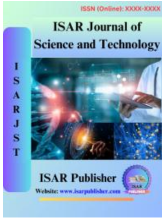

ISAR Journal of Science and Technology

Volume 3, Issue 11, 2025, Page: 11-24

Abbriviate Title- ISAR J Sci Tech

ISSN *(Online)*- 2584-2056

https://isarpublisher.com/journal/isarjst

Decarbonizing Oil Refineries: The Transition to Green Electricity in High-Temperature Processes

Mustafa Abdul Kareem Abbas Al-Shnawa

Electrical Department, Maintenance Authority, South Refineries Co., Ministry of Oil, Basrah, Iraq.

***Corresponding Author**

Mustafa Abdul Kareem Abbas Al-Shnawa

Electrical Department, Maintenance Authority, South Refineries Co., Ministry of Oil, Basrah, Iraq.

Article History

Received: 02.08.2025
Accepted: 15.10.2025
Published: 11.11.2025

Abstract: Decarbonization of oil refineries has taken one of the priorities with the light of the global concerns to mitigate the consequences of climate change. One of the largest parts of greenhouse gas emission by the industry, as the oil refining sector, is heavily pressured to switch to low carbon technologies. With the particular emphasis put on introducing green electricity into the high-temperature processes, this document offers the means of doing so by decarbonizing oil refineries. In the past, this industry has been relying on fossil fuel as energy source in a process, particularly in the processes such as Distillation, cracking as well as reforming where a lot of heat is required. This is a necessary change towards more sustainable energy solutions in the curbing of the level of carbon emissions in the refinery processes. The renewable sources of energy such as solar, wind, and hydrogen have potential of becoming an alternative to the normal fossil fuels. Incorporation of these technologies in the refinery processes not only assists in compliance with tighter environmental standards but also helps the industry prepare for long-term success in a more and more low-carbon economy. There are technical, economic and regulations issues that refineries face in the adaptation of these new technologies but with some government incentives, industry cooperation, and the state of innovation, they should be able to overcome them. Case studies are also included highlighting the success of decarbonization strategy implementations in the refineries around the world. The use of green electricity for lowering emissions from the energy-consuming refining process is emphasized, and the possibility for energy storage and for building a hybrid system, which guarantees stable power supply is mentioned. Addressing both the environmental impacts and the operating requirements, the document presents overall vision of the way refineries of oil can develop the future, which will be more sustainable.

Keywords: Decarbonization, Oil Refineries, Green Electricity, Hydrogen, Solar Energy, Wind Energy, Carbon Emissions, Energy Transition.

Cite this article:

Al-Shnawa, M.A.K.A., (2025). Decarbonizing Oil Refineries: The Transition to Green Electricity in High-Temperature Processes. *ISAR Journal of Science and Technology*, *3*(11), 11-24.

1. Introduction

1.1. Background on Oil Refining Industry

Oil refining industry started in mid-century of 1800s, and has become the corner of the modern civilization, delivering vital transportation fuels and petrochemical products. Being one of the largest industries across the world, a very significant role in the motion of economies, where the global refined petroleum market was estimated at around $ 2.31 trillion in 2021 and is expected to show annual growth at a compound annual growth rate of 13.1%. However, the sector is under pressure to shift towards environmental sustainability, especially from the huge amount of greenhouse gas emissions that contribute approximately 13% of U.S. industrial emissions, [1] and [2].

Refineries function via different processes that extract the crude oil into usable products like gasoline, diesel, and petrochemical forefathers. With further advancement in technology, this industry has to embrace innovation and accommodate shifting market dynamics resulting from changes in regulation that will reduce carbon footprints. This adaptation consists of the shift toward cleaner energy alternatives in response to the loss of demand for oil as popularity of electric vehicles increases, [3].

However, oil refining sector continues to be the key in addressing global energy demands and actively seeks decarbonization opportunities through innovative measures like carbon capture and storage (CCS), electrification in operations, and exploitation of renewable sources of energy, [4] and [5]. Table 1 shows CO_2 emissions reduction.

Table 1: CO_2 Emissions Reduction (200,000 bbl/day Refinery).

Scenario	**Annual CO_2 Emissions (tons)**	**Reduction (%)**	**Description**
Baseline (fossil fuels only)	2,700,000	–	Typical fired heaters, SMRs, gas turbines
Electrification (95% efficiency)	1,200,000	~55%	Electric heaters replace fired heaters
+ Green Hydrogen (PEM electrolysis)	900,000	~67%	Replaces grey hydrogen (SMR-based)
+ Solar Thermal for Process Heat	700,000	~74%	CSP used for distillation, preheat, hydrocracking
+ Full Hybrid + CCUS	400,000	~85%	All-electric + green H_2 + CCS + TES + BESS

1.2. Importance of Decarbonization

Conversion of oil refineries for the sake of mitigating carbon emission is needed to alleviate the pressing issues as effect of climate change and air quality degradation. The refining industry of petroleum creates a considerable amount of gas emissions, catalyzing about 13% of industrial emission in the U.S and 3% of the total emission in the country. With increased strides worldwide to reach net zero carbon emission, transformation of this industry is greatly required. It is not only because of regulatory pressure and environmental obligations but also due to an encouragement of green power by the marketplace that the decarbonization drive is made, [1].

In the past, the refining industry has been using fossil fuels. However, an increasing awareness is being developed, according to which, sustainable solutions need to be incorporated into the operating practices. Switching to processes that release fewer carbon emissions can significantly improve air quality, replace the dependence on scarce resources, and at the same time satisfy the constant demand for refined fuels, particularly in such difficult areas as aviation and transport. More so, vast emission reductions can be achieved through the application of next generation technologies such as electrification, use of carbon capture utilization and storage (CCUS) and use of hydrogen fuel switching, [4].

Participation in decarbonization will not only be in line with the climatic objectives throughout the world, it will also ensure competitive edge of refiners in the transforming energy trajectory. By adopting the new practices and technologies, the refineries are able to consider the new market trends and positively impact the environment. This development will require joint contributions of industry players, policymakers, and researchers to come up with supportive environments that will realize these valuable changes, [6] and [7]. Table 2 presents evaluation of technology.

Table 2: Technology evaluation.

Technology	**Temp Range (°C)**	**Application**	**Efficiency**	**CAPEX ($/MW)**	**Notes**
Electric Resistive Heaters	300–850	Distillation, cracking	>95%	$1M–1.8M	Requires grid, transformer upgrades
Inductive Heating	500–900	Visbreaking	High ramp	Pilot-scale	Good for rapid heating, early TRL
CSP (Solar Thermal)	300–650	Steam, heat loops	30–45%	$4M–7M	Land intensive, best in high-DNI areas
PEM Electrolyzers	N/A	Green H_2 generation	55–65%	$1,000–1,500/kW	Commercial scale, storage needed
Membrane Separation	<150	Fractionation	50% energy saving	R&D	Disruptive for low-temp separation
Battery Energy Storage	N/A	Grid smoothing	–	$400–600/kWh	2–4h duration typical, expensive for large scale
Thermal Energy Storage	500–650	Solar heat storage	80–90%	Medium-high	Molten salts proven in CSP

1.3. Purpose of the Document

The framework of this paper is to have a general evaluation of the pathways and problems with regards to the decarbonization of oil refineries. The purpose of this research will fulfill an urgent requirement of refining sector to convert to low-carbon operation due to the high demand of sustainable energy solutions in the world. Discussing the effects of traditional refining on the environment, the document attempts to highlight the pressing need of the change as well as quantifying the innovativeness of the methods, which can assist in the kind of change.

In this it will integrate the already existing research and case studies exhibiting the successful annotations of the decarbonization technologies and sustainable activities in the refineries. In addition, a discussion will also be conducted concerning specific technological advancements, such as alternative sources of renewable energy and more efficient, modernized process heating technologies that might be able to reduce reliance on fossil sources of energy significantly. In addition, it tries to discover economic viability and fund opportunities which are of high essence, in terms of attaining such transitions.

It is hoped that this can be a good aid to policymakers, industry-related parties and researchers by critically assessing the regulatory frameworks and the concerted effort of the industry that will guide toward the overcoming of those objectives. Finally, it is expected to make a considerable impact on the debate regarding sustainable refining procedures by offering recommendations that can be implemented and proposing future lines of research.

2. The Environmental Impact of Oil Refineries

2.1. Emissions and Pollution

Oil refineries contribute a lot to air pollution and emission of green house gases therefore they are major players in the decarbonization process. These energy-intensive processes emit 0.2 to 0.3 tons of carbon dioxide (CO_2) per ton of crude oil processed, whereby shockingly, 73% of the emissions come from the heating system. Refineries also release harmful pollutants like volatile organic compounds (VOCs), particulate matter, benzene, nitrogen oxides (NOX), carbon (CO), and sulfur dioxide (SO_2) which bad for the health, especially among the marginalized communities. Neighbors of Refineries have increased incidence of breathing problems, cancers and heart problems, [8] and [9].

Further, oil refiners are in constant contradiction to air quality rules where some of them are penalized for going beyond emission limits and misreporting hazardous pollutants. However, these fines are usually small in comparison to their profits. The environmental implication goes beyond air quality since refining may cause pollution in water and degradation of the soil due to spillage or leakage. Faced with increasing global pressure on the industries to minimize their carbon footprint through shifting to cleaner options such as biofuel or hydrogen, the raillery emissions are an acute challenge within the energy sphere, [10] and [11].

2.2. Resource Consumption

In essential resources such as energy and clean water, being used, oil refineries signify the largest consumers of the same. The refining process consumes great amounts of energy that is more than 90 % being utilized directly for heating and generation of steam required for the chemical reactions that transform crude oil into marketable products. This insatiable need of energy has made petroleum refining the number one fuel consumer in U.S. (manufacturing sector that adds up substantially to the greenhouse gas emissions and other pollutants), [5].

Moreover, considerable amount of water is required in such facilities whose main purposes are cooling and production of steam. This dependence is often much above the local water sources which would be, and this may cause thermal pollution after discharge has taken place of the heated waste water to the natural water bodies thereby negatively affecting the aquatic ecosystem. Furthermore, when refined, various kinds of waste materials are generated through the process, such as solid and waste water that must undergo treatment before being eliminated, hence causing more environmental problems, [12].

However, numerous refineries have put measures to reuse waste generated by their activities such as refinery gas and petroleum coke that can be used as alternative fuels or raw materials. Although this competition strategy helps in mitigation of some of the environmental effects, it indicates a bigger concern concerning resource efficiency in the industry. It is vital to promote innovative technologies and methods that will enable the reduction of resource consumption with an ability to maintain high standards in the production process to move the oil refineries towards sustainable decarbonization perspective, [13] and [14].

The refining process utilizes lots of energy as depicted in Figure 1 and most of the energy in the process is sucked up in the high-temperature activities like distillation and cracking. Most green gas emissions are produced during these operations. It identifies the energy consumption breakdown of the common operations of refineries and indicates that much of the consumed energy is directed to high-temperature processes such as distillation, cracking and reforming.

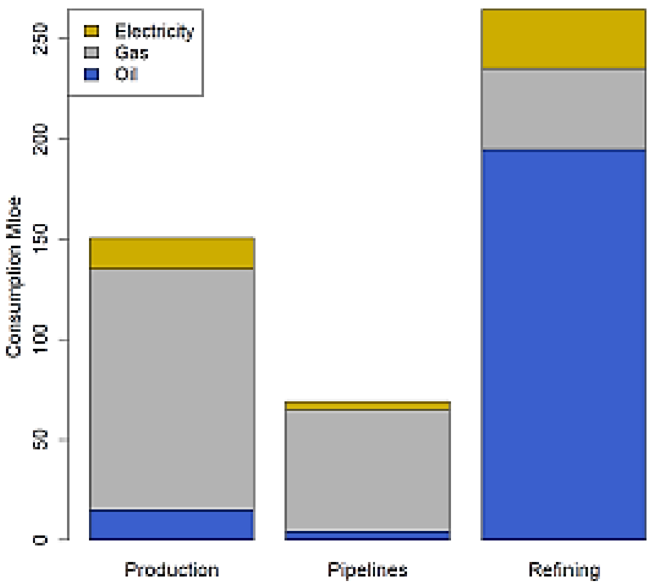

Figure 1: Energy consumption in oil and gas industry, [12].

2.3. Comparison with Renewable Alternatives

Oil refining industries are under pressure to decarbonize as it comes under the scanner with regard to the impact on the environment of fossil fuels especially the Greenhouse gas emission. On the other hand, cleaner alternatives from renewable energy sources (RES) such as wind, solar, and biomass present better alternatives that can reduce emissions largely from refining. Renewable technologies could also be used in refineries to reduce the volatility of markets of fossil fuel, thus improving energy security, [12].

The adoption of renewable may use various forms that may include adoption of solar thermal systems to produce heat, use of wind energy in order to reduce reliance on traditional electricity. innovations such as electrolysis for hydrogen production from renewables are a move towards low emission solutions, as this helps in operation efficiency at a time when stricter environmental rules are being applied, [13].

Currently, the concerns are still pending, such as the intermittency of some forms of renewable energy that require proper energy storage and hybrid systems in order to match supply with the demand. Renewables though may not be applicable to all situations due to geographical, and infrastructural issues, their increasing competitiveness of renewables against fossil fuels justifies their presence in the refining industry, [15].

Financing hybrid systems to integrate the traditional processing with novel breakthrough renewable technology can ease the way, while taking care of the economic and ecological needs. Mutual collaboration between the policymakers and the stakeholders in the industry is important for creating an environment that prepares to adopt these progressive measures, [16]. Table 3 shows sample techno-economic case for refinery size: 200,000 bbl/day and electrified FCC + H_2 replacement.

Table 3: Sample techno-economic case – FCC unit electrification + green H_2

Item	Value
Electrification CAPEX	$160M
Hydrogen Electrolyzer CAPEX (100 MW)	$120M
CO_2 Reduction	1.6 million tons/yr
CO_2 credit ($80/t)	$128M/yr savings
Payback (simple)	~2.2 years

3. Understanding High-Temperature Processes in Oil Refineries

3.1. Overview of High-Temperature Processes

High temperature operations are very important in the industry of crude oil refining, which consume a lot of energy and is very complicated. Such operations involve distillation, cracking, reforming and treating of hydrocarbons, all involving the heat up of substances at very high temperatures, from about 200 °C to 850°C. The heat of these temperatures aims at enhancing the vaporization and chemical conversion of base hydrocarbons into more useful products, [9].

The distillation unit is generally the initial stage of refining process where the crude oil is heated to about 390 °C to divide the crude oil into different fractions depending on the boiling points. This one operation represents a significant fraction, around 30-40% of the total energy spending of the refinery. After these, processes like fluid catalytic cracking (FCC) and hydrocracking work at such high temperatures, which continue to disintegrate on heavier fractions to produce lighter products such as gasoline and diesel, [12].

The energy that is required in such high temperature operations is chiefly derived through the direct burning of fuels in furnaces called 'fired heaters.' These units are vital in the production of the process heat, which is required for the chemical reactions going on in the refinery. Approximately 90% of the fuel burned onsite in a typical refinery is burned for heat and steam generation, which substantially implicates greenhouse gasses discharged from a refinery, [12].

Considering the fact that refineries are one of the top largest industrial energy consumes and they release high volumes of carbon dioxide mostly through thermal operations, it is expedient to start looking for alternative sources of energy. The integration of the renewable energy technologies that can supply heat or power may play a role in alleviating some of these impacts on the environment, while still being operationally efficient, [17].

3.2. Role of Energy in High-Temperature Processes

Mainstreams of traditional energy sources include natural gas and fossil fuels, combustion of which leads to heat productions for distillation columns and reactors. On the same note, many refineries also use by-products such as the waste gases as an alternative fuel in order to minimize waste while meeting the heating demand. This equates a balance between direct heating through furnaces and indirect heating to produce steam for efficiency, [3].

With the industry going towards decarbonization, the combination of renewable sources of energy such as solar or wind energy offers prospects for sustainable energy solutions. The usage of green electricity can help to make production cleaner the operational needs. Nevertheless, it is a difficult task to adapt existing refinery configurations to take up renewable sources of power because of irregular power supply, [12] and [13].

The role of energy in high-temperature operations is very critical towards designing strategies to improve performance and preserve the environment in refining sector, [18].

4. Green Electricity: A Sustainable Solution for Refining

4.1. Definition and Types of Green Electricity

Renewable energy is the electricity produced from energy sources that are not environmentally destructive, especially regarding emitting carbon-based emissions into the atmosphere. Resources like solar, wind, hydroelectric, and geothermal are some of the sources that fall under this category. Renewable electricity can be divided into a number of types depending on the technology and resources used. Solar power is collected through photovoltaic cells that convert the sunlight directly to electrical power, or through solar thermal systems that utilize sunlight to create heat that is used to generate electricity. Wind energy is harvester through wind turbine that produces electrical energy out of moving air, the kinetic energy. Hydroelectric energy uses flowing water to turn turbines hence generating electricity, [7].

Another important type of renewable electricity is bioenergy, which is produced from such organic materials as the remains of plants and animals. This energy can be used in both electricity generation and biofuel production using such processes as anaerobic digestion or fermentation. Geothermal energy utilizes the heat within the earth, as a way of generating steam that is used to power turbines in the process of generating electricity, [9].

All renewable forms of electricity provide different benefits regarding sustainability and mitigation of carbon footprints. The incorporation of these friendlier environments is not just creating a cleaner environment, but also helps improve energy security through diversifying the energy mix safeguarding the country from relying highly on fossil fuels, [13].

5. Technological Pathways for Integrating Green Electricity

5.1. Renewable Energy Sources Suitable for Refining

Some of the renewable energy alternatives that are most appropriate for the oil refining process (include solar, wind, geothermal and hydrogen technologies. Solar power comes in two major forms of harnesses: photovoltaic (PV) systems that directly convert sunlight to electricity and concentrated solar power (CSP) that uses mirrors to concentrate the sun light to produce high temperature stream for industrial processes). CSP is interesting in its ability to implement thermal energy storage to guarantee energy availability at the lack of sunlight. This feature is what makes it a very dependable option for the refineries that need a constant operation, [7].

Wind energy also represents a feasible alternative renewable energy. Refineries can use the excess electricity generated from the wind farms to produce hydrogen from water electrolysis. This approach does not only offer the solution for clean energy, but also helps the integration of more amounts of wind power into the electrical grid, [12].

Geothermal energy provides a constant and low emitting heat supply that is directly relevant to refining processes. Much geothermal resource can be exploited to cater for the heat requirements of operations in many areas, [17].

Apart from that, the development of biofuels is another desirable decarbonization strategy for the refining industry. The use of advanced biofuels development is using the already existing infrastructure and is low carbon emission. Taken together, these renewable technologies offer a large scale of opportunities for reducing carbon footprints and oil-refining practices' sustainability, [21] and [22] and Figure 2.

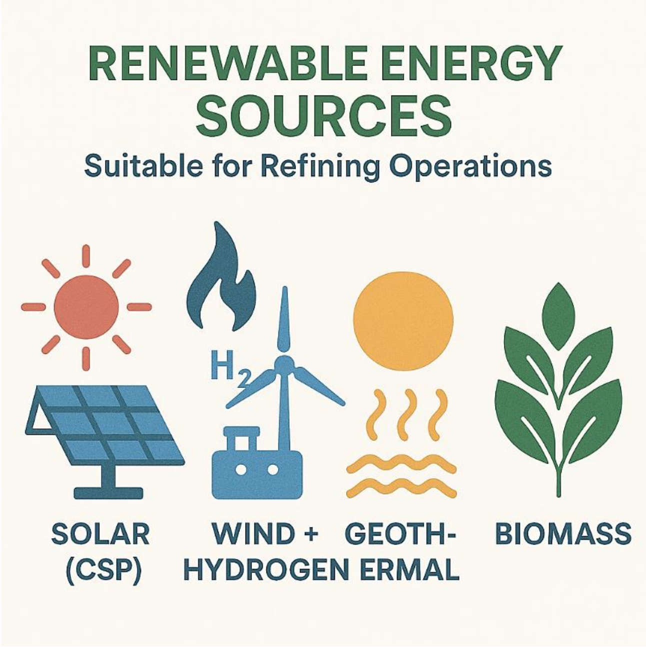

Figure 2: Renewable energy sources suitable for refining operations.

5.2. Innovations in Process Heating Technologies

Process heating technologies advancements are important for oil refineries to go low carbon. One of the major successes is electrification of heat generation whereby renewable sources of energy is used. Switching from old fossil fuel systems to the electric heating alternatives, refineries can dramatically cut down on the greenhouse gas emissions. This transitional shift is not only a reduction of direct emissions coming from combustion but further, the integration of low-carbon electricity into refining operations, [15].

Another promising solution is the hydrogen fuel switching. Refineries are very high consumers of hydrogen and if the low carbon hydrogen, which is produced from renewable sources or by means of electrolysis, is being used the amount of emissions from high-temperature processes can be reduced drastically. For this technology to be implemented there is a need to adjust the existing infrastructure to adapt to the use of hydrogen as a reliable source of energy for vital processes such as the hydrocracking and steam methane reforming, [21].

Moreover, state-of-the-art membrane technology provides a novel solution, which may substitute a number of energy-consuming distillation processes. Studies show that polymer membrane can help separate the crude oil mixtures at lower temperatures and with minimal energy consumption, hence minimal carbon emissions and energy consumption in the refineries, [32].

Development and application of these technologies are key measures in making this refining industry more sustainable. Constant investing in research, development and pilot programs will be needed to validate their effectiveness at a larger scale as well as to facilitate a smooth transition of the practices to the existing refinery practices, [24].

5.3. Hybrid Systems Integration Strategies

Integration of hybrid systems in oil refineries is a major breakthrough in reducing carbon emission by a great margin and improving energy efficiency. Such innovative systems integrate the old refining procedures with renewable sources of energy including solar power, wind power and low carbon hydrogen forming a smooth relationship between them, which makes the energy switching process easy. One of the significant methods is the electrification of high-temperature processes that have been based on fossil fuel initially. Drag-type electric furnaces have advanced such that they can generate the required amounts of heat required for processes such as steam cracking in conjunction with renewable electricity, [23].

Investment in these hybrid technologies will require cooperation among different sectors and the need to comply with the set standards to have a successful implementation. In addition, pilot projects, displaying such integrations will be crucial sources for insights and benchmarks for other players in the industry, [23].

Prestigiacomo et al. (2024) argue that concentrated solar thermal sporadically mixed with molten salt storage has made it possible to use continuous operations at high temperatures in Spanish chemical refineries. In the same way, Brolsford (2023) states that Indian Oil has started to introduce wind-electric hybrid power grids in their Gujarat refineries to mitigate Scope 1 emissions.

These projects emphasize the fact that hybridization cannot be a universal solution but it needs to be adjusted to local energy profiles and heat demand patterns. Iraqi fractions may give precedence to solar-CdTe-electric combination since DNI is high in comparison to the U.S. Gulf Coast refineries where gas is inexpensive.

6. Challenges in Transitioning to Green Electricity

6.1. Capital and Investment Challenges in Decarbonizing Refineries

The technical and financial obstacles to decarbonizing oil refineries. Refineries need to retrofit their current infrastructure to support electrification, the incorporation of RES and hydrogen production mechanisms and this may be complicated to retrofit and restructure the processes. Financially as well, the state of IT may demand an extensive capital investment and this can discourage the smaller refineries or the ones located in the developing parts of the globe against making such transitions. The fact that it requires invested capital in the form of money at the start and also that this does not promise any guaranteed returns further worsens matters, making it hard to find the required finances. To alleviate such barriers, governments and industry stakeholders should work together to offer incentives and financial frameworks to enhance an easy shift to low-carbon future.

Diverse complexities associated with financial and infrastructural issues are posed in the decarbonization of oil refineries. One of the main barriers is a high amount of capital required for the new technologies, which may discourage the stakeholders from the decarbonization drive. The level of sophistication that is involved in the refinery operations tends to demand huge financial commitments for an upgrade or replacement, incurring issues of justification of cost in the absence of assured returns, [1].

Further, the absence of the operational history of emerging technologies affects the confidence of the investors and the uptake of the technologies is made sluggish. Decision makers may be reluctant to invest into innovations such as CC and RE integrations without appropriate KPIs. Issues of misperceptions about the viability of variable renewable energy to operate on continuous refinery processes impede advancements, as the involved actors are not convinced of its reliability for high capacity outputs, [6].

Resource limitation makes the situation even worse, especially a lack of professionals capable of introducing new technologies efficiently. This gap of expertise can suffocate innovation and encourage operators to stick to the traditional practices, [10].

Initial capital needs to electrify the heat and hydrogen retrofit and retrofit usually cost greater than 2B to serve a mid-sized refinery. This is further complicated by the retrofitting cost of the processes (e.g. SMR to electrolyzer), which is an additional levels of financial risk of uncertainty, especially in those nations that do not have the incentive of a price on carbon.

6.2. Regulatory and Policy Hurdles Faced by the Industry

Some of the regulatory and policy challenges the oil refining business is facing are challenging its decarbonization efforts. The slow pace of regulatory framework development that struggles to adapt to new technologies and procedures that are highly desired to reduce greenhouse gas emissions is one of the most significant issues. Most times, the already existing rules continue to favor the antique fossil fuel which drives the driving power and thus inhibits innovation. Another problem with the emerging green technologies is that policymakers have not been consistent in backing them and this has led to an investment dilemma and the delaying of development of new infrastructure required [1].

Secondly, refinery upgrade is also a labor-consuming project hence it provides a lot of challenges economically. The equipment that is installed in the refineries have long lifecycles and therefore they do not help in justifying the retirement or retrofitting of old units unless caused by major changes in the regulations or competition in supplies. This is to be exacerbated by the rigorous permitting process which may tend to slow the implementation of new technologies, [2].

Moreover, the lack of comprehensive policies that promote low-carbon changes restricts the range of financial backing that might be accomplished through the participation and contributions of society and businesses. Existing funding mechanisms do not always reflect real requirements of refineries planning to adopt advanced biofuels, green hydrogen, or the carbon capture and storage technologies, [13].

Lastly, there are discrepancies in environmental controls from region to region that makes it even harder for refinery operators. Deviations in standards may pose difficulties in situations regarding upholding consistency in the operation between and across regions; this goes on to affect the businesses' ability to compete and make investments in the industry, [13].

6.3. Integration of Green Electricity in High-Temperature Refinery Processes

To match this load with electricity means strong interconnection of the grid or systems dedicated to renewables and the challenges of capacity factors on wind/solar and the need to back that up or store it, [1] and [4].

The technological solutions provided to the electrification topic are electric resistive heaters, inductive and microwave heating and renewable integration pathways. Electric resistive heaters have a maximum temperature of 800C, and are efficient to operate, although retrofitting fired heaters with them at 95% efficiency implies a 105 MW electric supply needed. Localized high-intensity heating, it is applied in inductive and microwave heating and potentially in hydrocracking and visbreaking. Solar thermal (CSP) can offer process heat of up to 600 ^{o}C and save 6500 tons CO_2/year of emissions. Wind + electrolytic hydrogen harnesses the power of the wind and on-site electrolytic hydrogen production through PEM electrolyzers minimizes scope 1 emissions, [9-10].

Combining electric and thermal energy sources, thermal energy storage systems, and battery systems for the grid with continuous operation is called hybrid system engineering. Energy management is high-advanced process control to match renewable generation with steady heat loads, including load shifting and real time optimization, [12] and [16].

This research shows that, refinery emissions across the entire site could be decreased by 65-85 percent by full electrification and using 100 percent green power, leading to annual avoided CO_2 emissions of 1.6-2.3 million tons when a 200,000 bbl/d refinery was considered, [17] and [21].

Electrification of refineries Engineering constraints involve electrical supply and transformer upgrade to increase capacity, materials retrofit and integration of control process. Hybrid renewable-electric systems can be optimised by using digital twins and sophisticated sensors. Case studies demonstrate that solar PV with electrolytic H_2 production can decrease the emissions by 60,000 tons CO_2/yr when the sources of electricity are the same, [23-24].

Electrification at high temperatures is a frontier area (see the high-efficiency electric arc and high-efficiency plasma technologies). The electrification combined with carbon capture to make the system net-zero is also under consideration, [24-25].

The following table 4 gives an overview of the key technological solutions available of hooking up green electricity to high-temperature refinery operations, including key technical and financial information.

Table 4: Technical Pathways for Decarbonizing High-Temperature Refinery Processes.

Technology/Option	**Temp Range / Capacity**	**Application in Refinery**	**Efficiency / CO_2 Savings**	**CAPEX / Notes**	**Source(s)**
Electric Resistive Heaters	300–850°C / up to 100 MW	Fired heaters, distillation, cracking	>95% efficiency	$1–1.8M/MW; grid upgrade, controls needed	[Byrum et al., 2021]; [CATF, 2024]
Inductive / Microwave Heating	500–900°C / pilot scale	Visbreaking, thermal cracking	High ramp rate; early TRL	Emerging tech, limited commercial deployment	[IEA, 2023]; [Vogt & Weckhuysen, 2024]
Solar Thermal (CSP)	300–650°C / 5–100 MWth	Direct process heat	Reduces 6,500 tCO_2/yr (for 20 MW plant)	Requires land + high DNI; TES optional	[Prestigiacomo et al., 2024]; [SolarPACES, 2024]
Wind-Powered Electrolysis (H_2)	MW–100 MW electrolyzers	Green H_2 for hydrotreating	55–65% conversion efficiency	Commercial 20 MW electrolyzers available	[WRI, 2021]; [OGCI, 2023]
Membrane Separation	<150°C / low-energy	Product separation, pre-distillation	Up to 50% energy savings	Early stage; low TRL	[Georgia Tech, 2020]; [DOE, 2022]
Battery Energy Storage (BESS)	10–100 MWh	Backup, grid stability	Short duration (≤4 hrs)	$400–600/kWh	[IRENA, 2022]
Thermal Energy Storage (TES)	500–650°C / molten salt	CSP-based heat storage	10–20 hrs discharge	Proven at industrial CSP sites	[SolarPACES, 2024]; [Prestigiacomo et al., 2024]
Hybrid Electric + Thermal Systems	Custom	Electrification + renewables + backup	Up to 85% CO_2 reduction (system-wide)	Requires AI/digital twin optimization	[CATF, 2024]; [Matthey, 2022]

7. Economic Viability and Long-Term Benefits

7.1. Cost-Benefit Analysis of Transitioning to Green Electricity

The tendency towards sustainable electricity in oil refineries is a significant change that is weighted with not only financial implications but also a number of advantages that require careful consideration. According to estimates, the replacement of traditional systems of energy with low-carbon one may cost from several billions to up to twenty billions of dollars per refinery (depending on the type of technology applied and the scale of its implementation). However, the initial costs can be recovered in the long term through huge savings on operations. Switching to renewable energy can help save on the costs of fuel and maintenance and decrease the dependence of oil markets that are prone to instability, [13].

Additionally, shift to sustainable electricity can contribute to reducing greenhouse gas emissions considerably, following the international climate goals and the requirements of regulation. However, innovations such as electric boilers and drives can reduce emissions more than by 65% by 2040, if they are powered by low-carbon sources. Additionally, the efficiencies that are achieved through electrification can deliver a positive ROI as time progresses because of lesser energy consumption and improved process performance, [18].

Policy incentives are also important in making the economy viable. Some of the financing mechanisms such as tax credits or subsidies to integrate renewable energy can help to decrease some of the starting financial issues while encouraging further industry adoption of the cleaner technologies, [22].

In conclusion, even though the transition to sustainable electricity requires a massive upfront investment, cost-benefit analysis indicates that there are a few chances of the ROI in 4-7 years based on carbon pricing and subsidy regimes. Long term reduction of OPEX is also achieved through energy saving of electrification and fuel switching, [25] and [27]. Green electricity will significantly reduce CO_2 emissions by up to 70 percent and minimize dependence on FFO unstable fossil markets by electrifying high-temperature units. Refineries will be able to enhance the energy security, brand image, claim tax credits, and other financing that depends on the ESG as the costs of renewables decrease.

7.2. Long-Term Profitability Projections

The shift towards decarbonization in oil refining industry indicates huge profit potential in the long term despite the high upfront cost required. As refineries embark on balancing green electricity with low carbon technology, they are presented with the opportunity to rely on new income streams from products that are gradually being embraced by the consumer base and the regulators. Company leaders are willing to spend on the low-carbon projects that imply the returns from 12% to 15%, which is significantly higher than the current yields of the renewable electricity projects, about 6% to 8%, [13].

Investors are waking up to the fact that physical threats of climate change, including extreme weather events and rising sea levels, need to be taken into consideration when planning finances. By planning effectively in regard to infrastructure, businesses are able to minimize the expenses of the climate-related problems in the long run. The fact that the refineries are able to cope with the intricate economic landscape in the way that they utilize the opportunities that decarbonization offers will generate their competitive edge in a constantly shifting business landscape, [21].

7.3. Funding Opportunities and Financial Incentives

The cost of transporting oil refineries towards greener operations, due to high, amounts of financial expenditure, is demanding of a lot of finance; nevertheless, there exist many means and the financial incentive to undertake it. Governments and institutions are slowly finding the way to round up to make such a shift by providing various kinds of grants, loans and tax credits which are planned to work towards cutting down carbon emission in high-yield industries like refining. Indicatively, a minor amount of funds of the European Union has been put down to ensure that there is an enhancement of investments in low carbon fuel and technology hence the accumulation of a commitment to superimposing on EU climate objectives, [7].

It is as well the importance of private financing in this change. Banking bodies have developed transition financing models that are custom-made to help them offer customized debt and equity solutions that can help in the decarbonization process. All these measures normally require the clients to provide elaborate transition plans which outline their plans to reduce emission without incorporating the economic feasibility. The investment companies are focusing on the inefficient-to-abate industries and are investing in initiatives that aim at increasing the energy efficiency or are developing RES, [15].

In addition, the companies exist focused on investing in climate solutions and technologies to combat decarbonization, including Energy Impact Partners. This is because their investment has numerous carbon free types of energy which reflects the progress of sustainable finance which is not merely helpful to the environment as well as to the economy, [15].

In conclusion, the fusion of both government subsidies initiatives and that of the private sector offers a whole plan of gathering the capital requisite, which the refineries need in an attempt to successfully change over to the greener operations, [27].

8. Case Studies and Real-World Applications

8.1. Successful Implementations Worldwide

Other oil refineries were in other regions are making vigorous efforts in an attempt to realize decarbonization and stand on green technologies. An example would be Repsol with its ambitious projects in Cartagena and Bilbao, Spain, which will be labored towards the production of liquid fuels towards low carbon. All of this is in line with the plans of Europe to achieve substantial emission reductions and is a reflection of how the current infrastructure can be re-engineered to support innovative processes in the future, particularly the production of e-fuels that can be based on renewable hydrogen and captured carbon, [7].

Fredericia refinery is not an exception in Norway since it is pursuing a similar course of events by partnering with Ever fuel to develop green hydrogen solutions that will easily integrate into its refining process. These alliances depict the immense potential of the conventional oil companies to engage the R&D innovators in the renewable energy sector thereby clearing space within the existing projects to evolve them, [7].

Moreover, the refinery in Seine-et-Marne, France run by Total Energies initiated the projections towards fuel feedstock generation in biowastes as being sustainable. What is even better about this strategy is that it reduces wastage and enhances the concept of the circular economy that makes refining practices many times better, to make them more sustainable, [27].

As such, there are about thirty projects which are either underway or will be achieved by 2030 across Europe which will take care of the problem of sponsoring low-carbon liquid fuel production. Collectively, these projects have a chance to produce as much as 9.3 million tons of low carbon fuels annually which is a pointer of how this industry is willing to embrace the change with the escalated requirements of legislation, [27].

These are examples to show that by using the already available resources and encouraging innovation using alliances and cutting-edge technologies, oil refining business can achieve remarkable feats under decarbonization without losing operation viability, [27].

8.2. Lessons Learned from Case Studies

Analysis of decarbonization oil refinery offers information on prospective activities. One key lesson is the requirements of transparent and credible transition plan. Firms that involve the stakeholders in addressing the net-zero plans through free communication create trust and collaboration. The use of such frameworks as provided by the Transition Plan Taskforce strengthens the capabilities of organizations to evaluate the progress and change strategies, [27].

Successful decarbonization highly depends on efficient funding mechanisms. Collaborative projects for example Sweden's H_2 Green Steel call for both equity and debt but emphasize on the need to have an oversight to provide as well as cover for the stakeholders in meeting challenges for infrastructure problems as related to sustainable technology, [27].

In addition, it is essential to add innovative technologies into the existing work. Companies such as Skyven prove the fact that different financial models can embrace high adoption rates for decarbonization solutions for problems experienced since the industrial process heat days, [27] and Figure 3.

The case of Repsol, H_2 Green Steel and TotalEnergies suggests pilot-testing to full conversion. The modular electrolysis systems created by Repsol enabled the adoption of green hydrogen in phases, and Skyven Innovations showed how thermal electrification would be de-risked by the process of financial structuring.

Conversely, the absence of consultation with communities during Colombian CCS projects contributed to time delays in the case of technical success (Yángess et al., 2022). In the case of Iraq, the decarbonization programme should be deployed using such lessons in future due to the lack of social trust about the refinery operations.

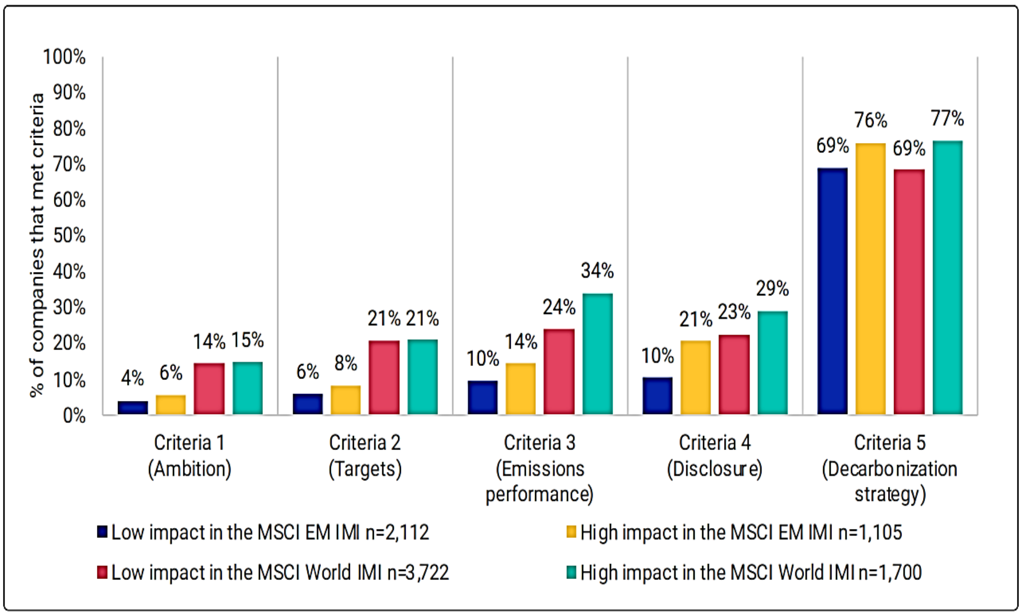

Figure 3: Performance across maturity-scale criteria by impact categories and markets, [27].

8.3. Iraqi-specific data for refining operations, greenhouse gas emissions, growth rates, and decarbonization budgets

The refineries in Iraq largely depend on natural gas and fossil fuels in their refining process thus leading to a huge amount in the emission of CO_2. The poor structural energy rehabilitation system in the region is an addition to massive amounts of gas burned off in the process of refining. The forms of heaters, fired heaters, and steam methane reformers utilized in refining activities of Iraq contribute to excessive production of carbon because of hydrocracking and catalytic cracking.

The possible decarbonization options in Iraq are solar energy with abundant resources that is in pilot to supply process heat and electrical needs of the refineries. In addition, in places such as Kurdistan, Iraq possesses the potential of getting wind energy, which can be tapped in the making of hydrogen through the electrolysis process.

Iraq has pledged under the Paris treaty to cut emissions, yet there are no significant incentives in its plans to use carbon capture, hydrogen or electrifying refineries. Iraqi refineries may be considered to be funded internationally through decarbonization projects as the world strives to invest in renewable energy in developing economies.

Iraq-Specific CSP Feasibility:

Solar Resource:

Basrah DNI = ~2,000 kWh/m²/year — ideal for CSP

1 m² of mirror area can generate ~0.25–0.3 MWh/year process heat.

Potential:

- 100 MWth CSP plant can supply ~20–25% of total refinery heat demand
- Avoids ~6,500 tons CO_2/year
- Pair with TES (molten salt) for 24/7 operations

Iraq-Specific Data and Decarbonization Estimates:

The Iraq oil refining industry is a critical part of the Iraq economy and the industry processes an average of more than 1.1 million barrels per day (bmd) in the largest oil refineries in Iraq including Baiji, Basrah, Daura and Kirkuk. RAI IEA statistics reflect that refining capacity will increase to 1.6 million bpd by 2030, as per the domestic fuel demand and its export policy.

Emissions Profile:

CO_2 Emissions per bbl: ~0.28 tons CO_2/bbl refined

Annual Emissions (2023): ~310 million tons CO_2 from oil sector, of which ~9.5–10 million tons are directly from refinery operations.

Emission intensity is higher than OECD refineries due to outdated fired heaters, poor efficiency, and heavy reliance on gas flaring and fuel oil. Table 5 shows growth projections.

Table 5: Growth projections.

Year	Refining Capacity (bpd)	Refinery GHG Emissions ($MtCO_2e$)
2023	1.1M	9.5–10
2025	1.3M (projected)	11–12
2030	1.6M (target)	13–14

Decarbonization Budget and Financial Needs:

The refining industry in Iraq requires massive upgrades to comply with the Paris Agreement INDC pledge (Educate 14 reduction of CO_2 emission by 2035). According to the case studies in India, UAE and internal analysis, based on the studies:

Full Decarbonization CAPEX Estimate:

Electrification of heaters (FCC, distillation): $1.2B – $1.5B

Green hydrogen electrolysis (100 MW systems): $150M

CSP integration (Basrah & Nasiriyah): $350M

Digital controls, energy storage, hybrid systems: $300M

Total Needed: ~$2B – $2.3B over 10 years

Annual CO_2 reduction potential: ~7.2–8.1 $MtCO_2$

Cost per ton abated: ~$40–65 (moderate vs. global average of $80+)

Resource and Geography Suitability:

Solar Irradiation (DNI): 2,000–2,300 kWh/m²/year in Basrah/Nasiriyah — ideal for CSP

Wind Speeds: ~6.5–7 m/s in Kurdistan — viable for H_2 electrolyzer integration

Energy Losses: Up to 30–40% of thermal energy lost due to poor insulation and lack of recovery systems. Table 6 shows Summary.

Table 6: Summary.

Metric	Value
Refining Capacity (2023)	1.1 million bpd
CO_2 Emissions (Refineries)	~10 $MtCO_2$/year
Emissions/Bbl	0.28 tons CO_2/bbl
CSP Potential (Basrah)	High (2000+ DNI)
Wind-to-H_2 (Kurdistan)	Feasible (6.5+ m/s avg)
Budget for Decarbonization	~$2–2.3B (2025–2035)
Cost per Ton CO_2 Abated	$40–65

Figure 4 shows energy flow diagram showing traditional vs. green electricity-integrated refinery energy architecture.

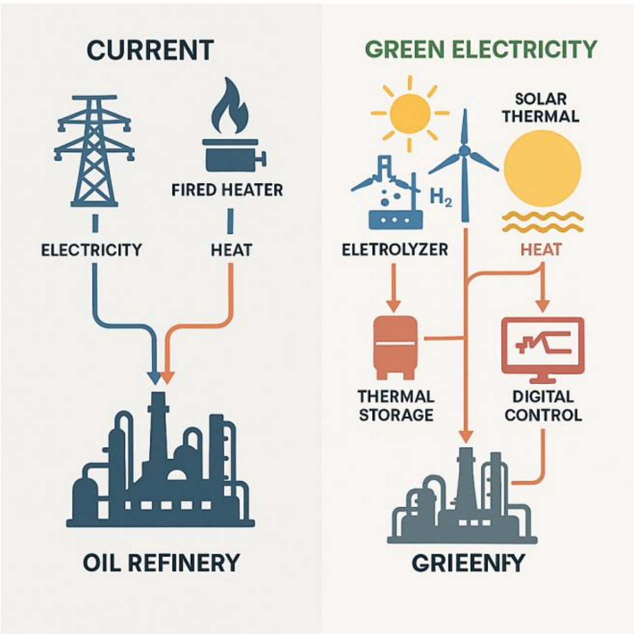

Figure 4: Energy flow diagram showing traditional vs. green electricity-integrated refinery energy architecture.

9. Policy Framework and Industry Collaboration

9.1. Necessary Policy Changes to Support Transition

De-carbonizing oil refineries will entail an overall overhaul of policy, in order to support and expedite this process. The policymakers should ensure stable regulatory environment that does not depend on change of political personnel and, thus, seeding in long term investments to clean technologies. This framework should have incentives such as tax credits that will be given to refineries that try out low-carbon innovations such as carbon capture and electrification, [2].

Further research and innovation on the use of renewable energy in refineries requires more public funding. Moneys from programs such as the one based in European countries (European Globalization Adjustment Fund) can help in the transitions of workforce and technology development. Investment in infrastructures for green hydrogen production and renewable energy is very important to achieve a smooth transition, [7].

The regulatory provisions must also be tacit with regard to stringent level of emission; that they should avoid faulting refineries who cause the environmental effects as they embrace cleaner activities, [26].

In addition, policies need to involve communities to reduce the social impacts of decarbonization. Improved transparency in emission reductions will earn public trust, whereas improved local air quality monitoring systems will protect the communities from risks arising from environmental refining activities, [28] and [29].

9.2. Importance of Industry Partnerships

Joint approaches in the oil refinery industry are important for decarbonization that facilitate innovation and sharing of resources between the players within the industry including refineries, technology developers, government agencies, and academic institutions. Cooperation is important as low-carbon technologies continue to develop in order to cope with the challenges of promoting solutions such as green hydrogen and carbon capture, [2].

By collaborating, the players in the respective industry are in a position to share best practice and insight, thus creating an enabling environment for innovative solutions, but with minimized redundancy. Partnerships are also utilized to increase access to funding through joint endeavors and sustain advocacy for regulatory support to the decarbonization drive. A consolidated industry voice can shape policy-making and encourage environment friendly investment based on the climate agenda, [2].

In addition to the experience of Sweden, in the OGCI roadmap (2023), joint R&D clusters are highlighted in order to make technology scaling less risky. Matthey (2022) states that synergistic decarbonization in the Humber region in the UK helped hydrogen co-firing in FCCs because they used the same infrastructure.

The pattern can be replicated elsewhere such as Basrah by solar developers and regional universities developing such partnerships. These collaborations are already provided by the IEA Middle East Cooperation Program in terms of capacity building.

10. Future Outlook: The Path toward a Decarbonized Refining Sector

10.1. Trends Influencing Future Developments

A number of large trends that shape the decarbonization of the industry colonizes the oil-refining industry. Introductions in greater use of renewable energy are being driven by cost improvement and procedural innovation, and the usage of solar and wind energy lowers the cost of fueling electricity, therefore, enabling the refiners to use the green electricity in their operations. There is also an uprising pressure to electrify the process of refining with most oil companies having a net-zero emission target by 2050. Mixed systems that employ the common refining techniques along with innovative applications such as carbon capture utilization and carbon storage (CCUS) stand to ease the emissions without impairing the performance. The environment of investment is shifting and making transitions investable needs well put up business cases. Market demands are also shifting due to various geopolitics, with the refiners trying to switch to practices that have a low impact on the environment such as biofuel and hydrogen production based on local conditions and energy policy of the world, [6], [9], [15] and [28].

10.2. A Vision for Sustainable Refining Practices

An innovative approach towards a visionary strategy on hunting sustainable refining operations incorporates an easy transition to the adoption of new technologies and new practices in line with the international goals at decarbonization. The net-zero oil and gas companies by 2050 is a commitment of the industry and the core of this initiative. This is a very ambitious target and, therefore incorporates a multifaceted strategy and will entail the enhancement of energy efficiency, adoption of electrification, and adopting hydrogen fuels, [7].

Moreover, carbon capture, utilization, and storage (CCUS) technologies are to be included in the strategic process of all refineries. The level of more than 90% of capture of CO2 emissions by these innovations in point sources in refinery makes such innovations more sustainable in operation and economic viability, [15].

It is significant that stakeholders in the industry, including technology developers, policy makers and regulatory bodies to help them overcome the existing challenges during the time. With a positive policy environment, investments in low carbon technologies can be stimulated simultaneously with ensuring that the concerns that are being voiced by the locals in the midst of the transition process are put into consideration, [18].

Lastly, this vision is one that should be reappear to consider the skill of the workforce with regard to the regular education on new technologies and improved processes. They will provide sustainable impacts on both environmental health and economic sustainability in the transformation of the refineries into sustainable developments to low-carbon future, [21] and [30] and Figures 5 and 6.

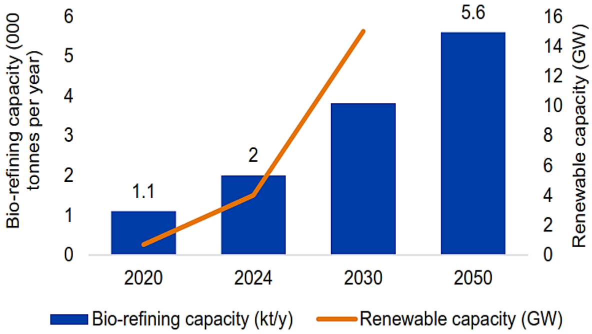

Figure 5: Projects of bio refining capacity, renewable capacity, [7].

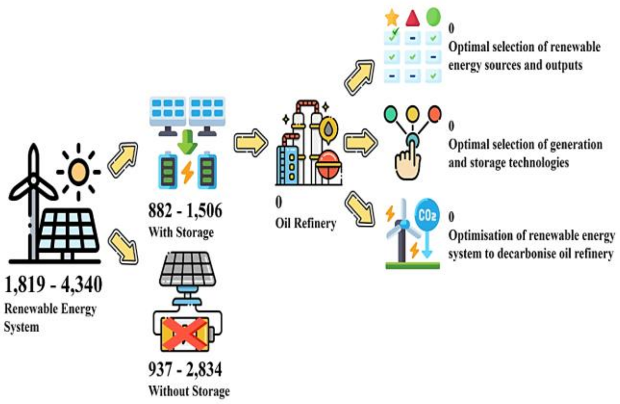

Figure 6: The analysis of keywords (On the basis of search in Scopus and Web of Science 20192024 June), [21].

11. Conclusion

Dcanarbonization of oil refineries is not only a green requirement but also an opportunity to the industry not only to survive but also to thrive in the new global energy world. The demand of fossil fuels continues, thus, with the transportation and chemical petrochemicals industries, the pressures mount on the refineries to produce less carbon emission. This necessitates a strategic communication to the use of renewable types of energy sources like hydrogen and technology of electrification in operations.

Coming solutions refer to the fact that current refineries can expand with the help of the new technology which will decrease the emissions instead of productions. Reducing the greenhouse gas emissions can be achieved through the adoption of carbon capture and storage (CCS) and renewable feedstocks, whose adoption can make the difference by significant percentages. Joint business working with the creation of biofuels and utility companies can mutually benefit and initiate the culture of innovation in the practices.

However, this change comes with some challenges, including economic constraints, which have old regulation systems and require revision, and technical barriers that must be removed to enable achievable solvability. Policy environment shall be well considered in facilitating the use of low carbon technologies and also in provision of employment opportunities to the employees who shall be displaced in the traditional refining jobs.

In essence, by adopting these changes, the refineries can re-invent their purpose, they are no longer slaves to the past of unquestioned unsustainability but vital participants in the new sustainable world, and they are also able to achieve climate targets without jeopardizing energy security and cost-effectiveness.

It describes how a refinery can become a cleaner process by incorporating renewable energy (namely, solar, wind, and hydrogen) into the business models and substantially decreasing the number of carbon emissions and increasing the energy efficiency. Part of the transition deals with energy storage capabilities to stabilize the intermittent renewable power and better optimize refinery operations, notably in high-temperature, high-cost cyclic processes such as distillation and cracking. Figure 7 shows hybrid system integration for decarbonizing refining operations.

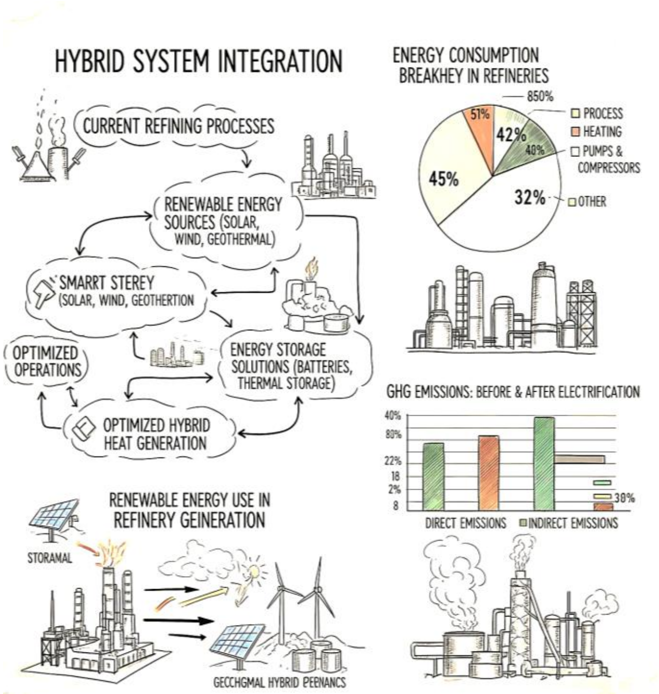

Figure 7: Hybrid System Integration for Decarbonizing Refining Operations.

12. Recommendations

In order to successfully spur the decarbonization of the oil refining business, an adequate strategy has to be adopted. At the outset, refineries should aim at pouring money into excellent technologies, such as carbon capture, utilization, and storage (CCUS), which can significantly reduce emissions from critical operations. The liaison with the academia and research institutions will be essential in enhancing the financial feasibility of the technologies and integrating them into the existing system of operations, [4].

The second one in the queue is shifting to low-carbon sources of energy. Alternative source of fuel should also be invested at the refineries in the way of electrifying the heat production and clean hydrogen generation. The emission of greenhouse gases is not the only way in which this change can take place but it is part of the wider trends in the industry that lead to sustainability, [12].

Also one can enter into partnership with the suppliers of renewable energy to incorporate green electricity in the process of refineries. Such a strategic initiative is one of those that assist in reducing the cost of operation and enhancing the strength of the energy supply chains.

It should be facilitated going through such transitions using such financial instruments as carbon credits and tax incentives. Of utmost importance is the fact that the policymakers ought to devise regulatory mechanisms which promote the adoptability of green technology and to give incentives to the early adopters, [15].

Besides, in-depth life cycle assessments are essential towards gaining an in-depth insight of the implication of the environment in relation to the various pathways. Such kind of insights can be used in decision making processes and to be more open in the entire sector, [23].

Finally, workforce development measures should also be put into consideration when the skills required are to be embedded into the employees so that they can handle new technologies in an efficient manner. The refineries are able to gradually bring them to sustainable practices without interfering with job security through investment with Human Capital coupled with technological development, [30] and [31].

References

[1] S. Griffiths, Benjamin K. Sovacool, J. Kim, M. Bazilian and Joao M. Uratani. "Decarbonizing the oil refining industry: A systematic review of sociotechnical systems, technological innovations, and policy options". Jan 2022. https://www.sciencedirect.com/science/article/pii/S2214629622000494

[2] A. Nurdiawati and F. Urban. "Decarbonising the refinery sector: A socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden". Jan 2022. https://www.sciencedirect.com/science/article/pii/S2214629621004497

[3] Eliezer A. Reyes Molina, Kathleen P. Sweeney, Sam J. Root, N. Guaita, W. Cheng, Frederick C. Joseck, L. Todd Knighton and Richard D. Boardman. "INL RPT-24-78634 Technical and Economic Assessment and Gap Analysis of Advanced Nuclear Reactor Integration with a Reference Oil Refinery". Jan 2024. https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_118552.pdf

[4] Z. Byrum, J. Wilcox and H. Pilorgé. "Technological Pathways for Decarbonizing Petroleum Refining ". (accessed May 10, 2025). https://www.wri.org/research/technological-pathways-decarbonizing-petroleum-refining

[5] H. S. R. C. &. S. O. Program. "Environmental Impact of the Petroleum Industry". Jan 2003. https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.files/fileID/14522

[6] "Green refineries: Decarbonize, convert, or close?". (accessed May 10, 2025). https://www.dnv.com/article/green-refineries-decarbonize-convert-or-close/

[7] A. López, A. Ure, A. Wolf, M. Galante, T. Scarbrough, S. F. (Ricardo), C. Jans and N. R. (Argus). "WHAT FUTURE ROLE FOR CONVENTIONAL REFINERIES IN THE DECARBONISATION TRANSITION?". Jul 2022. https://www.transportenvironment.org/uploads/files/ED15882-Ricardo-refineries-study-for-TE-Final-report-15Jul2022-2_2024-04-29-153217_kopu.pdf

[8] G. Blogger. "How process electrification can decarbonize oil refineries and petrochemicals". Jan 2024. https://blog.se.com/energy-management-energy-efficiency/2024/10/01/process-electrification-helps-cut-co2-in-refining/

[9] A. Deaconu. "Decarbonizing The Crude Oil Refining Industry". Feb 2025. https://epcmholdings.com/decarbonizing-the-crude-oil-refining-industry/

[10] F. Baars and S. Parvez. "Refinery decarbonisation. What, when, how, and at what cost?". Jan 2022. https://decarbonisationtechnology.com/article/136/refinery-decarbonisation-what-when-how-and-at-what-cost

[11] M. C. P. d. Moura. "Oil Refineries: A Deadly Industry". Sep 2024. https://blog.ucs.org/cecilia-moura/oil-refineries-a-deadly-industry/

[12] S. Ericson, J. Engel-Cox and D. Arent. "Approaches for Integrating Renewable Energy Technologies in Oil and Gas Operations". Jan 2019. https://www.nrel.gov/docs/fy19osti/72842.pdf

[13] C. D. S. D. o. Energy. "Industrial Decarbonization Roadmap". Jan 2022. https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf

[14] J. B. Mariano and E. L. L. Rovere. "Environmental Impacts Of The Oil Industry". Jan 2017. https://www.eolss.net/sample-chapters/c08/e6-185-18.pdf

[15] E. M. Staff. "Refining Transformed: Innovations for a Sustainable Future". Nov 2024. https://energiesmedia.com/the-future-of-the-refining-industry-innovations-and-sustainability/

[16] S. Kraemer. "Published at Energy - Concentrated solar heat for the decarbonization of industrial chemical processes: a case study on crude oil distillation - SolarPACES". Apr 2024. https://www.solarpaces.org/published-at-energy-concentrated-solar-heat-for-the-decarbonization-of-industrial-chemical-processes-a-case-study-on-crude-oil-distillation/

[17] C. Prestigiacomo, A. Giaconia, F. Proietto, G. Caputo, I. Balog, E. Ollà, C. F. Terranova, O. Scialdone and A. Galia. "Concentrated solar heat for the decarbonization of industrial chemical processes: a case study on crude oil distillation". Apr 2024. https://www.sciencedirect.com/science/article/pii/S0360544224004900

[18] E. Vogt and B. Weckhuysen. "Reinvent oil refineries for a net-zero future". May 2024. https://www.nature.com/articles/d41586-024-01323-x

[19] M. Goret-Rana and C. Keeley. "Transition to net zero: steps to decarbonize the oil refining industry". Jun 2022. https://matthey.com/documents/161599/440784/Transition+to+net+zero%2C+steps+to+decarbonize+the+oil+refining+industry.pdf/0778f7d0-b01b-0db3-7e0a-be4b53ff2cf5?t=1654704110197

[20] R. Brelsford. "Indian Oil approves plan to power refineries with renewable energy". Oct 2023. https://www.ogj.com/refining-processing/refining/optimization/article/14300253/indian-oil-approves-plan-to-power-refineries-with-renewable-energy

[21] C. Y. F. Lau, Y. E. Chew, B. S. How and V. Andiappan. "Planning and Optimisation of Renewable Energy Systems for Decarbonising Operations of Oil Refineries". Mar 2025. https://link.springer.com/article/10.1007/s41660-024-00461-z

[22] M. Barry. "OGCI sets out roadmap to decarbonize refining | OGCI". Oct 2023. https://www.ogci.com/news/ogci-sets-out-roadmap-to-decarbonize-refining

[23] Z. Byrum, H. Pilorgé and J. Wilcox. "Technological Pathways for Decarbonizing Petroleum Refining". Jan 2021. http://www.yrdcpcn.com/upload/2024/0401/18baa61d-6b34-4882-a2b7-eb50775ec6d1.pdf

[24] K. Thompson, R. Mathias and M.G. Finn. "Membrane Technology Could Cut Emissions and Energy Use in Oil Refining". Jul 2020. https://news.gatech.edu/news/2020/07/16/membrane-technology-could-cut-emissions-and-energy-use-oil-refining

[25] G. Wakim and T. Lockwood. "Technical and Cost Considerations for Decarbonizing the "Refinery of the Future"". Jul 2024. https://www.catf.us/resource/refinery-of-the-future/

[26] Z. Byrum and C. Dellesky. "A Low-Carbon Future in the US Depends on Decarbonizing Petroleum Refineries". Oct 2021. https://www.wri.org/insights/technologies-decarbonize-petroleum-refineries

[27] "Case Studies on Transition Finance and Decarbonization Contribution Methodologies". Jan 2022. https://assets.bbhub.io/company/sites/63/2024/09/Case-Studies-on-Transition-Finance-and-Decarbonization-Contribution-Methodologies-Sep-2024.pdf

[28] "World Energy Transitions Outlook 2023". (accessed May 10, 2025). https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2023

[29] "A Vision for Poland's Clean Energy Transition". Apr 2024. https://www.catf.us/resource/a-vision-for-polands-clean-energy-transition/

[30] "Making an Impact with Oil Refineries and CCUS Technology". May 2025. https://www.carbonclean.com/insights/carbon-capture-for-refineries

[31] É. Yáñez, H. Meerman, A. Ramírez, É. Castillo and A. Faaij. "Fully integrated CO2 mitigation strategy for an existing refinery: A case study in Colombia". Jan 2022. https://www.sciencedirect.com/science/article/abs/pii/S0306261922002215