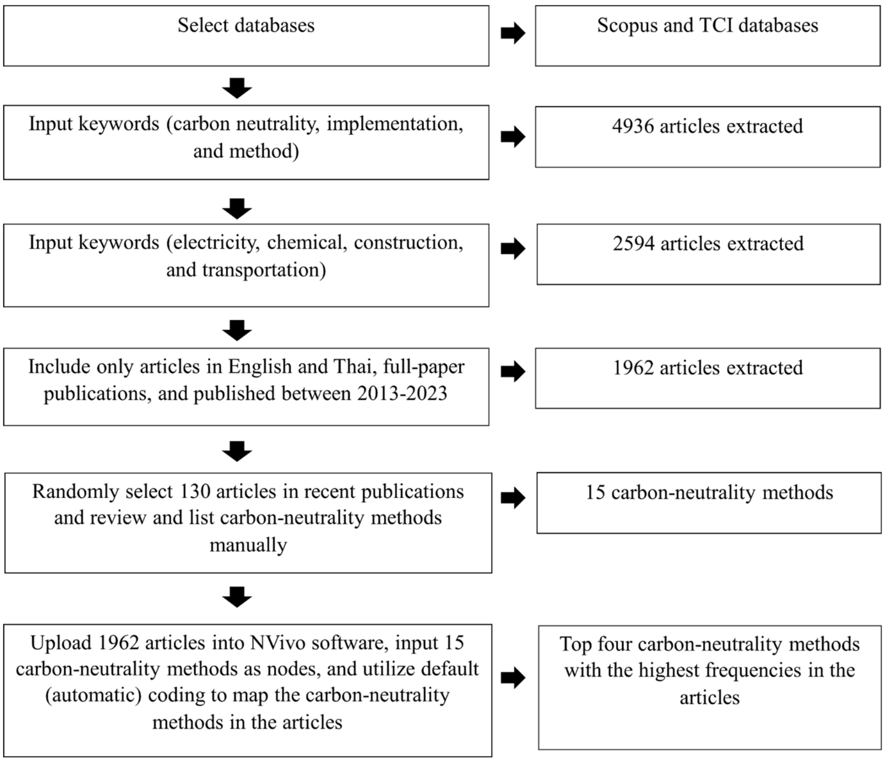


Fig. 5. Carbon neutrality method selection.

The list of 15 methods was then analyzed using NVivo software version 10 to identify the methods mostly mentioned in the articles. The 1962 extracted articles from the Scopus and TCI databases were inputted into the software with the 15 carbon neutrality methods inserted as nodes in the software. The automatic coding (i.e., default function) was utilized to map the nodes found in the 1962 articles. The frequencies of appearance of the 15 methods were listed from the software results and the four top methods, representing 80% of the total frequencies were selected (see Table 1). The cut-off level of 80% is a standard parameter employed in various scholarly journals and is used as a cut-off level for carbon neutrality method selection [48]. Four most prevalent methods, namely renewable energy (solar, wind, and biomass), carbon sequestration, CCS, and EVs, are examined to achieve carbon neutrality in the long term. These four methods align with Thai's national policies. For instance, the Power Development Plan stated that by 2037, half of electricity generation will come from renewable energy sources like solar, wind, and biomass. The National Energy Plan aims to raise the utilization of renewable energy to 7% by 2030 and 17% by 2037 [49].

Table 1. Carbon neutrality methods frequently appear in the articles (NVivo results)

Carbon neutrality method	NVivo results	
	Frequency (%)	**Cumulative frequency (%)**
Renewable energy (solar, wind, and biomass)	47	47
Carbon sequestration	14.9	61.9
CCS	12.3	74.2
EV	6	80.2
Carbon trading	5.4	85.6
Hydrogen energy	3.1	88.7
Nuclear energy	2.8	91.5
Geothermal energy	2.4	93.9
Carbon tax	2.3	96.2
Digital technology	1.7	97.9
Hydropower	0.9	98.8
Carbon offset	0.4	99.2
Recycled materials	0.4	99.6
Tidal energy	0.3	99.9
Synthetic fuel	0.1	100

IV. Results and Discussion

A. Carbon Neutrality Implementation Methods for the Electricity Sector

Common carbon neutrality methods in electricity include renewable energy (especially solar and wind), carbon sequestration, and CCS.

1) Renewable energy for the electricity sector

Coal-fired power plants generate most CO_2 emissions in electricity generation. Many research studies recommend renewable energy to reduce emissions. Wu *et al.* [50] stated that solar power is an alternative source to coal-fired electricity generation. Solar PV-based electrification in industrial sectors and buildings can significantly aid in reaching carbon neutrality targets. In Thailand, solar energy is implemented as an innovation. Solar floating is a new solar technology suitable for medium or large-sized industries with limited spaces [51]. In this technology, solar panels float in the sea using special plastic pellets with strong impact resistance. The panels are added with environmentally- and animal-friendly chemicals that minimize the accumulation of sea squirts. The high investment cost is a crucial concern for this solar technology [51].

Wind energy is also a renewable source for the electricity sector. A key concern lies in the geological location. Long *et al.* [52] mentioned that the locations, particularly between 30N and 60N latitudes, have great potential for worldwide electricity generation and CO_2 emissions reduction. In advanced deployment scenarios, wind power may account for over 30% of worldwide electricity output [39]. Wind power has low GHG emissions and air pollutants throughout its life cycle (i.e., manufacturing, installation, transportation, maintenance, and disassembly). It emits only 8− 20 g of CO_2 per kWh of electricity generation, about 1% of coal [53].

Using biomass with CCS (BECCS) is crucial in achieving net-zero emissions by 2050 in the energy sector. The BECCS system is flexible, has a short start-up time, and can be used to support the grid's capacity for PVs [54]. Nevertheless, constant supplies of biomass remain a challenge as they reduce the quantity of arable land accessible for agriculture and can result in environmental damage [55].

2) Carbon sequestration for the electricity sector

Power-generating facilities generate high CO_2 emissions. A portion of CO_2 is naturally stored in oceans, plants, and soils, but a growing quantity is released into the atmosphere. Biological and physical carbon sequestration reduces CO_2 emissions in the energy sector. Forests, peat marshes, and coastal wetlands excel in biological carbon sequestration. Plant tissues, such as durable tree bark and vast root systems, serve as reservoirs for carbon storage [56]. Soils harbor a substantial amount of carbon that plants absorb from the environment over their lifespan. In regions with colder climates, soil can retain carbon for an extended period. Fig. 6 shows types of geologic carbon sequestration from power plants in Norway.

Fig. 6. Carbon sequestration from power plants in Norway [56].

1) CCS for the electricity sector

Coal is mostly used for combustion in thermal power plants. CO_2 separation technologies can be employed in the fuel-burning processes to capture CO_2 after combustion or remove carbon from the fuel before combustion. CO_2 that has been captured is commonly compressed to a high density at the location and stored by injecting CO_2 into subsurface geological formations or the deep ocean. Implementing carbon capture technology in coal-fired power plants can reduce CO_2 emissions by 90% during the power generation process. This leads to a reduction of GHG emissions up to 80% in the post-combustion system, 86% in the oxyfuel combustion system, and 86% in the pre-combustion system, depending on the type of capture solvent used [57–59]. These reductions are compared to power plants that do not employ carbon capture technology. Coal-producing regions can employ CCS techniques to mitigate emissions by installing retrofits or utilizing low-emission sources, such as hydrogen-based fuels and chemicals [57–59].

In Thailand, the Mae Moh power station in Lampang province utilizes the post-combustion technology with Mono-Ethanolamine (MEA) solvent for carbon capturing [60]. The energy demand in the MEA-based CO_2 capture process arises from the consumption of steam or heat in the stripper for CO_2 scrubbing and solvent regeneration. By employing the MEA solvent, flue gas, which consists of CO_2, water vapor (H_2O), and nitrogen (N_2), is subsequently transported in a direction opposite to the solvent-filled absorber. Following the scrubbed gas's water wash, CO_2 regeneration occurs as it is extracted, pressurized into a supercritical state, and transported for storage in the ocean or geological repositories. The gas undergoes compression and dehydration prior to transit through onshore pipelines. Ultimately, it would be delivered to CCS plants to produce commercial chemicals based on CO_2 [60].

B. Carbon Neutrality Implementation Methods for the Chemical Sector

Common carbon neutrality methods used in the chemical industry, specifically producing olefins, include renewable energy, carbon sequestration, and CCS. Olefins are organic compounds composed of hydrocarbons, specifically ethylene and propylene, that are used in plastics and chemical industries. Manufacturing olefins by steam cracking liquid feedstock consumes large amounts of energy and produces high GHG emissions.

1) Renewable energy for the chemical sector

In recent years, various studies have been conducted on green and low-carbon techniques for chemical manufacturing. For example, traditional ethylene manufacturing, as a part of olefins production, uses electrified furnaces that consume 8% of total energy demand [14, 61]. Solar energy, when used in the electrified steam cracking process, drastically reduces GHG emissions (see Fig. 7). The use of solar electricity in the electrified steam cracking process follows the decarbonization of industrial processes.

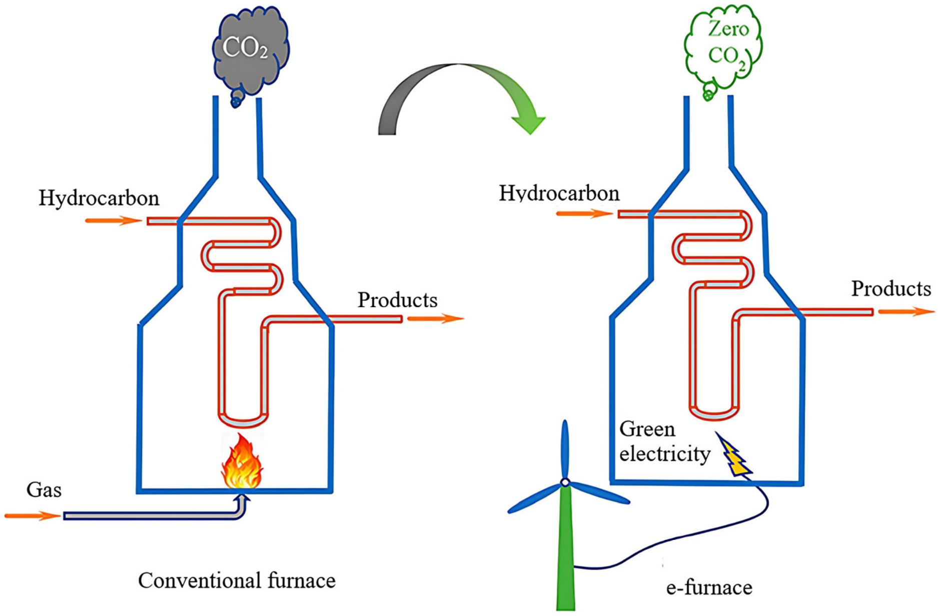


Fig. 7. Electrified steam cracking process [14].

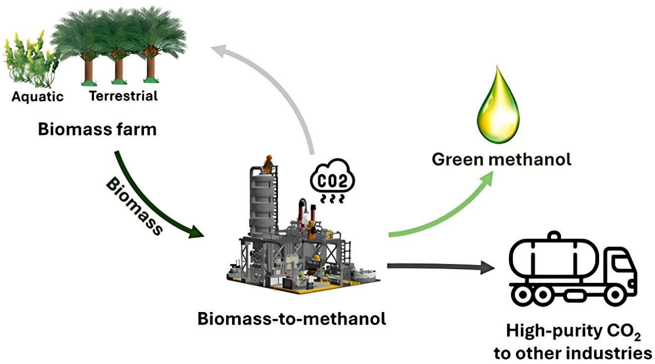


Fig. 8. Green methanol produced from biomass [62].

Petrochemicals dominate the chemical industry's feedstock. Major chemical products in the petrochemical industry include, for instance, ethylene, propylene, and methanol [62]. They account for one-third of the sector's overall energy requirement. To minimize the emissions, they could be produced, directly and indirectly, using the so-called green methanol as an intermediate to olefins and aromatics, i.e., via methanol-to-olefins (MTO) and methanol-to-aromatics (MTA) processes [62]. Green methanol may be produced directly from sustainable biomass resources or by hydrogenating captured CO_2, see Fig. 8 [62].

Kircher [63] mentioned that chemical production in Europe in the future will be based on primary (e.g., wood from forests), secondary (e.g., forest industry's by-products), and tertiary (i.e., residues from the processing of primary biomass and post-consumer materials suitable as raw materials for recycling) biomass. Primary biomass is a source for functionalized products, while secondary and tertiary biomass are preferred for synthesis gas production.

2) Carbon sequestration for the chemical sector

Petrochemical production engages in the utilization of biological carbon sequestration. Notably, forests, peat marshes, and coastal wetlands exhibit exceptional proficiency in carbon sequestration in this sector.

3) CCS for the chemical sector

In Thailand, the Thailand Board of Investment introduced several tax exemption schemes to promote domestic and foreign investments in low-carbon technologies in the energy, transport, chemical, waste, and agriculture sectors. In the chemical sector, the scheme focuses on CCS technologies for the petrochemical and natural gas separation plants to achieve carbon neutrality.

Light olefins are highly used in plastic and textile production. Steam cracking is the primary method for light olefins production, which is considered a CO_2-intensive technique. CCS systems may be used to achieve carbon neutrality. Following the CO_2 collection process, the gas undergoes purification and compression, usually reaching a supercritical state, to provide a concentrated stream that can be transported through pipelines to the storage. Geologic carbon sequestration stores CO_2 in subterranean geologic structures [64]. CO_2, in a supercritical state, is injected into an underground porous rock formation that has either stored or formerly contained fluids. Injecting CO_2 at depths exceeding 800 m in a standard reservoir ensures that the pressure maintains CO_2 in a supercritical state, reducing the likelihood of CO_2 migration from the geological formation [64, 65].

C. Carbon Neutrality Implementation Methods for the Construction Sector

Common carbon neutrality methods used in the construction sector, specifically cement production, include renewable energy, carbon sequestration, and CCS. Concrete, a primary resource for construction, emits high CO_2 emissions as by-products from the cement clinker process.

1) Renewable energy for the construction sector

The calcination of limestone, which forms the basic chemical reaction, is responsible for 65% of the total CO_2 produced inside the confines of the cement plants [39, 66]. A hybrid process that combines the concentrated solar thermal technology (or solar calciner) in cement production has been introduced to reduce the use of fossil fuels and CO_2 emissions by 40 % and the climate change impact by 81% compared to the traditional calcination process [67, 68]. The concentrated solar power systems use mirrors or heliostats to concentrate large areas of sunlight into targeted areas. The heat is used to generate steam to power turbines and produce electricity. The captured heat can be retained over lengthy periods at a low cost and with little energy loss [67].

2) Carbon sequestration for the construction sector

The construction industry utilizes the carbon sequestration method to convert CO_2 into mineral forms sequestered within the concrete. This was achieved by introducing CO_2 into the fresh concrete mixture during the mixing process. An unsealed mixture would facilitate the release of additional CO_2 gas into the atmosphere, interfering with the chemical interaction between the newly formed concrete and CO_2, enhancing its compressive strength compared to concrete without CO_2 [9].

3) CCS for the construction sector

Cement production involves heating and combining powdered limestone with various components, forming an intermediate substance known as clinker. CO_2 emissions can be reduced by diminishing the need for clinker by, for instance, replacing it with waste materials, such as blast furnace slag and coal ash [64, 65]. Moreover, installing CCS facilities with cement kilns may capture CO_2 emissions for other uses. Alternative fuels like refuse-derived waste, biomass, and hydrogen may be used with the kiln to reduce CO_2 further [64, 65]. The Norcem cement plant in Brevik, Norway, is undergoing construction for the world's inaugural cement CCS project. The plant is expected to capture 400,000 tons of CO_2 annually [69].

Besides energy and CCS interventions, material substitutions (e.g., timber for cement) and innovative design can also contribute to construction sector decarbonization.

D. Carbon Neutrality Implementation Methods for the Transportation Sector

Renewable energy, carbon sequestration, and electric vehicles (EVs) are common carbon neutrality methods used in transportation. However, EVs are less directly applicable here beyond electrifying company vehicle fleets.

1) Renewable energy for the transportation sector

Concerns about environmental degradation associated with the combustion of hydrocarbon-based fuels in internal combustion engines urge using green energy. Alternative fuels include bio-alcohols, biodiesel, biomethane, hydrogen, and electricity from fuel cells [70]. Amin *et al.* [71] mentioned that hydrogen receives the highest attention as an alternative transportation fuel, and electrolytic hydrogen production from PV generation currently represents an attractive production route. In contrast, Moreira *et al.* [72] commented that biofuels can present low carbon footprints in the transportation sector if properly produced. Using biofuels in combination with partial electrification in light-duty vehicles enhances energy efficiency and reduces GHG emissions.

2) Carbon sequestration for the transportation sector

Biological carbon sequestration from natural forests and oceans could be employed to reduce CO_2 emissions from the transportation sector.

3) EVs for the transportation sector

EVs are a key technology to decarbonize road transport and could reduce 30% of CO_2 emissions. BEVs can reduce lifecycle CO_2 emissions by 30% on average; the benefit can range from a 37% reduction in coal-dependent grids to 90% in hydro-powered grids [73]. Dulau [74] mentioned that the eco-friendliness of BEVs depends on the power mix, which refers to the ratio of the electricity generation sources powering it. FCEVs' eco-friendliness depends on hydrogen production, mostly from steam reforming of natural gas and other fossil fuels, and only a small amount from renewable energies. Jaspers *et al.* [75] added that hydrogen has the potential to serve as an energy carrier. Utilizing a solid oxide fuel cell powered by biofuels within FCEVs makes it possible to minimize emissions. Green hydrogen or e-fuels for long-haul transportation may be possible for future decarbonization.

E. Summary of Results

Carbon neutrality is a growing concept that minimizes CO_2 and GHG emissions. The systematic literature analysis finds that renewable energy, carbon sequestration, CCS, and EVs are the most prominent carbon neutrality implementation methods across Thailand's carbon-intensive industries, collectively accounting for 80% of references to decarbonization strategies in the literature (see Table 2). Solar power is a common renewable energy type used in the four carbon-intensive industries. Various solar power systems may be used, such as PVs, concentrated solar power, solar water heating, and solar air heating [76]. It is mostly used to replace coal and fossil fuels in the production processes. Biomass is an alternative source of energy. It is mainly used to produce biogas and biofuels. Biofuels, specifically biodiesel and bioethanol, are widely used in transportation to lower the requirement of fossil fuels and natural gas. In the electricity sector, solar energy helps decarbonize other carbon-intensive sectors, which are used for chemical production processes (the chemical sector), heating buildings (the construction sector), and charging EVs (the transportation sector). Renewable electricity can produce renewable hydrogen for materials, chemicals, and power production.

Solar energy should be encouraged in the Thai industries as it provides several benefits: reducing GHG emissions from the energy sector, lowering expenditure on energy, reducing dependency on energy reports, and supporting the development of the green economy [77]. The investment costs of solar installation in Thailand and countries in different regions are compared to examine the possibilities of this method. Table 3 shows that by comparing Thailand with Asian countries, the solar installation cost in Thailand is in the average range, lower than that in Japan by over half and higher than that in India by about 15% [78]. The cost is also cheaper than that in countries such as Australia, America, and most of Europe, regardless of the average living expenses.

The Thai government should promote the use of solar energy as a part of carbon neutrality plan to meet the targets set in the country's green policies: Alternative Energy Development Plan (targeting to utilize renewable energy by 30% by 2037), Power Development Plan (by 2037, half of electricity generation will come from renewable energy), National Energy Plan (utilize renewable energy by 7% in 2030 and 17% in 2037), and Thai EV 3.0 and 3.5 schemes (targeting that by 2030, 30% of new vehicles production are zero-emission vehicles); see Fig. 9 [49]. Some challenges may be noted. Solar systems require high investment and maintenance costs; installing them requires specialized knowledge and skills. Some industries may have limited spaces for solar system installations [79].

Biomass is also a widely used renewable energy source in Thailand's electricity, chemical, and transportation sectors. Rice husk, bagasse, and oil palm residues are common biomass sources for electricity generation. Contrarily, cassava, sugarcane, and maize are used to produce bioethanol and biodiesel. The Thai government promotes the use of this biofuel to replace methyl tertiary butyl ether in 95-octane gasoline for the whole kingdom [80].

Table 2. Summary of carbon neutrality methods employed in the four industries

Industry	Renewable energy			Carbon sequestration	CCS	EVs
	Solar	Wind	Biomass			
Electricity	√	√	√	√	√	
Chemical	√		√	√	√	
Construction	√			√	√	
Transportation	√		√	√		√

Table 3. Investment in solar energy [76]

Region	Country	Investment cost ($/kW)
Asia	Japan	2101
	Korea	1326
	Saudi Arabia	1267
	Indonesia	1192
	Thailand	910
	China	879
	India	793
Australia	Australia	1554
Africa	South Africa	1671
America	Canada	2427
	USA	1549
	Brazil	1519
	Mexico	1481
	Argentina	1433
Europe	Russia	2302
	UK	1362
	Turkey	1206
	Germany	1113
	France	1074
	Italy	870

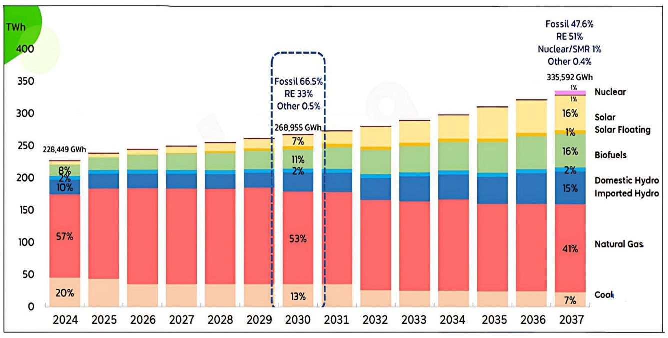


Fig. 9. Plan for Thailand's solar and other renewable energies [77].

Success use of renewable energy (i.e., solar, biomass, and wind power) depends on various factors, such as geographical locations, seasonal variations (e.g., variations of solar radiation and the intermittent nature of wind energy), technology requirements, investment, and government supportive policies.

Carbon sequestration through tree and ocean absorption is another common method employed in the four industries. It is a viable approach in all industries. Nevertheless, Jat *et al.* [81] commented that carbon sequestration is limited by biophysical, technical, and economic aspects. Different soil properties may have different carbon saturation, which refers to the maximum capacity of soil to retain carbon. The use of soil carbon sequestration must also be traded off with other economic constraints, such as land use and incentives.

CCS is increasingly used worldwide. However, implementation involves commercial, storage, and infrastructure challenges and risks. A major commercial challenge is the high investment cost. The captured CO_2 is typically stored underground, and the underground storage sites must be regularly assessed, which could be time-consuming and expensive. Suitable sites are typically located in remote areas, and CO_2 is transported through pipelines. The cost of the pipeline system can be high with numerous public resistances [82]. CCS technologies may be energy-intensive, and the implementation must consider renewable energy. The long-term growth of CCS also depends on the size of the future CCS market [83].

EVs are a green vehicle choice for public and private transportation. However, electricity generation for EVs should integrate renewable energy, including solar, wind, and biomass, to minimize CO_2 emissions. FCEVs will become the best EV choice when hydrogen is obtained from nuclear power and renewable energy sources [74].

This study provides insights into methods used to achieve carbon neutrality in different industries. Related stakeholders may use the study results to plan for efficient carbon neutrality implementation to achieve the country's targets. The priority could be solar power implementation as it has been increasingly used in industrial and residential sectors. EV industry should also be continuously promoted with the use of renewable energy in the electricity generation to achieve carbon neutrality as planned.

Future studies may be conducted to examine trends of renewable energy usage in Thailand using quantitative analyses to facilitate the interpretation. Increasing the number of databases in the study may yield better outcomes. In addition, there may be biases associated with manual groupings of keywords. It is also noted that less frequently mentioned methods (e.g., carbon trading and hydrogen and nuclear energy) should not be overlooked. Specifically, hydrogen used in the chemical sector, green building design in the construction sector, and nuclear energy may be studied in future studies.

This study followed PRISMA guidelines where feasible (i.e., search, screening, data extraction). Nevertheless, due to the broad scope, some elements (like exhaustive screening of each article's findings) were beyond scope, which could be tackled in future work. Therefore, a full systematic review following PRISMA guidelines may be conducted to increase the accuracy of the study results. Ultimately, achieving carbon neutrality will likely require a portfolio of these methods tailored to each industry's context. This study highlights the most prominent options and can guide policymakers and industry leaders in their long-term decarbonization strategies.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

T.C. conducted the literature review, performed the analysis, and wrote the manuscript. R.C. conducted the literature review and wrote the manuscript. All authors had approved the final manuscript version.

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