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Research Article

Recent Applications in Decarbonization in Oil and Gas Energy Transition

Ekrem Alagoz[1]*, Emre Can Dundar[1] and Yasin Ozkan[2]

[1]Turkish Petroleum Corporation (TPAO), Turkey

[2]University of Calgary, Canada

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***Corresponding author:** Ekrem Alagoz, Turkish Petroleum Corporation (TPAO), Turkey, ORCID: 0000-0002-2622-0453, Email: ealagoz@tpao.gov.tr

ABSTRACT

Decarbonization of the oil and gas sector is an urgent issue in light of the ongoing climate crisis. The objective of this paper is to provide a comprehensive overview of recent applications and progress in decarbonization efforts in the oil and gas sector. A total of 35 relevant research papers were reviewed and analyzed.

The current situation of the oil sector, its place in the global energy mix and the urgent need for decarbonization in light of the changing climate are all discussed at the outset of the article. This is followed by an examination of the economic and technological aspects of decarbonization, including the cost and capacity requirements of electrification and the deployment of renewable gas. The paper then moves on to explore the various strategies and pathways for decarbonizing the oil and gas sector, such as the decarbonization of diesel and the potential of CO_2-EOR for the near-term. Additionally, the paper assesses the political and economic drivers of decarbonization, including the role of industrial decarbonization via natural gas and the limitations of transport decarbonization. The article finishes with a review of the prospects and problems facing the electrification of peak loads and the socioeconomic effects of decarbonization in the oil and gas sector. The paper concludes by highlighting the importance of integrated policy and technological solutions for successful decarbonization of the oil and gas sector.

Overall, this article offers a thorough review of the continuing efforts to decarbonize the oil and gas industry as well as the opportunities and obstacles encountered during the process. It is hoped that the insights provided in this paper will be valuable to researchers, policymakers and industry stakeholders working towards a more sustainable energy future.

Introduction

Decarbonization of the oil and gas sector is a critical issue in the fight against climate change. The continued extraction, production and consumption of fossil fuels is the largest contributor to global greenhouse gas emissions and the leading cause of climate change. The oil and gas sector has been a central focus of international efforts to mitigate the impacts of climate change and reduce greenhouse gas emissions.

In light of this, a comprehensive understanding of the progress and challenges of decarbonizing the oil and gas sector is essential. The objective of this paper is to provide a comprehensive overview of the recent applications and progress in decarbonization efforts in the oil and gas sector. The paper is based on a review of 40 relevant research papers, which were analyzed and synthesized to provide an overview of the current state of the art in decarbonization efforts in the oil and gas sector.

The paper is organized into sections that examine the current state of the oil industry and its role in the global energy mix, the economic and technological aspects of decarbonization, the strategies and pathways for decarbonizing the oil and gas sector, the political and economic drivers of decarbonization and the challenges and opportunities facing the decarbonization of the oil and gas sector. The paper concludes by highlighting the importance of integrated policy and technological solutions for successful decarbonization of the oil and gas sector.

The insights and findings from this paper are expected to be valuable to researchers, policymakers and industry stakeholders working towards a more sustainable energy future.

Decarbonization Pathways and Strategies

For the purpose of lowering greenhouse gas emissions and ensuring a sustainable energy future, decarbonization pathways and techniques are crucial. A range of decarbonization options, including renewable energy, energy efficiency and carbon capture and storage, can be deployed to achieve significant reductions in emissions. However, the choice of pathway and strategy will depend on a number of factors, including the availability of resources, the specific needs of individual countries and the ability to implement and scale the technologies.

In conclusion, the development of effective decarbonization pathways and strategies is crucial for ensuring the energy transition towards a sustainable and low-carbon future. The viability, economic viability and social acceptability of these pathways and initiatives depend on a multi-stakeholder approach comprising the government, business and civil society. We will delve deeper into this topic and examine the different decarbonization pathways and strategies in the following sections.

A shift in the climate? The historical perspective of the oil industry and decarbonization

The article[1] discusses the dilemma faced by the global oil industry in light of the need for decarbonization to prevent catastrophic climate change. It examines the industry's historical response to market and government pressure and argues that while some companies have developed proactive decarbonization strategies, the industry as a whole has taken little meaningful action due to factors such as continued fossil fuel demand, vested interests and the voluntary nature of climate governance.

The study[1] discussed the challenge of decarbonization in the context of the global oil industry and the role of fossil fuels in the global primary energy supply. Just little less than in 1973, 81% of the world's primary energy supply in 2016 came from fossil fuels. Despite efforts to replace oil with coal and gas, demand for transportation fuels increased, accounting for more than 60% of all oil use in 2016. The article covered various decarbonization strategies, such as limiting emissions, switching to low- or zero-emission alternatives, removing carbon dioxide and limiting the availability of fossil fuels. The article further discussed the challenges of decarbonization, such as the difficulty of replacing oil, the political controversy surrounding direct restrictions on emissions and the limitations of carbon capture and storage technologies. The article also discussed the position of the oil industry on climate change mitigation, which has traditionally been in favor of market-based and voluntary measures, rather than direct restrictions on emissions or production of fossil fuels.

In the late nineteenth century, people started to become concerned about pollution and how industrialization was affecting their health. Due to a strong growth ethic and a fiercely competitive market, the oil sector during this time neglected to take the environment into account. But as air and water pollution increased, oil corporations gradually developed an ethic of efficiency that associated polluted wastes with inefficiency and called for technical fixes. Public environmental concerns reemerged in the 1960s and it was believed that business could only be brought into compliance by regulation. During the majority of the 1970s, the oil sector was vehemently opposed to total governmental regulation. However, the 1980s saw a shift in the industry toward compliance and a gradual shift toward a more proactive approach to environmental issues, which in the 1990s gave rise to corporate environmentalism, also known as strategic environmentalism. Because of increased public and political interest in environmentalism during the decade, spurred on by environmental and human health crises, the environment became a strategic concern. Due to this, corporate environmentalism was adopted and in the 1990s, sustainable development emerged as a key paradigm. Green capitalism was given a framework by sustainability, wherein the goal of commercial success or economic growth did not conflict with environmental preservation. Companies were urged to include environmental considerations into their business decision-making and to show their commitment to sustainability through reporting requirements, voluntary certification programs and sustainability indices. A new position for business was created in environmental governance as a result of this paradigm shift and large corporations started to take a more active role in environmental issues. They teamed up with governments and environmental pressure groups to jointly develop environmental regulations based on the principle of voluntary action.

The late 1980s saw the emergence of climate change as a significant environmental issue. Due to an imminent existential threat, the oil sector opposed proposals controlling and taxing CO_2 emissions. The oil industry had a unified front against these measures in the 1990s, especially in the United States but also in Europe. The world's prolonged reliance on fossil fuels improved the industry's position. The paradigm for sustainable development that simultaneously arose altered the industry's function in environmental governance. With the alignment of business and environmental objectives, private sector is now seen as a contributor to environmental governance and as a potential source of sustainability. Following 1992, the UNFCCC established an international regime that acknowledged private enterprise as a significant stakeholder in emissions reduction goals. Although the 1997 Kyoto Protocol didn't put any direct pressure on the oil industry to decarbonize, its conclusion represented a compromise between the pro-regulation positions of the EU and the US. While U.S. oil corporations are still falling behind, European oil companies have made a commitment to decarbonization in line with global standards.

The response of the oil sector to the problem of decarbonizing the energy system to stop catastrophic climate change is also explored. It mentions that the oil sector resisted laws limiting and pricing CO_2 emissions when it became clear that climate change was a serious issue in the late 1980s. The role of private sector in environmental governance was, however, altering under the framework for sustainable development that simultaneously evolved and corporations were increasingly seen as contributors to environmental governance. The UNFCCC international regime that emerged after 1992 exhibited sustainability's hallmarks and the private sector was acknowledged as an important voice in successive UNFCCC meetings and conferences, according to the article. The U.S. oil business is still falling behind while European oil corporations have committed to decarbonization in line with global standards. The essay ends by emphasizing that there is still much work for business historians to undertake in order to properly place these characteristics in historical context and comprehend their full significance and impact.

An entire economy mexico's deep decarbonization roadmap

The Paris Agreement's objectives are not supported by Mexico's present climate change strategy. By 2050, a different route utilizing the Deep Decarbonization technique has been created to keep global warming to 1.5 to 2 degrees above pre-industrial levels while sustaining comparable GDP and population growth in the energy and non-energy sectors. The pathway involves switching to renewable electricity as the primary energy source, expanding the use of electric vehicles and public transportation and enhancing agriculture and forestry management techniques. Decision-making on the part of policymakers, including adjustments to fiscal and industrial strategy, will be necessary to execute this road quickly. The "Deep Decarbonization Routes for Latin America" project include this.

To be in line with the objectives of the Paris Agreement, a comprehensive pathway for decarbonization has been outlined for the main emitting sectors of the Mexican economy. The roadmap calls for significant structural changes to be made to the major economic sectors beginning in 2020 and implementation delays could prevent the Paris goals from being reached. Each industry has an own story of development in terms of technology and emissions. All of them must be accomplished in order for the overarching national goal to be accomplished and any decrease in ambition in one area must be made up for by an increase in other areas.

Creating a timeline for the rollout of electric vehicles (EVs), halting investment in oil and gas projects, developing an asset optimization strategy for existing oil and gas assets, rerouting funds from suspended oil and gas projects into transmission, distributing funds from urbanization and public transportation strategies and encouraging energy markets to invest in renewable generation capacity are some short-term policy measures to jumpstart the decarbonization process in Mexico. To ensure that climate action complies with the nation's international commitments, decision-makers should consider these measures, especially as the Government of Mexico updates its Nationally Determined Contributions (NDC). Furthermore, **(Figures 1 and 2)** demonstrates a DDP scenario which shows a decrease in demand for oil-based fuels, specifically gasoline and diesel, due to shifts in transportation and electrification. This results in a fall in upstream and refining activities, which lowers energy consumption for the entire industrial sector, including oil and gas, by 36%. The scenario also depicts fuel switching through electrification and a partial substitution of natural gas and hydrogen for fossil fuels, which reduces emissions by using fewer fossil fuels and decarbonizing the power grid. The DDP scenario incorporates carbon capture, in which half of the CO2 captured from the production of biofuels, electricity and hydrogen will be geologically stored and the other half will be used to make synthetic fuels. The southern and southeastern regions, where oil resources and processing infrastructure have historically been present, offer the best investment potential for these initiatives.

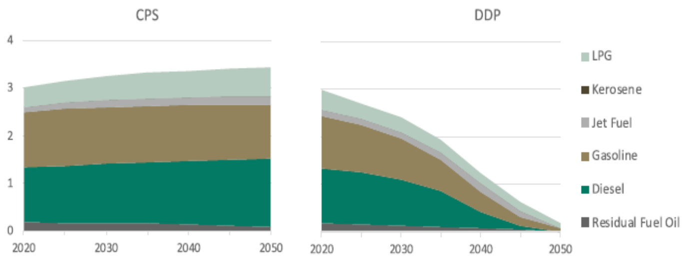

Figure 1: Demand for fuels made from petroleum[2].

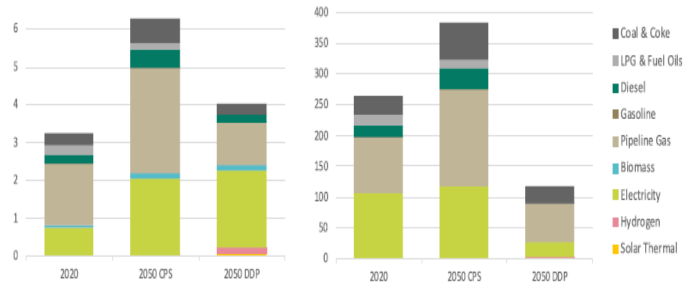

Figure 2: Energy demand (measured in exajoules) and resulting emissions (measured in million metric tons of carbon dioxide) for the industrial sector, including the oil and gas industry[2].

The study[2] adds to the body of literature by reiterating the cost-effectiveness of a highly renewable electric system and the large infrastructure expansion required to supply electricity for industry, buildings and transportation. According to the report, lowering the goal from 2 to 1.5 degrees Celsius narrows the variety of technological options that will be accessible by 2050 since bioenergy and efficiency limitations create gaps that can only be filled by clean electricity. The study also reveals that the need for equally urgent actions in the transportation, urban planning and oil and gas sectors is paralleled by the risk of emissions lock-in through any delay in acting inside the power system. Additionally, the study emphasizes the crucial role that Agriculture, Forestry and Other Land Use (AFOLU) played in bringing national emissions into compliance with the Paris Agreement. It also highlights the need for additional research on the decarbonization options available to that sector, including potential trade-offs between forest management, agricultural productivity, social inclusion and consumer behaviors, as well as sustained integration of AFOLU within future work analyzing Paris-agreement.

Decarbonization roadmaps for ASEAN and their implications

This article[3] presents decarbonization roadmaps for the ten nations of ASEAN (The Association of Southeast Asian Nations). **(Figure 3)** shows the overall view of ASEAN energy use and CO2 emission. This figure examines CO2 emissions by sector and fuel type to understand the magnitude of decarbonization and where efforts should be focused in Indonesia, Thailand, Malaysia, Vietnam, Philippines, Singapore, Myanmar, Cambodia, Laos and Brunei.

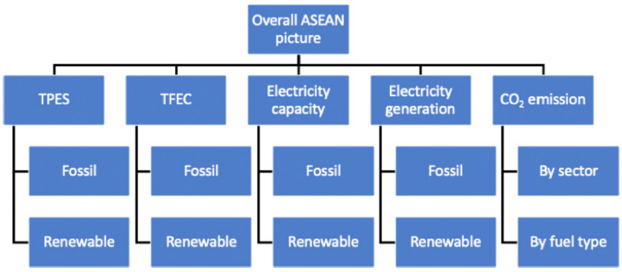

Figure 3: Overview of energy consumption and CO2 in the ASEAN region. Total Primary Energy Supply (TPES) and Total Final Energy Consumption (TFEC)[3].

According to **(Figure 4)**, in 2018, the International Renewable Energy Agency (IRENA) reported that the ASEAN region had a total primary energy supply (TPES) of 28.18 EJ, with 20.5% coming from renewable energies. Cambodia had the highest ratio of renewable energy to total energy supply (62%), while Brunei had the lowest (0%). Fossil fuels, such as coal, oil and gas, made up 80% of TPES. The top energy-using countries in ASEAN were Indonesia, Thailand, Malaysia, Vietnam and the Philippines. As a result, the study examines the region's current energy consumption and CO2 emissions and discovers that, despite the fact that fossil fuels have been gaining ground on renewable energy, decarbonization efforts should concentrate on raising the share of renewable energies in electricity generation and putting CO2 reduction strategies in place for fossil fuel power and industrial plants. The study then conducts a technology mapping exercise for each nation to identify high impact, high readiness decarbonization technologies. The roadmaps typically cover topics including transitioning from coal to gas for power production, employing carbon capture and storage (CCS) technology, converting from internal combustion vehicles to electric vehicles and using blue hydrogen to decarbonize businesses that are difficult to decarbonize. The article makes policy recommendations, including the implementation of a carbon price, the formation of a national hydrogen strategy, intergovernmental coordination and financial support for R&D aimed at enhancing carbon capture effectiveness[3].

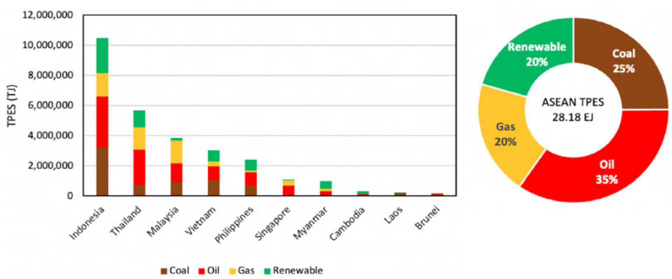

Figure 4: Total Primary Energy Supply (TPES) by (a) country and (b) energy source in the ASEAN region in 2018[3].

For the 10 ASEAN member countries, the study intends to develop decarbonization road maps. Fossil fuels are expected to remain a significant component of ASEAN's energy mix for the foreseeable future, according to the study, which showed that renewable energies have been falling behind fossil fuels over the past 20 years. Thus, efforts to minimize carbon emissions should concentrate on both technologies that lower CO_2 emissions from fossil fuel power and industrial facilities as well as increasing the share of renewable energies in electricity generation. In order to identify decarbonization technologies with a high effect and high readiness for particular countries, the study also carried out a technology mapping exercise for all 10 ASEAN nations. Using carbon capture and storage (CCS) technologies to decarbonize fossil and industrial plants, replacing internal combustion vehicles with electric vehicles and for nations with coal and natural gas resources, converting them to blue hydrogen through chemical processes and using CCS to mitigate the emitted CO2 are some of the common themes from the roadmaps. The implementation of a credible carbon tax, the creation of a national hydrogen strategy and intergovernmental cooperation to create regional CCS corridors are just a few of the policy ramifications of these roadmaps. Future studies should concentrate on saline aquifer characterization for CO2 storage, carbon capture efficiency improvement at the plant level and sustainability challenges of hydropower and bioenergy in ASEAN.

Decarbonizing singapore with domestic H2 production from natural gas

The use of locally produced hydrogen from natural gas with CO2 capture and sequestration or "blue" H2, is explored in this research[4] as a means of assisting Singapore's ambition to achieve a considerable decrease in CO2 emissions by the year 2050. The whole cost or emissions of the complete supply chain, from H2 production to consumption in the electricity, industry, home, marine and road transport sectors, are minimized using a superstructure-based model. The findings indicate that decarbonizing Singapore through domestic blue H2 production will have a relatively high carbon avoidance cost.

The article discusses a study on the potential for hydrogen production in Singapore in order to achieve decarbonization goals. The study focuses on "blue" hydrogen, which is produced from natural gas with carbon capture and sequestration. The study examines the cost of hydrogen, the emissions avoided and the supply chain for hydrogen production under three different demand scenarios for the transport, power, industrial and domestic sectors. The results show that while larger facilities are more economical, the cost of hydrogen is relatively high at the beginning due to low utilization of facilities. The study also finds that the cost of carbon emissions avoided through hydrogen is higher than \$100/tonne CO2 for the power and marine sectors and that using hydrogen to generate electricity is 30-50% more expensive than using natural gas with carbon capture and sequestration. Alternatives such as importing blue hydrogen from countries with access to low-cost carbon storage should be considered to overcome the barriers of local production.

Decarbonizing canada's remote microgrids

The cost of decarbonizing remote microgrids in Canada that now rely on fossil fuels for electrical supply is examined in this paper[5]. The least expensive decarbonization option for each settlement from now until 2050 is determined by the study using a cost-based methodology and a binary integer optimization model. The model considers historical wind and solar statistics, projected costs for generation and storage and whether it is advantageous to switch from fossil fuels to renewable energy sources now or in the future. The findings suggest that the cost of decarbonizing these microgrids is reasonable and that, for the majority of settlements in 2020, wind turbines will be the least expensive choice, while solar panels will be. The report recommends that communities currently use diesel or heavy fuel decarbonize as soon as possible, while communities utilizing natural gas should hold off until more affordable production and storage technologies become available. Additionally, it suggests giving fly-in villages and larger settlements priority.

In order to determine the least expensive option for each off-grid settlement from now until 2050, the article analyzes the cost of decarbonizing remote microgrids in Canada utilizing a cost-based methodology and a binary integer optimization model. The study discovered that the cost of decarbonizing remote microgrids in Canada is not prohibitive and that the timing of the switch from fossil fuel generation is related to the renewable power technology used (solar or wind). The report advises that although communities using natural gas should wait until production and storage solutions become more affordable, those using diesel or heavy fuel should decarbonize as soon as possible. The study also discovered that decarbonizing remote microgrids later will prefer solar panels over wind turbines since solar panel costs are predicted to fall. Overall, the study revealed that costs are reasonable and consistent with another research on decarbonization.

The study looks at the use of renewable energy microgrids in Canada's outlying communities and discovers that the overall cost of decarbonizing these microgrids is consistent with earlier studies. It concludes that although communities using natural gas should wait until production and storage technologies become more affordable, those that currently use diesel or heavy fuel should decarbonize as soon as possible. The analysis also reveals that decarbonizing remote microgrids later will benefit solar panels over wind turbines because of anticipated falls in solar panel prices. The cost of a hybrid system, which has advantages and disadvantages and blends renewable energy with current fossil fuel technology, is one of the study's key findings. The use of annual averages for the wind and solar capacity factors, the absence of transportation costs, the uncertainty surrounding the cost of generation and storage technologies in the future and the fact that hydroelectricity or tidal power were not considered for any of the settlements are some of the study's limitations. Future research, according to the paper, should concentrate on finance strategies, more detailed data, transportation expenses and sensitivity studies that account for vulnerability to price changes and operational concerns.

Ways to lessen indonesia's reliance on oil and accomplish longer-term decarbonization

The article discusses[6] the challenges faced by Indonesia in decarbonizing its energy system by 2050. It proposes a shift from oil to electricity as the main source of energy for cooking stoves and vehicles. The study uses causal loop diagrams to analyze the constraints, resource availability and regulation of the energy system. It also assesses the role of private companies in promoting renewable energy and competitive pricing. The results indicate that fossil sources will remain significant in the future, requiring the implementation of carbon capture storage technology to complement renewable energy promotion.

Authors drawn an outline and proposed a hypothesis for research in **(Figure 5)**. The purpose of the dynamic hypothesis is to understand the shift towards a carbon-free energy system in Indonesia can be accomplished through the substitution of oil with government support for renewable energy and subject to market and carbon capture and storage factors.

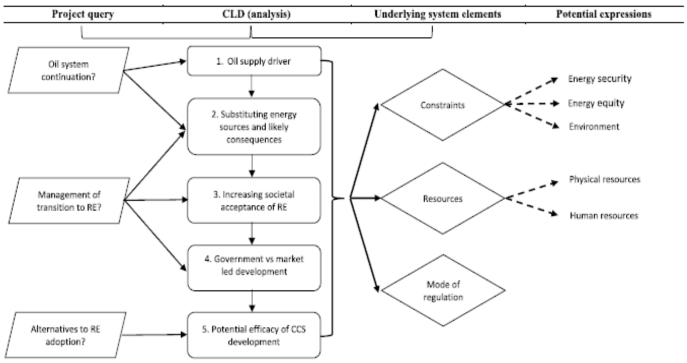

Figure 5: Project inquiries, complexity leadership theory analysis and underlying system components[6].

The article examines the possibility of reducing Indonesia's dependency on fossil fuels and decarbonizing its energy system by 2050. A systems approach is taken, considering the energy trilemma, resource availability and mode of regulation. The conclusion is that the shift from oil to renewable energy is possible, but depends on changes in energy demand patterns, investment from the government and competition from private companies. The study suggests that coal and gas will likely still play a significant role and that carbon capture storage technology may be necessary. The study is limited by its small sample of interviewees and does not consider nuclear and hydrogen energy as alternative sources.

Through the substitution of oil with renewable energy, subject to market and CCS influences, the hypothesis on lowering Indonesia's reliance on oil and decarbonizing its energy system until 2050 has been studied. With caveats, the conclusion backs up the theory. According to the research, switching from oil will only happen if energy demand patterns change. Renewable energy sources can solve the energy trilemma and the energy equity limitation, but persistent government investment and effort are needed. The research will go in the following directions: quantitatively testing the hypothesis; investigating the large-scale development of CCS if it becomes more prevalent by 2050; and developing scenarios for renewable energy and the role of CCS in the energy system, including nuclear and hydrogen energy, market-led energy policy and benchmarking with other developing nations. However, there are still certain drawbacks, including a small sample size, a qualitative approach and the omission of alternative energy sources.

A decarbonization roadmap for Singapore and its energy policy implications

In order to attain net-zero carbon emissions by the second half of the century, Singapore, a signatory to the Paris Agreement, is given a decarbonization roadmap in the paper that is proposed[7]. There are four primary parts to the plan: 1) Capturing and compressing CO_2 generated from industrial sources in Jurong Island using centralized post-combustion carbon capture technology, shipping it to a neighboring nation and permanently depositing it in a subterranean reservoir, Production of hydrogen in a methane steam reforming facility integrated with a carbon capture facility; modernization of the refining industry through the introduction of bio refineries; increased output at petrochemical facilities; and use of post-combustion carbon capture; and refueling of the transportation industry through the introduction of electric and hydrogen fuel cell vehicles, as well as the use of biofuels for aircraft and hydrogen for ships. The impact of this roadmap on Singapore's energy policies is also covered in the study.

Based on an examination of Singapore's energy environment and a technology mapping exercise, this article offers a route for Singapore to reach net-zero emissions by the year 2100. There are four primary parts to the plan: 1) To lower the cost of CO2 collection, transport and storage, capturing CO2 from various sources in a centralized post-combustion carbon capture plant on Jurong Island, shipping it to a neighboring nation and permanently storing it in an underground reservoir, 2) Using an SMR plant to produce hydrogen from natural gas and connecting it with a centralized carbon capture facility, Refueling the transportation sector involves replacing internal combustion engines (ICE) with electric and hydrogen fuel cell vehicles, using biofuels for aviation and hydrogen for ships and 3) modernizing the refining sector by including biorefineries to produce renewable biofuels and biochemicals. The policy ramifications discussed include enacting a sufficient carbon tax, setting goals for renewable fuels, creating a roadmap for the energy transition that incorporates the use of hydrogen, involving the public in efforts to increase public awareness and acceptance of CCS, collaborating with other governments to create an ASEAN CCS corridor, establishing CCS regulations, establishing PPPs for the implementation of CCS projects and funding regional CCS research.

Oil and gas companies' strategic planning: the decarbonization transition

This study [8] aims to help oil and gas companies develop strategies to adapt to the growing renewable energy sector and climate concerns. It examines the global energy system and decarbonization strategies for major players in the oil and gas market and suggests ways to improve strategic planning systems for oil and gas companies to ensure sustainability in the context of a global energy transition. The study also provides a theoretical background based on strategic planning concepts and methods and proposes a climate adaptation strategy for a Russian oil and gas company using the company's business capabilities.

This study examines the challenges facing the oil and gas industry due to the shift towards a low-carbon economy and the impact of the COVID-19 pandemic on supply and demand. It suggests that decarbonization is becoming an important aspect of the industry and that companies need to develop strategies to adapt to this change. The study argues that there is no one-size-fits-all approach and that companies need to find a balance between emission reduction and economic efficiency. It also suggests that investment in low-carbon energy has a lower return than oil and gas projects, but companies that do not adapt to the energy transition will become outsiders.

The essay makes the case that oil and gas corporations still have a part to play in the shift to a low-carbon economy, despite the fact that the renewable energy sector is expanding. The move toward decarbonization has presented new challenges for the oil and gas sector, but businesses are equipped to handle them thanks to their ability and creative thinking. The article identifies three key strategic priorities for oil and gas companies in the era of energy transition: maintaining traditional hydrocarbon-based operations while implementing new solutions to reduce carbon footprint, analyzing new benchmarks of growth and integrating low-carbon solutions into their portfolio and planning for flexibility to adapt to the changing energy landscape. It suggests that companies who can transform and scale their processes and combine traditional and low-carbon energy sources will be the future winners in the energy market. Figure 6 illustrates global oil and gas companies' strategies for energy transition.

Company	2050 Emissions Target	Reduction of Oil Production	Increase in Gas Production	Solar Energy	Wind Energy	Geothermal Energy	Energy Efficiency	Bioenergy	CCUS	Low-Carbon Hydrogen	Nature-Based Solutions
Shell	Net zero (Scopes 1, 2, 3)	✓		✓	✓		✓	✓	✓	✓	✓
TotalEnergies	Net zero (Scopes 1, 2, 3)		✓	✓	✓		✓	✓	✓	✓	✓
BP	Net zero (Scopes 1, 2, 3)	✓		✓	✓	✓	✓	✓	✓	✓	✓
Eni	Net zero (Scopes 1, 2, 3)	✓	✓	✓	✓		✓	✓	✓		✓
ConocoPhillips	Net zero (Scopes 1, 2)						✓		✓	✓	✓
Exxon Mobil	Net zero (Scopes 1, 2)		✓				✓	✓	✓	✓	
Chevron	Net zero Upstream emissions (Scope 1, 2)		✓			✓	✓	✓	✓	✓	✓
Equinor	Net zero (Scopes 1, 2, 3)		✓	✓	✓		✓		✓	✓	
Saudi Aramco	Net zero (Scopes 1, 2)		✓				✓		✓	✓	
CNPC	"Near zero" emissions		✓	✓		✓	✓		✓	✓	✓
Petrobras	Net zero (Scopes 1, 2)			✓	✓	✓	✓		✓		✓

Figure 6: Objectives and key focus areas for the growth of international petroleum and gas corporations in light of the transition to alternative energy sources[8].

The study examines the challenges faced by the oil and gas industry in the transition to a low-carbon economy and the effect of the COVID-19 pandemic on supply and demand. It suggests that companies should focus on maintaining traditional practices while also actively seeking new solutions to reduce their carbon footprint, analyzing new benchmarks of growth and improving flexibility in their strategic planning. The study also suggests that oil and gas companies have the opportunity to make fundamental changes that will lead to sustainable development. The study aims to provide a model of strategic planning and identify ways for companies to ensure a sustainable position in the new market paradigm.

The report draws conclusions regarding how the global energy system will be impacted by climate change and the necessity for major companies in the oil and gas sector to update their strategic plans. It highlights the significance of sound strategic planning in a highly volatile market context to ensure oil and gas businesses' long-term viability during the energy transition. Identifying the company's place in the low-carbon market, looking for opportunities that foster flexibility and efficiency, shifting from a focus on short-term shareholder return to a focus on long-term value and going beyond current business models organizational structures and corporate cultures are some of the main characteristics of strategic planning in this era. The study also proposes a climate adaptation strategy for the oil and gas company LUKOIL and suggests further research on strategic planning for oil and gas companies.

During the COVID-19 pandemic lockdown, global CO2 emissions experienced a record drop, reaching levels not seen since 2006. On April 7, 2020, emissions fell by 17% compared to pre-pandemic levels, largely due to widespread lockdowns that restricted travel, dining and shopping. Despite this significant drop, the reduction highlighted the challenge of achieving sustained long-term reductions necessary to combat climate change. The temporary reduction in emissions due to the pandemic underscores the limited impact of short-term behavioral changes. Even if global emissions drop by 4-7% in 2020, this falls short of the 7.6% annual reductions needed over the next decade to keep global temperature rise below 1.5 degrees Celsius. Scientists stress that temporary drops won't alter the climate trajectory, as CO2 can remain in the atmosphere for up to a century. Historical patterns suggest that emissions typically rebound following economic downturns, as seen after the Great Recession of 2009. This trend is beginning to reemerge, with emissions in China and oil demand in the U.S. and Europe rising as lockdowns ease. To prevent a return to pre-pandemic emission levels, governments need to implement green stimulus measures that promote clean energy in power generation, transportation and buildings. Structural shifts in the energy system are necessary to meet ambitious decarbonization targets. The pandemic has primarily reduced transportation emissions, which accounted for 53% of the decline on April 7, unlike past recessions that mainly affected industrial emissions. The long-term impact on emissions will depend more on the global economic response to the pandemic rather than the temporary effects of lockdowns[9].

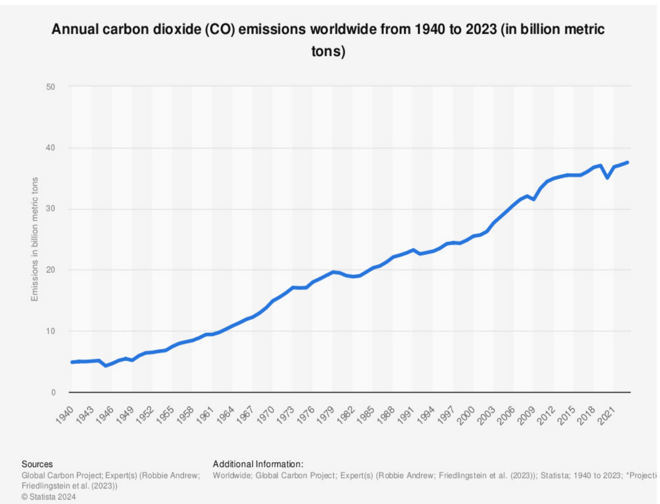

Figure 7: Objectives and key focus areas for the growth of international petroleum and gas corporations in light of the transition to alternative energy sources[10].

Here is the graph showing the effect of the COVID-19 pandemic on global CO_2 emissions:

- Pre-Pandemic: 100% (baseline emissions)
- April 7, 2020: 83% (17% reduction)
- End of April 2020: 100% (emissions returned to pre-pandemic levels)
- 2020 Estimate: 93% (projected 4-7% reduction for the year)

The graph illustrates the sharp drop in emissions during the peak of the lockdown and the subsequent return to pre-pandemic levels, highlighting the temporary nature of the reduction without long-term structural changes.

Energy management decarbonization policy and its implications for national economies

The article[11] discusses the formation of modern environmental policy and the importance of decarbonization in addressing climate change. It analyzes the shift towards global regulation and the impact on national economies through the control of the oil and gas sector. The article also examines the concept of greening and challenges the idea of global warming as the sole cause of climate change, pointing to regional geographical cooling. The article highlights the development of wind farms in developed countries as a result of their limited own reserves of fossil fuels and the global policy promoting decarbonization in energy.

The process of decarbonization is driven by the priority of combating climate change in environmental policy, supported by nominal economic policies and highlighted in scientific publications. However, the real national policy remains focused on practical economic needs and the availability of resources, such as coal, for electricity and heat production. Despite its accessibility and low cost of production, the absence of appropriate environmental technologies for coal burning remains a challenge. The global environmental policy's focus on prohibition and increased wind farm development is part of a move towards full state control over carbohydrate extraction and processing by economically powerful countries and financial groups, with a vague but pursued purpose.

In light of the trend toward global decarbonization, certain potential and difficulties for Russia and its areas

The scenario for Russia's energy transition in the article[12] takes into account the nation's natural resources, oil and gas infrastructure and economic structure. Russia may use its current oil and gas production infrastructure to produce hydrogen and store CO_2 by taking advantage of the global trend towards energy and economic decarbonization. To create carbon farms, which have the potential to grow into a high-tech enterprise, a network of carbon testing sites is being established, one of which is at Kazan Federal University.

The article proposes a new approach to energy transition in Russia, taking into account the country's available natural resources and existing oil and gas infrastructure. The aim is to create and implement industrial technologies for generating hydrogen and sequestrating carbon dioxide, both using biological systems and by injecting it into natural reservoirs. A carbon testing area in Tatarstan run by Kazan Federal University is being established as a center for data collection and validation, which will form the basis for estimating greenhouse gas emissions and sinks in the region and the country. The lack of information on carbon fluxes in the soil and the subsurface layer and on the carbon balance in ecosystems is noted and seen as necessary for the development of nature-like carbon sequestration technologies.

The constraints of transportation decarbonization in the context of present growth paradigm

In order to achieve ambitious greenhouse gas reduction targets, the study[13] analyzes the viability of four transportation decarbonization plans for 2050 using the MEDEAS-World model. The findings imply that switching just to electric vehicles is insufficient to achieve GHG reduction targets and may even result in mineral scarcity. The Degrowth paradigm, which combines a switch to lighter electric vehicles and non-motorized modes with a decrease in overall transportation demand, is the only approach that will work.

The MEDEAS-W model, which incorporates several choices for electrification, vehicle substitution, modal changes and demand-side management, is used in the study to analyze four decarbonization scenarios for global transportation by 2050. The scenarios demonstrate that the current trend of increasing the usage of electric vehicles is insufficient for lowering GHG emissions and may result in a decline in the economy owing to a lack of liquid fuels. The scarcity is temporarily avoided by a rapid switch to electric vehicles, but this won't be enough to cut GHG emissions by 2050. In addition to raising worries about important mineral sources like lithium, copper and magnesium, the widespread usage of electric vehicles makes it difficult to fully electrify light vehicles without strong recycling regulations.

The essay considers replacing current cars with extremely light vehicles, including e-bikes and mopeds, as a strategy to short-term delay the lack of liquid fuels and economic decline. Yet, the number of emissions reduced in this scenario is quite moderate. It is challenging to electrify freight transportation and decarbonization calls for a major shift in how freight is transported worldwide. The only scenario that accomplishes the dual objectives of energy savings and GHG emissions reductions, mimicking the Degrowth paradigm, is one with strong policies for a switch to light vehicles, ambitious mineral recycling and a severe fall in transportation demand, notably air travel. In order to reach decarbonization goals, the essay emphasizes the necessity for policies that support behavioral change and mode shift toward low-carbon transportation. There is a lot of room for energy savings and a decrease in GHG emissions with the promotion of public transportation and traffic limitations. Future study will concentrate on a more thorough simulation of the Degrowth scenario, including an investigation of household income and geography, as well as the effects of taxes on various fuels.

Techno-Economic Analysis of Decarbonization

Impact of climate change and align with global efforts to transition to a low-carbon energy system. The oil and gas sector is responsible for a significant share of global greenhouse gas emissions and therefore it is critical to find ways to reduce these emissions while ensuring that the energy supply remains reliable, affordable and secure.

A techno-economic analysis of decarbonization in the oil and gas sector can help to identify the most promising and cost-effective decarbonization options, as well as the barriers and challenges that must be overcome in order to achieve a successful transition. This analysis can also provide insights into the trade-offs between different decarbonization options, such as the cost and feasibility of transitioning to renewable energy sources, the benefits and limitations of carbon capture and storage and the potential for energy efficiency improvements.

In conclusion, the techno-economic analysis of decarbonization is a crucial component in understanding the path towards a sustainable energy future. By providing insights into the costs and benefits of different decarbonization options, this analysis helps to inform effective policy and strategy development. In the following sections, we will provide a more in-depth examination of the recent advancements and findings in this area to further our understanding of the role of techno-economic analysis in the energy transition.

Cost and capacity requirements for decarbonizing building heating in Metro Vancouver, British Columbia, through electrification or renewable gas transition alternatives

This study[14] compares two pathways for reducing carbon emissions from building heating in Northern countries, specifically in Metro Vancouver, Canada. The first pathway is to replace natural gas heaters with electric heat pumps, while the second pathway is to replace natural gas with renewable gas. Under nine distinct scenarios, the study evaluates the ideal annual system cost and capacity needs for each approach. The findings demonstrate that both pathways might be less expensive, although the renewable gas pathway's cost distribution is more constrained. With colder temperatures favoring the renewable gas pathway and milder temps favoring the electrification method, the system cost is sensitive to heat demand. The study emphasizes the demand for improved comprehension of heating profiles and related energy system requirements.

This study evaluates the costs and energy system capacities needed to eliminate natural gas consumption in the building heating sector of Metro Vancouver, Canada. The two pathways considered are direct electrification with heat pumps and substitution via renewable gas. Results show that both pathways are feasible, but the cost range is narrower for the renewable gas pathway. The study also found that the system cost is sensitive to heat demand, with colder temperatures favoring the renewable gas pathway and milder temperatures favoring the electrification pathway. The study also highlights that the transition pathways require the installation of additional electricity generation capacity and energy storage. However, the installation of large-scale storage infrastructure to meet the peak demand appears to be challenging.

The article discusses the challenges of fully electrifying heat energy demand, particularly in relation to storage capabilities. It compares the storage capabilities of natural gas and electricity systems and notes that the compressibility and energy density of natural gas make it well-suited to meeting large peaks in demand that occur during cold weather events. The article also mentions Canada's potential for underground hydrogen storage, particularly in the Western Canada Sedimentary Basin, despite the many difficulties it now faces. The paper indicates that in order to limit investment risk and cut costs, legislative measures like subsidies and price guarantees may be required. The article also points out that while direct electrification and renewable gas pathways can both cut combined emissions from power and heating by roughly 80%, they only account for a small portion of British Columbia's overall emissions. The article's conclusion mentions that the study does not account for emissions produced by wind and solar power plants.

This study compares the storage capabilities of gas and electricity systems and shows the challenges of fully electrifying heat energy demand. The compressibility and energy density of natural gas make it more suitable for supplying large peaks that occur during cold weather events. The study suggests that replacing natural gas with renewable gas can help limit the increase in peak electricity demand and storage capacity requirements. The study also suggests that the cost effectiveness of the renewable gas pathway will depend on developing low-cost, large-scale hydrogen storage. The study concludes that both direct electrification and renewable gas pathways reduce the combined electricity and heating emissions by about 80%, but these sectors represent a fraction of overall emissions in British Columbia. The study notes that the majority of remaining emissions come from the power grid and these emissions will decline if neighboring jurisdictions decarbonize their electricity generation.

This study compares the use of electrification and renewable gas technology as alternatives for reducing greenhouse gas emissions in the building heating sector of a metropolitan area where hydropower-dominant generation provides flexible and low carbon electricity. The study found that both pathways can reduce emissions and supply energy demands, but a combination of both may be the most cost-effective solution. However, the study has several limitations and assumptions that warrant further investigation. These omissions include not modeling the transition routes to be mutually inclusive, not investigating the costs of changing the electric or gas distribution systems to be in line with considerable fuel substitution and not enhancing the spatial resolution of the energy system model. The analysis also depicts Metro Vancouver as a single node without the need for energy transmission, which may reveal affordable improvements and geographic designs required to handle rising electricity demand and hydrogen concentrations.

This analysis looks at the challenge of reducing greenhouse gas emissions in the building heating sector of a metropolitan area where the majority of electricity is generated from hydropower. The study compares two transition pathways, electrification and renewable gas and finds that both can reduce emissions and supply energy demands, but a combination of the two will likely be the most cost-effective solution. The study also notes that the costs of transitioning the gas or electric delivery systems to align with significant fuel substitution of natural gas have not been explored in detail and that new infrastructure, modifications and upgrades will be needed to connect either new electric loads or to move large volumes of hydrogen. The study concludes that enabling the gas system to continue to provide its services via renewable gas adoption may be a cost-effective strategy to mitigate climate change.

Economic evaluation of natural gas decarbonization method for bitumen recovery from oil sands carbon emissions reduction

The economic feasibility of employing natural gas decarbonization (NGD) to reduce CO2 emissions from oil sands recovery operations is assessed in this study[15]. By extracting carbon from natural gas, NGD produces hydrogen and produces carbon black instead of CO2 emissions. The steam produced by the hydrogen compensates for a sizeable portion of the water losses from bitumen recovery. In terms of energy effectiveness and economic viability, the study contrasts a combined oxy-combustion and NGD process with traditional steam aided gravity drainage (SAGD), considering elements like oil prices, CO2 tax and credits and possible earnings from the carbon black product. The results of this study will aid potential investors and the oil sands sector in decision-making regarding investments in the technology's development and commercialization.

This study offers a cost-benefit analysis of the in-situ bitumen recovery from oil sands using the natural gas decarbonization (NGD) method. It contrasts an oxy-combustion and NGD method with the standard steam aided gravity drainage (SAGD) approach in terms of energy and cost. Energy efficiency, the cost of avoiding CO2 and possible sales of the carbon black product are all considered. According to the study, while the carbon black generated by the process can be viewed as a benefit, the amount of hydrogen energy generated is only 54% of the energy contained in natural gas. The NGD process in conjunction with oxy-combustion results in lower steam-to-oil ratios and less steam is needed for bitumen mobilization, which reduces the need for and expense of water handling. The NGD method has a fixed cost investment that is much higher than the traditional approach. According to the study's findings, using the NGD technique to collect bitumen from oil sands can only be competitive with the traditional method if the CO2 tax is close to CA$200/t CO2. Policymakers, potential investors and the oil sands industry can utilize the report to help them decide whether to invest in furthering the development and commercialization of the technology.

Decarbonization solutions for the Indian aluminum industry: An environmental, technological and economic analysis

In order to meet sustainable development goals, this study[16] explores the difficulty of reducing CO2 emissions in India's aluminum production business. The study examines the cost of producing aluminum by combining carbon capture and storage with aluminum production paths at both the system and national levels. The findings show that primary aluminum production has a higher carbon footprint than recycling aluminum and that using captive wind and solar energy can meet the CO2 emission requirements of the beyond 2-degree scenario while other captive energy sources and grid electricity require significant CO2 removal. To reduce overall costs, the study offers an optimum combination of decarbonization and aluminum manufacturing paths.

This paper offers a framework for decarbonization analysis and looks at the economic and environmental effects of three aluminum manufacturing pathways in India. According to the study, the most expensive pathway for producing aluminum is primary production, while recycling and re-melting aluminum are less expensive due to lower capital and utility expenses. Yet, if deep decarbonization is the desired outcome, either primary aluminum or recycling aluminum may be the most cost-effective route. The analysis also reveals that wind and solar energy are the cleanest forms of energy and thus supplying aluminum with just wind or solar energy would allow for the achievement of the decarbonization goals. Carbon capture and storage, however, will be required if the energy for the aluminum industry comes from other sources, such as natural gas, diesel or coal. It is discovered that the price of prevented CO2 emissions is between \$2.1 and \$4.4 per ton. The study concludes that carbon capture and storage should be used for natural gas, diesel and coal-based captive power as well as aluminum recycling and solar or wind-based captive electricity.

The study focuses on the effects of various aluminum production pathways on the environment and the economy as well as the prospect of adopting carbon capture to meet rising aluminum demand in India while also reaching decarbonization goals. The study concludes that while employing renewable energy sources like wind and solar energy can lessen the requirement for carbon capture and storage, energy storage is required to meet 100% of the demand for renewable energy. The report advises more investigation into how to lower carbon emissions using new technologies and alternative fuels, as well as supply chain analysis to better allocate resources and lower carbon footprint.

Evaluating strategies to decarbonize oil and gas supply chain: Implications for energy policies in emerging economies

The rating of 8 experts in the Iranian OGSC is used in this study[17] to assess the performance of the 14 decarbonization solutions for the oil and gas supply chain (OGSC). The Trial and Assessment in Decision-Making To investigate cause-and-effect links and develop a prominence relationship map for each stream in the OGSC, laboratory approach and intuitionistic fuzzy sets are utilized. The most efficient methods for decarbonizing the OGSC, according to the results, are CO2 flooding technology upstream, renewable energy integration for transportation midstream and carbon collection, utilization and storage technologies downstream. In order to help researchers and practitioners focus on the most promising decarbonization options, the study contributes to the field by offering a supply chain-wide evaluation of these strategies and their prioritization. If put into practice, these ideas might make the OGSC supply chain climate-friendly and make it easier to reach net-zero CO2 emissions.

The oil and gas supply chain (OGSC) decarbonization strategies that have been proposed in the literature are examined in this study. Eight specialists from the OGSC in Iran rank the strategies. In order to examine causal links between the techniques, the study employs intuitionistic fuzzy sets and the Decision-Making Trial and Evaluation Laboratory method. The CO2 flooding technology, flare gas recycling technology, renewable energy integration for transport, carbon capture, utilization and storage systems and flare gas recovery were identified to be the five techniques that are most important for the decarbonization of OGSCs. The other nine strategies are regarded as semi-critical and belong to the effect group, having an indirect impact on other key strategies, whereas these five are considered key strategies and are part of the cause group. The study also demonstrated the importance and applicability of each option for decarbonizing the OGSC. Using the intuitionistic fuzzy DEMATEL method, the causal links between the strategies are assessed in order to assist OGSC stakeholders in making the transition to decarbonization and selecting more environmentally friendly solutions.

This study uses 14 strategies that were identified in the literature and ranked by eight experts to decarbonize the oil and gas supply chain (OGSC). Five methods are highlighted as being extremely important and falling under the cause group. These strategies are divided into three streams and further divided into cause-and-effect groups. The paper also identifies certain drawbacks and areas for further research, including the need to replicate the findings in different supply chains and geographical contexts, solicit more expert input and use different approaches to examine how the various tactics interact with one another. Due to growing public knowledge of environmental issues and demands from society, business and politics, the study underlines the significance of decarbonization in the OGSC industry. The adoption of these strategies can help the O&G industry contribute to addressing climate change.

Technology for fossil fuel decarbonization to combat global warming

The generation of hydrogen-rich fuels for reducing the problem of CO2 greenhouse gas climate change depends on the synthesis of hydrogen from fossil and carbonaceous fuels. Steam reforming and water gas shift, which use mostly natural gas as the fuel source, are the traditional techniques of producing hydrogen from fossil fuels. Pyrolysis or the heat breakdown of methane into hydrogen and carbon, is an alternate method. The schematic diagram of natural gas thermal breakdown in a reactor with molten metal is shown in **(Figure 8)**. Although this system is less developed than the standard one, it provides advantages in terms of cost and carbon control. The hydrogen can be utilized as a fuel for transportation or turned into methanol, while the carbon can be stored or sold as a material good. The TDM process's potential advantages support its continued effective development[18].

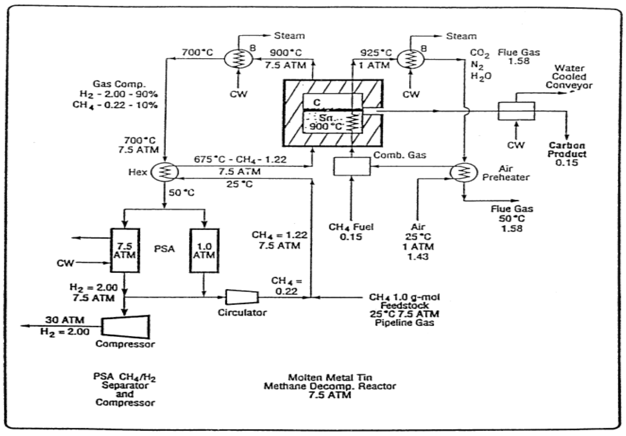

Figure 8: Generation of hydrogen through the thermal breakdown of natural gas in a molten metal reactor[18]

The impact of electrification-induced peak loads and gas infrastructure limitations on New York State's decarbonization paths

The study[19] compares ways to meet New York State's emissions reduction goals with and without specified zero-carbon electricity targets. The findings indicate that, if the zero-carbon power requirements are lowered, considering the electrification of buildings and vehicles can assist reach the same emissions targets at a cheaper cost. The effect of electrification on peak loads and restrictions on new gas infrastructure is also examined in the study. To achieve the 40% emissions reduction goal by 2030, two options are being evaluated. Cost of the first track, which includes 100% electrification, 11 GW of wind and solar and 21 GW of new gas generation, is $63/MWh. Cost of the second pathway, which excludes new gas generation, is $72/MWh and requires 60% electrification and more wind and solar. Both routes are less expensive than one that costs $92/MWh and combines a 40% reduction aim with a 70% renewable target. The study finds that the LCOEs can be managed by shaving new higher peak loads and that limiting peak gas flow has a small impact on LCOEs.

The paper compares the cost of reducing greenhouse gas (GHG) emissions in New York State through specified zero-carbon electricity (ZCP) targets or through electrification of buildings and transportation. The results show that relaxing ZCP targets and focusing on electrification can achieve the same GHG emissions reductions at lower levelized costs of electricity (LCOEs). The paper also examines the impact of electrification on peak loads and gas infrastructure and shows that peak shaving and limiting gas generation capacities can help keep LCOEs manageable. The findings have implications for other regions with similar renewable portfolio standards, potential peak loads from electrification and gas infrastructure constraints.

The GT20_PS pathway, which requires 100% electrification of buildings and vehicles in the next decade, has the lowest levelized cost of electricity (LCOE) but has some implementation concerns. The NoNewGT PS pathway is more likely to be used since it avoids new gas turbine (GT) buildouts and electrifies at a slower rate. Both paths have comparable annual costs for the production of electricity, but the NoNewGT PS has a larger power consumption and, as a result, higher consumer savings on fossil fuels. Four categories-renewable and storage, gas generation, baseload generation and transmissions—account for the annual cost of energy supply. The potential savings from reduced fossil fuel use brought on by electrification of buildings and vehicles for the HighRE PS and NoNewGT PS routes between 2019 and 2035. These two pathways have similar electricity supply costs averaging $15.0B/year and $14.3B/year respectively over 17 years, with different investments in renewable generation and battery installation or gas generation.

Due to the growth in electrification and decrease in fossil fuel use in the construction and transportation sectors, the NoNewGT PS pathway of power supply shows potential savings of $148B over 17 years (2019-2035) compared to the current scenario. Although the end-use fuel cost savings are almost equal to the increase in electricity supply prices, the HighRE PS pathway has comparable electricity supply costs. The estimated cost of electrification along the NoNewGT PS track is $95 billion, which includes capital expenditures for infrastructure investments and equipment upgrades. These expenses are comparable to the $148 billion in fuel savings, which could cover them. The model's findings show that electrification-induced winter peak loads differ geographically from existing summer peak loads, which has consequences for regional systems' electrification planning methods. The outcomes allay worries that the electrification progress in downstate areas might be hampered by greater distribution upgrading expenses.

This paper studies the potential pathways to reduce greenhouse gas (GHG) emissions in three dominant energy sectors (electricity generation, buildings and vehicles) using the System Electrification and Capacity Transition model (SECTR-NY) in New York State. The study compares the outcomes of two sets of pathways: "LowLCOE" pathways that prioritize early electrification and have GHG reduction targets but no zero-carbon electricity targets and "HighRE" pathways that have both GHG emissions reduction targets and zero-carbon electricity percentage targets (LCOEs). Peak shaving lowers LCOEs, whereas restrictions on natural gas demand and electrification rates have little effect on LCOE. The study also looks at how four options affect the paths. The study's findings, however, should only be used as a guide when formulating policies because they do not take consumer costs or technological improvements into account. To completely comprehend the trade-off between zero-carbon electricity and electrification advancement, more study is required.

Decarbonization of Fossil Fuels

The decarbonization of fossil fuels is a critical component of the global effort to reduce greenhouse gas emissions and address the impacts of climate change. The oil and gas industry, which is heavily dependent on fossil fuels, is a major contributor to global carbon emissions and must be a key player in the energy transition.

Several approaches to decarbonizing fossil fuels have been developed, including carbon capture and storage (CCS), cleaner burning technologies and the use of renewable energy sources to produce hydrogen and other low-carbon fuels. CCS involves capturing carbon dioxide emissions from power plants, industrial processes and other sources and injecting them into underground reservoirs for long-term storage. Cleaner burning technologies, such as advanced combustion systems, can reduce emissions from fossil fuel power plants, while renewable energy sources can be used to produce hydrogen and other low-carbon fuels for use in transportation and other applications. The deployment of these technologies will require significant investment and the development of policies and incentives to support their implementation will be critical. Additionally, the economic and social implications of the energy transition must be considered, as the shift away from fossil fuels will have impacts on energy prices, energy security and energy-intensive industries.

In conclusion, the decarbonization of fossil fuels is a crucial step towards a more sustainable energy future and requires a multi-faceted approach. The development and implementation of new technologies and approaches to decarbonize fossil fuels will be crucial in achieving significant decarbonization. In the following sections, we will delve into the various efforts being made in this area, exploring the progress and potential impact of these efforts.

A CFD study is advancing natural gas transmission networks' transition to a low-carbon future.

In order to comprehend the effects of hydrogen on the system's components and flow conditions, the article[20] conducts a computational analysis on the transport of hydrogen and natural gas mixes through a gas pipeline system. To forecast the behavior of various H2/NG blends, the analysis considers a blending station, pumping and injection techniques and varied pipeline geometries. The findings demonstrate that after 20 to 30 pipe diameters, good mixing is achieved in the blending station, pumping gas by a piston type compressor causes flow pulsations and asymmetries in the flow are found when the fluid's direction changes, but 20 diameters downstream, the flow is fully developed. The study emphasizes the need for further knowledge and expertise on the subject.

This article addresses the possibility of employing green hydrogen to decarbonize the gas industry and provide a cost-effective transportation route for massive hydrogen supply. It explains that the impact of hydrogen on the proper operation of its components determines whether the natural gas infrastructure is appropriate for this use and that computational studies like CFD simulations can be used to predict the expected environment in the pipe system and evaluate the readiness of the system. The article continues by presenting the findings of a CFD study that simulates the transport of H2/NG blends in a gas setup representative of the transmission gas network. It concludes that a good mixing is attained in the blending station once a pipe length equivalent to 20 to 30 diameters is reached and pumping gas by a piston type compressor exhibits pulsations in the flow regardless of the composition of the blend.

The study uses computational fluid dynamics (CFD) tools to simulate the behavior of mixtures of hydrogen and natural gas in a hypothetical setup, including a blending station and a natural gas pipeline. The study finds that good mixing is achieved in the blending station after 20-30 pipe diameters and pumping of the blend with a piston-type compressor can cause pulsations in the flow which can be mitigated. Asymmetries in the flow are found when the direction of the fluid changes after a reduction in pipe size, but the flow becomes fully developed 20 pipe diameters downstream. The study also finds that changes in fluid direction in the pipeline after expansion do not cause significant forces on instrumentation elements and the design of the pipeline should primarily consider pressure rather than fluid forces. It also finds that the flow pattern after expansion depends on the Reynolds number and the composition of the fluid.

The work considers a simplified hydrogen injection system and a section of a natural gas pipeline while developing models that predict the behavior of H2/CH4 mixtures in an imagined configuration using CFD tools. The study discovered that the installation of a static mixer in the circuit is unnecessary since good mixing between the streams may be generated after a length of pipe corresponding to 20-30 diameters from the junction point of these streams is reached. Additionally, it was discovered that homogeneous methane-hydrogen mixtures stored in tanks do not segregate under the conditions examined in the study, but homogenization does require a relevant amount of time when a tank is filled with hydrogen that is not of the same concentration as the hydrogen already in the tank. The study also discovered that the flow pattern following the expansion of the gas pipeline is dependent on the Reynolds number and that the forces exerted by the fluid on the duct walls and weld rings in the change of the pipe section are practically minimal. The pumping of H2 and CH4 by a piston type compressor will ultimately result in a pulsing flow that can be dampened by adding head losses to the circuit or by adding a buffer with a volume equal to the circuit.

Decarbonization: Doing more with less

The article[21] discusses the progress of decarbonization, which is the reduction of carbon dioxide emissions and how it contributes to the reduction of material intensity. It is found that decarbonization occurs at a global level of 0.307% per year and the reduction of energy intensity of value added is 1.70% per year, resulting in an overall reduction of carbon intensity of value added of 1.307% per year. The article also shows how widespread decarbonization is in five sample nations and points out that both developing and developed nations are going through the same decarbonization process. Yet, it is noted that some developing nations are raising their primary energy's carbon intensity, which could counteract the decarbonization of industrialized nations. The article suggests that reorganizing the energy system to rely more on natural gas, biomass, nuclear energy and other zero-carbon options, such as the methane economy, could prevent the possibility of an increase in carbon dioxide emissions faster than economic growth. This would result in a greater role for energy gases and hydrogen in conjunction with electricity.

The article discusses the potential benefits of transitioning to an energy system that relies on electricity and hydrogen as complementary energy sources. This transition would greatly reduce the total mass flow associated with energy activities and resulting emissions, as electricity is emission-free and hydrogen combustion results in water. The transition to this type of energy system would also align with the emergence of new technologies that offer increased flexibility, productivity and environmental compatibility. The author suggests that hydrogen-electricity economy would be more compatible with advancements in microelectronics, bio- and nanotechnologies, virtual reality and information and communication systems.

A systematic examination of sociotechnical systems, technological advancements and policy choices for decarbonizing the oil refining business

The oil refining industry has played a crucial role in modern society by producing transportation fuels, petrochemical feed stocks and other products but it has also led to greenhouse gas emissions and local air pollution. As seen in **(Figure 9)**, 84% of the world's primary energy came from fossil fuels, with oil being the most prominent source at 33% in 2019. Although renewable energy sources have gained traction, oil still plays a significant role in the transportation sector. Despite facing challenges regarding its carbon footprint, oil remains the dominant energy source.

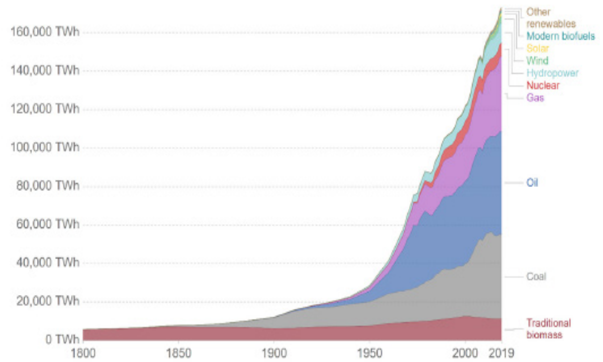

Figure 9: Worldwide consumption of primary energy by source, 1800 to 2019[22].

In order to investigate how the oil refining business can decarbonize and adapt to a carbon restricted future, this research[22] offers a thorough and critical literature assessment. To comprehend the whole spectrum of industrial and economic operations where a decarbonized oil refining business is predicted to stay significant and to evaluate the main technological, economic, social and political issues that will probably affect its evolution, a sociotechnical approach is utilized. The report identifies important decarbonization potential for this business while also highlighting gaps in the body of knowledge about its decarbonization. The information offered is anticipated to give practitioners, academics and policy makers the tools they need to progress the transition of the oil refining sector to a low-carbon economy.

Because its products are incompatible with international efforts to combat climate change, the oil refining sector is frequently referred to as a "sunset" sector. Unfortunately, this viewpoint does not completely acknowledge the significance of the entire socio-technical system of the sector and the systems to which it is related. When low-carbon energy transitions take place, the oil refining sector is projected to be crucial in the energy markets. However, there are numerous potentials for the sector to decarbonize and develop into one that provides low-carbon feed stocks and fuels to other sectors, like chemicals, shipping and aviation, which all need to decarbonize. The paper highlights these opportunities and identifies gaps in existing literature on decarbonizing the oil refining industry and proposes future research agendas to fill these gaps to help policymakers, researchers and practitioners advance a low-carbon transition of this industry.

The oil refining industry is facing challenges in becoming more sustainable and addressing climate change. The industry's importance and the complexity of the system make it difficult to implement a one-size-fits-all solution. The barriers to decarbonization include technical, economic organizational, policy and social factors. However, with low-carbon interventions and support from institutions and markets, it is possible for the industry to evolve and transition to a more sustainable future. Despite the challenges, the oil refining industry will likely play a vital role in the energy landscape for decades to come and achieving decarbonization is an existential challenge for the industry.

Effective catalytic co-hydroprocessing of residual lipids with gas-oil to decarbonize diesel

In this work[23], the impact of co-hydroprocessing leftover lipid (waste cooking oil) with a heavy petroleum fraction on the creation of a more environmentally friendly hybrid diesel fuel was assessed. The study discovered that the addition of WCO increased hydrogen consumption while increasing diesel content (13%), with no adverse effects on the hydroprocessing reactions. According to the findings, co-hydroprocessing residual lipids within a refinery can offer an efficient and low-risk option to incorporate leftover liquid biomass into transportation fuels without major capital investments and that an ideal percentage of WCO to add to the feedstock is between 5 and 10%.

In order to create a hybrid diesel fuel with higher sustainability, this study assessed the impact of employing residual lipid (Waste Cooking Oil, WCO) in the catalytic hydroprocessing of Heavy Atmospheric Gas Oil (HAGO). According to the study, adding more WCO to the feedstock increased the amount of diesel by up to 13% while having no effect on the targeted HAGO hydrotreating processes. But as the WCO content climbed, so did the consumption of hydrogen. When compared to traditional HAGO hydrotreating without WCO, the ideal WCO ratio in the feedstock was discovered to be 5-10%, which led to an increase in hydrogen consumption of 6.5%.

An initial evaluation of the economics of decarbonizing aviation fuel

This study[24] assesses the economics of decarbonizing the aviation sector by mid-century, which is crucial for limiting global warming to 1.5 degrees Celsius. In **(Figure 10)**, three different decarbonization strategies were considered: continuing to use fossil kerosene while capturing and storing carbon dioxide emissions directly in the air; creating hydrogen fuel from renewable electricity; and switching to synthetic renewable kerosene made from renewable energy. The study concluded that all three routes are economically viable and that their expenses will likely fall within the scope of recent fare changes. The study also discovered that while renewable kerosene may be readily available but likely has the highest cost and fossil kerosene combined with remote sequestration has the lowest short-term private cost but is not entirely sustainable. Hydrogen fuel, on the other hand, may be the least expensive option in the long run but requires the development of hydrogen-powered aircraft and infrastructure.

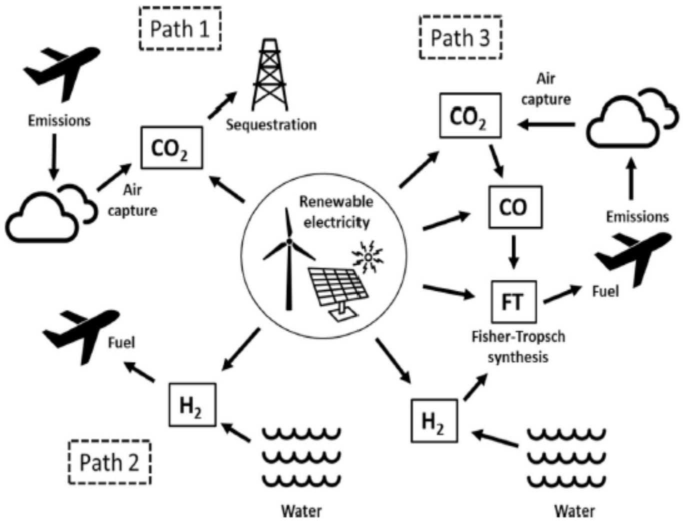

Figure 10: Schematic diagram of three aviation decarbonization ways[24].

This study looks at the economics of decarbonizing commercial air travel, which is a small but rapidly growing source of greenhouse gas emissions. In the study, three different decarbonization strategies are compared: using fossil kerosene with carbon capture and sequestration; creating hydrogen fuel from renewable electricity; and switching to synthetic renewable kerosene from fossil kerosene. In spite of being the cheapest choice in the short run, fossil kerosene with carbon capture and sequestration is not sustainable over the long term, according to the study. Although more environmentally friendly solutions, renewable kerosene and hydrogen fuel require more substantial modifications to the infrastructure of both fuel and aircraft. The study concludes that long-term, hydrogen fuel made from renewable power is probably the most cost-effective and environmentally friendly choice, but creating hydrogen aircraft designs must be a top priority.

This study compares the economics of different decarbonization paths for the aviation industry to assess their cost effectiveness. The study found that while all paths would be more expensive than current use of fossil kerosene, they are technically and economically feasible. The study suggests that the short-term solution would be to continue use of fossil kerosene with carbon sequestration, medium-term solution would be renewable kerosene and the long-term solution would be hydrogen fuel. However, developing hydrogen aircraft designs must be a priority. The study notes that implementing these changes requires public support and political will and that there are larger questions about the sustainable scale of the aviation industry and the need for more fundamental changes in the transportation industry.

Potential Of CO_2-Eor

Carbon dioxide enhanced oil recovery (CO_2-EOR) is a promising technology for decarbonizing the oil and gas industry. CO_2-EOR involves injecting pressurized CO_2 into depleted oil reservoirs to enhance the production of otherwise unrecoverable oil. This process not only increases the production of oil, but also helps to reduce greenhouse gas emissions as CO_2 is captured and stored underground.

There are several benefits to CO_2-EOR. Firstly, it is a cost-effective method of increasing oil production while also reducing greenhouse gas emissions. Secondly, CO_2-EOR can help to extend the life of depleted oil reservoirs, reducing the need for new oil wells to be drilled. Finally, CO_2-EOR has the potential to reduce the carbon footprint of the oil and gas industry, contributing to global efforts to decarbonize energy production.

Despite these potential benefits, there are also some challenges to the widespread adoption of CO_2-EOR. One of the main challenges is the high cost of capturing and transporting CO_2, which can make the process economically unviable. Additionally, there are concerns about the safety of CO_2 storage underground and the potential for CO_2 to leak and escape into the atmosphere.

In conclusion, CO_2-EOR is a promising technology for decarbonizing the oil and gas industry, but further research and investment is needed to overcome the technical and economic challenges associated with the process. If these challenges can be overcome, CO_2-EOR has the potential to play a significant role in the energy transition and contribute to a more sustainable energy future.

We will add some work which has been done in this area in the following sections, further exploring the technical and economic aspects of CO_2-EOR, the challenges associated with its implementation and the opportunities for further research and investment in this technology.

CO_2-EOR's potential for short-term decarbonization

The ability of carbon dioxide enhanced oil recovery (CO_2-EOR) to lower greenhouse gas emissions and its significance in decarbonization efforts are highlighted in this research[25]. It looks at the restrictions on CO_2 injection in the current legal and regulatory frameworks as well as the financial effects of integrating CO2-EOR with geologic carbon storage. The paper makes the case that CO_2-EOR can provide low-carbon oil to support the current energy infrastructure as it moves toward decarbonization and that stronger fiscal and regulatory incentives are required to scale up CO_2-EOR with storage globally. These incentives should include consistency and predictability in policy as well as targeted subsidies to support sizable capital investments in CO_2 capture and transportation infrastructure. The carbon capture, use and storage (CCUS) life cycle is demonstrated in **(Figure 11)**.

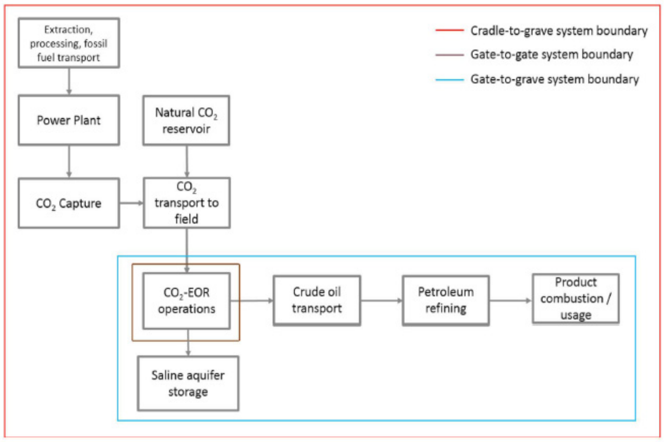

Figure 11: Carbon capture, utilization and storage lifecycle analysis[25].

According to the paper, carbon dioxide enhanced oil recovery (CO_2-EOR) has the potential to reduce carbon emissions in the initial years of operation and can be a significant contributor to the urgent need to combat climate change. The opportunity's near-term profitability can hasten the deployment of CCS (carbon capture and sequestration) and offer financial incentives for studies aimed at advancing this objective. It further claims that CO_2-EOR is the only commercially viable carbon utilization option that offers extensive permanent storage for captured CO_2 and that CCS is the only technology that can decarbonize specific industries, including steel, cement and petrochemicals. The study contends that stronger financial and regulatory incentives are required to scale CO_2-EOR with storage on a global scale so that it can be a successful endeavor that also lowers greenhouse gas emissions.

The paper makes the case that carbon dioxide enhanced oil recovery (CO_2-EOR), which has been developed under oil and gas regulatory framework while carbon capture and storage (CCS) has remained under a separate environmental law framework, has the potential to be a viable way to scale up CCS infrastructure. It implies that in order to ensure that the storage gained through CO_2-EOR is backed by thorough documentation and procedure, the legal and regulatory frameworks for the two would need to be reconciled. The paper also makes the case that CO_2-EOR infrastructure can be quickly and extensively developed, much like unconventional natural gas resources were in the US within a decade and that it can take advantage of rising carbon prices to create a climate mitigation technology for a changing energy landscape.

Decarbonization and Energy Sources

Decarbonization refers to the reduction of carbon emissions from energy production and use. It is a critical step in the transition to a more sustainable energy future and a key component of efforts to mitigate the impacts of climate change.

There are several energy sources that are being developed and used as part of the decarbonization effort, including:

- Carbon dioxide-free energy sources, such as wind, solar and hydropower, that are renewable.
- Nuclear power, which generates low-carbon electricity but

raises issues with waste and safety.

- Natural gas, which is being used more and more as a transition fuel since it emits fewer carbon emissions than coal or oil.
- Carbon capture and storage (CCS) technologies, which entail storing carbon dioxide emissions from industrial processes and fossil fuel power plants underground in order to significantly lessen their atmospheric impact.

In order to achieve significant decarbonization, a mix of these energy sources is necessary. For example, renewable energy sources like wind and solar can provide low-carbon electricity, while CCS can help to reduce emissions from fossil fuels. It is important to note that the transition to a more decarbonized energy system will not happen overnight and will require significant investment in new technologies, infrastructure and energy storage solutions. Nevertheless, the benefits of decarbonization are clear and include improved air quality, reduced greenhouse gas emissions and a more stable climate.

In conclusion, decarbonization is a critical component of the energy transition and will require a mix of energy sources and technologies to be successful. The transition will require significant investment, but the benefits are clear and the need for action is urgent.

We will add some work which has been done in this area in the following sections, further exploring the various decarbonization technologies and strategies, their potential benefits and challenges and the policies and programs that are being developed to support their implementation.

A meta-analysis of scenarios simulating the German energy system looks at future natural gas use in the context of decarbonization

According to the article[26], Germany wants to cut its greenhouse gas emissions by at least 80% by 2050 compared to 1990 levels and natural gas is seen as a transitional energy source in this process. To better understand how intensity decarbonization and decarbonization tactics affect German future natural gas consumption, the study assessed 36 scenarios from 11 recent studies. According to the study, natural gas usage stays essentially constant on average as long as GHG reductions are less than 70% from 1990 levels. Yet, despite comparable reductions in GHG emissions, German natural gas consumption varies in the scenarios by up to 500 TWh/a. The adopted decarbonization strategies are what are responsible for this disparity. Natural gas consumption significantly decreases in practically all scenarios taken into consideration as GHG emission reductions are reinforced and the variances of anticipated natural gas consumptions shrink. Natural gas must be substituted in order to attain these GHG emission levels and the only scenario that permits constant natural gas consumption levels is the one that permits large-scale carbon collection and usage.

The goal of Germany's attempt to cut greenhouse gas (GHG) emissions by at least 80% compared to 1990 levels by 2050 is examined in this article. To understand how intensity decarbonization and decarbonization tactics affect German future natural gas consumption, the paper evaluates 36 scenarios from 11 recent studies. According to its findings, the average amount of natural gas consumed stays nearly constant as long as GHG emissions are reduced by less than 70% from 1990 levels. Yet, almost all scenarios see a significant decrease in natural gas use as GHG emission reductions are increased. The variations in anticipated natural gas consumptions also become less. Changes to natural gas are no longer sufficient to reach certain GHG emission limits. According to the authors, actual decarbonization solutions range from widespread electrification of the end-use industries, to massive production of renewable energy sources (such as fuel and electricity), to extensive usage of synthetic fuels. All of these decarbonization techniques lessen the need for natural gas. Only a scenario that permits large-scale carbon capture, storage or use makes it possible to maintain current levels of natural gas consumption while yet meeting ambitious GHG reduction targets.

This study looks at the medium- and long-term evolution of the German energy system in terms of how natural gas usage has changed in relation to goals for reducing GHG emissions. Low abatement and high abatement scenarios are used to categorize the circumstances under investigation. No patterns in the long-term usage of natural gas can be found in low abatement scenarios. By 2050, natural gas use will have decreased under high abatement scenarios. With higher emission reduction targets, there is a stronger correlation between the decrease in emissions and the usage of natural gas. Long-term natural gas phase-out will be required by policies aiming for high abatement levels without taking GHG emission sequestration solutions into consideration. The report emphasizes that future research in this field should consider the underlying theories and analytical techniques used, as well as the issue of how the computed transition pathways were arrived at. More investigation is required, according to the article, to determine how changes in natural gas consumption would affect investments in and finance for gas infrastructure as well as the interactions between shifting supply and demand for the fuel.

Developments and possible decarbonization paths for Oman's transportation sector's greenhouse gas emissions

This work[27] studies the greenhouse gas emissions from transportation and investigates practicable routes for carbon-neutral mobility using Oman as a sample example for the Gulf Cooperation Council (GCC) countries. According to the research, which followed IPCC recommendations, the proportion of transportation emissions in Oman's overall greenhouse gas emissions increased from 8.1% in 2000 to 16.3% in 2015. Behind the oil and natural gas (26%) and energy industries (20%), transportation emissions ranked third in Oman for overall greenhouse gas emissions. Road transportation accounted for the largest portion of the transport sector's emissions, increasing from 66% in 2000 to 92% in 2015 **(Figure 12)**. The research advises phasing out fuel subsidies, creating a dependable public transportation system organizing for the electrification of road travel and employing rail for freight transportation to reduce emissions from the Omani transportation system.

This study shows that greenhouse gas emissions from transportation have doubled in Oman between 2000 and 2015 and that road transportation is the main source of emissions. The lack of a public transportation system and the culture of private car use, encouraged by highly subsidized fuel prices, are contributing to this trend. According to the research, Oman should gradually eliminate fuel subsidies while also creating a trustworthy public transit system, electrifying its roads and using trains to convey freight in order to reduce emissions. The long-term objective should be to create a comprehensive policy that integrates urban planning and transportation system modernization to lower emissions and enhance quality of life. The report also mentions that lowering emissions can enhance the general public's health by lowering air pollution and its associated health hazards.

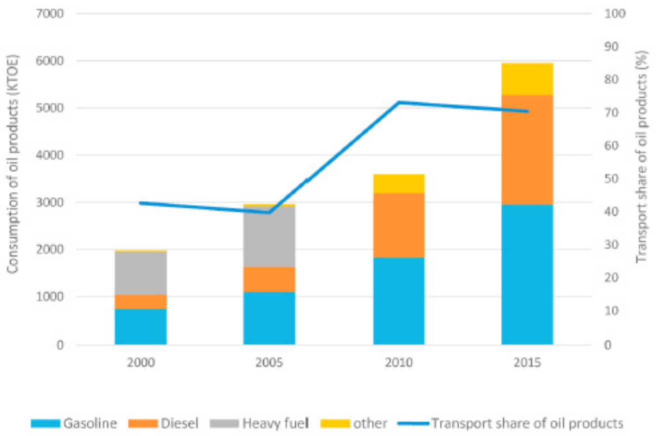

Figure 12: Use of refined oil products in Oman[27].

Industrial decarbonization with natural gas: An analysis of trends, socio-technical systems and policy choices

The function of natural gas in the worldwide industrial decarbonization process and how it might aid in decarbonizing industrial processes are both covered in the article[28]. The research gives evidence of significant impediments to industrial decarbonization via natural gas, including financial and infrastructural challenges, geopolitical and governance issues and contains a thorough and critical examination of over 400 studies on the subject. The review offers potential directions for additional study on the subject.

This paper presents a critical and systematic review of the potential for using natural gas to decarbonize industry, which is a significant source of greenhouse gas emissions. The review examines the opportunities, interventions, barriers and policies related to using natural gas in industrial processes across various sectors. The review found that natural gas is a viable option for decarbonizing industry due to its lower emissions and cost-effectiveness compared to other fossil fuels. However, there are barriers to implementation such as financing and governance issues that need to be addressed. The review also highlights the potential for using low-carbon hydrogen and carbon capture and storage (CCUS) as transformative solutions for decarbonizing industry. The paper suggests that a whole systems approach is needed to fully address the challenges of industrial decarbonization and points to future research gaps in this field.

Using synthetic methane to reduce carbon emissions in the european energy grid

The study[29] concludes that carbon pricing and power-to-gas technologies (green power-to-hydrogen followed by methanation) using captured CO_2 emissions are required to achieve deep decarbonization of energy systems. A CO_2 price of 160 euros per tonne by 2050 is found to be insufficient by the study's focus on the economics of decarbonizing the European electricity system using an energy system model. However, a CO_2 price path of 125 euros per tonne by 2040 to 160 euros per tonne by 2050 when combined with PtG technologies can result in a workable decarbonization of the European electricity system by 2050. Higher PtG expenses have little impact on the findings.

In order to decarbonize the power system by 2050, the study questions the viability and economic justification of integrating Power-to-Gas (PtG) into the energy system. The study discovered that PtG (green power to hydrogen followed by methanation with collected CO_2) and a carbon price of €160/tCO2 together would completely decarbonize the EU energy grid by 2050 and do it profitably. However, the study concluded that even under the proposed PtG regime, battery energy storage devices will remain cost-effective in 2050. The study revealed evidence in favor of the CO_2 price's effectiveness in reducing GHG emissions, however the Paris Agreement's goals cannot be met with just a carbon price of €160/tCO_2. The study concluded that long-term energy storage is required to achieve net zero GHG emissions and that the use of battery storage in conjunction with PtG would improve the utilization of renewable energy sources and reduce system costs. The results were unaffected by greater PtG costs, demonstrating PtG's excellent potential as a significant long-term energy storage system. An aggressive PtG policy is advised by the study to encourage R&D and deployment in order to save costs and accomplish technological advancements.

The study results are promising, but further research is needed in the use of hydrogen in power generation, methanation process and the role of other low CO2 technologies such as CCS or NPP. The study focuses on using synthetic methane to generate electricity, but alternative methods like using H2 directly in thermal plants and fuel cells should be studied. In many nations, there is minimal usage of hydrogen in gas networks and gas-fired power plants; more research is required. Without reference to the NPP question, the study demonstrates that investing in PtG is advised, although independent studies should be conducted to assess other technologies. The results show promise for long-term emissions storage, but the model does not account for all system components.

Political and Economic Considerations

The decarbonization of the energy sector requires not only technical solutions, but also political and economic considerations. Political support and leadership are essential for creating the policy and regulatory frameworks that will drive the energy transition. Additionally, the economic implications of the energy transition must be considered to ensure that the transition is economically viable and does not negatively impact communities or industries.

One of the key political considerations is the development of policies and regulations that promote the adoption of low-carbon energy sources and encourage the transition away from fossil fuels. This can include incentives for renewable energy development, carbon pricing and regulations on emissions from fossil fuels. From an economic perspective, the energy transition must be cost-competitive with the existing fossil fuel-based energy system. This will require significant investment in new technologies, infrastructure and energy storage solutions. Additionally, the impact of the energy transition on communities and industries that are heavily dependent on fossil fuels must be considered and addressed through policies and programs that provide support and retraining.

In conclusion, the decarbonization of the energy sector requires both political and economic considerations. Political support and leadership are essential for creating the policy and regulatory frameworks that will drive the transition and the economic implications of the transition must be considered to ensure that it is economically viable and does not negatively impact communities or industries.

We will add some work which has been done in this area in the following sections, further exploring the political and economic considerations surrounding the decarbonization of the energy sector and the policies and programs that have been developed to support the transition.

Understanding political and economic behavior in the oil and gas sector with regard to decarbonization

In order to determine how much publicly listed oil majors are decarbonizing, this study[30] examines their political and economic actions. The study gathered a variety of firm-level data from 2004 to 2019 and discovered that there is not always a correlation between a firm's political and economic activity. The study also discovered that, over the entire period examined, not a single company has switched away from fossil fuels and changes in corporate behavior have been quite minor. Instead of pursuing decarbonization, the most ambitious companies are engaging in risk mitigation through diversification and hedging. The survey also discovered that between 2010 and 2018, big oil and gas companies improved their anti-climate political positions. Companies that are making more headway in decarbonization are more likely to be based in or sell their goods to governments with stricter environmental regulations, have smaller refining industries and participate in more industry coalitions.

Three key conclusions emerged from the analysis of the political economy of the decarbonization initiatives of the oil majors: companies are not decarbonizing; instead, they are hedging, greenwashing or resisting; headquarters location matters; companies with headquarters in nations with stricter regulations are more likely to have pro-climate behavior; and some companies have improved their business practices, but primarily through a switch to gas and with little investment in renewables. The research topic is what forces would be sufficient to change the status quo of earlier decades and the methodology is generalizable to other industries. The ongoing COVID-19 dilemma, US climate policy and the impact of other businesses' activities are among the elements that could change the dynamics of decarbonization.

Global energy growth is outpacing decarbonization

CO_2 emissions from human activities have increased by 1.6% in 2017 and are expected to rise further in 2018 due to growth in oil, natural gas and the global economy. Despite some nations reducing their emissions, fossil fuels continue to be used for more energy than low-carbon alternatives. CO2 emissions will keep rising due to a healthy global economy, insufficient emissions reductions in developed nations and the need for more energy use in emerging nations. As all fossil CO2 emissions start to drop and are replaced by low-carbon technology, emissions will peak[31].

Due to predictions of ongoing economic expansion, including 6-8% in India and China and 2.5% in the United States, peak CO_2 emissions and a decline in world emissions are unlikely to happen very soon. We will be further away from the UN Framework Convention on Climate Change's objective to stabilize greenhouse gas concentrations and prevent harmful interference with the climate system as a result of this rise, which is predicted to result in an increase in CO_2 emissions.

Offering fossil fuel alternatives in a world that is trying to reduce carbon emissions

Due to its involvement in numerous ecological issues and relationship to the fossil-based energy system, the petrochemical industry is under pressure to change. This study[32] looks at how petrochemical corporations respond to these challenges by realigning their narratives, a subtle exercise of corporate discursive power that reframes the issues and potential solutions associated with transitions to a greener economy. In this paper, major petrochemical producers' communications on climate change and sustainability are analyzed and it is argued that these narratives emphasize the importance of the petrochemical sector for a smooth transition while downplaying criticism by characterizing it as the result of misunderstandings. By situating the industry as a component of the solution, this framing helps to ease the demand for deep mitigation. The argument demonstrates how narratives of petrochemical transition are comparable to but distinct from those of fossil fuel extractors and illustrates how downstream actors strive to legitimate the current energy regime.

Due to the petrochemical industry's crucial role in the fossil-based energy system and its involvement in numerous ecological issues, there is growing pressure on it to change. In order to navigate these challenges, petrochemical companies must actively promote strategic narratives that link their present and future operations to sustainability and decarbonization objectives. This is what this article examines. These narratives, also known as narrative realignment, contrast with the perspective of fossil fuel extractors by portraying the petrochemical industry as essential to a sustainable future. The employment of narrative realignment is an instance of discursive power intended to preserve advantageous socio-technical setups and increase the likelihood of "infinite" plastic futures. In order to fight the expansion of petrochemicals and solve current disparities in power consumption and distribution, the report advocates for future research that will evaluate the function of narrative realignment across industries that use a lot of energy. The conflict over the petrochemical industry's future is equally a conflict over the future of consumption.

Decarbonization and Renewable Energy

Decarbonization and renewable energy are two interrelated concepts that are crucial in the transition towards a more sustainable energy future. Decarbonization refers to the reduction of carbon emissions from energy production and use, while renewable energy refers to energy sources that are replenished naturally and do not emit carbon dioxide during operation.

Renewable energy sources, such as wind, solar and hydro power, play a crucial role in the decarbonization effort. They provide low-carbon electricity and help to reduce emissions from the energy sector. The use of renewable energy has increased significantly in recent years, driven by technological advances and declining costs. However, the widespread adoption of renewable energy is not without its challenges. One of the main challenges is the intermittency of renewable energy sources, which can make it difficult to ensure a consistent supply of electricity. This can be addressed through the development of energy storage solutions, such as batteries and pumped hydro storage. Another challenge is the cost of renewable energy, which must be cost-competitive with traditional fossil fuel-based energy sources in order to drive widespread adoption. This requires significant investment in new technologies, infrastructure and energy storage solutions.

In conclusion, renewable energy is a key component of the decarbonization effort and will play a crucial role in the transition to a more sustainable energy future. The challenges associated with renewable energy must be addressed through investment in new technologies, infrastructure and energy storage solutions. This will ensure that renewable energy becomes an increasingly important part of the energy mix and helps to achieve significant decarbonization.

We will add some work which has been done in this area in the following sections, further exploring the development and deployment of renewable energy technologies, the challenges associated with their integration into the energy mix and the policies and programs that have been developed to support their growth.

Geothermal potential evaluation for italian oil and gas fields: Toward a decarbonized era

This study's[33] objective is to calculate the geothermal potential that is still present in Italy's exhausted oil and gas sources. The study chose five promising fields based on information from the Ministry of Economic Development, publicly available data on hydrocarbon fields and the Italian National Geothermal Database. Their potential was evaluated using the volume method and a probabilistic method was applied to get a range of technical potential values. The findings indicate that there is considerable heat present in the hydrocarbon fields and it is crucial to examine current wells to ascertain the potential applications for this heat.

The objective of this study[33] is to evaluate the geothermal potential of Italy's depleting oil and gas resources. The volume technique was used to assess the geothermal potential of five fields. To get a distribution of values for the technical potential, a probabilistic approach was used (TP). The positive findings imply that harvesting the heat resource by reusing existing wells is doable. To determine the level of uncertainty around the study of the prospective assessment, a probabilistic approach was applied. The parameters that are affected by uncertainty are listed together with the related uncertainty range and distribution function.

The analysis summarizes the results of the evaluation of the recoverable heat stored in discovered hydrocarbon fields. The conventional representation of the probability expectation was used to summarize the results in **(Table 6)**, with a broad range of probability distribution. The preliminary analysis suggests that the available heat is significant, but a more accurate evaluation would require production data and petrophysical parameters like permeability. Previous works have shown that field-specific analyses can provide more detailed results, as demonstrated by Alimonti and Gnoni (2015) for the Villafortuna-Trecate well where the thermal power per well was estimated to be between 3 and 5 MW. Nevertheless, only a small portion of the heat that is accessible can be extracted from existing wells. Borehole heat exchanger technology was assessed by Alimonti and Soldo (2016) for the Villafortuna-Trecate field, where the heat extraction with a circulation water of 15 m3/h was predicted to be roughly 800 kW. This is an alternate method for harvesting the available heat.

The present paper explores the possibility of a decarbonized future through the repurposing of oil & gas fields for geothermal energy production. Based on data from the Italian Ministry of Economic Development, academic literature and the Italian National Geothermal Database, 42 sectors have been selected as the most suitable for repurposing. Using the volume method, the geothermal potential of 5 representative depleted oil and gas fields has been evaluated. With a range of 388-1330 MW for the Villafortuna-Trecate field and 2.1-14.6 MW for the Dosso degli Angeli field, the data point to an excellent technological potential for geothermal energy generation. The study also includes a probabilistic approach to overcome uncertainty in the reservoir parameters. The results are promising and suggest that the geothermal technical potential stored in the Italian oil & gas fields is significant.

Decarbonization: The next 100 years

In an essay from 1961, Alvin Weinberg wrote that the 20th century would be remembered for its large-scale scientific accomplishments (referred to as "Big Science"). Five years later, he introduced the term "technological fix" to describe engineering solutions for society's problems. Today, the author wants to discuss decarbonization, a significant challenge that requires both "Big Science" and two big technological solutions: Zero Emission Power Plants and the Continental SuperGrid.

The evolution of the energy system is marked by replacements of existing technologies with better and more efficient ones. The global energy system has been evolving towards hydrogen but needs to speed up to address climate change. Decarbonization requires big technological fixes such as Zero Emission Power Plants (ZEPPs) and the Continental SuperGrid. ZEPPs and SuperGrid will bring economic benefits to companies and nations and recognition to engineers, scientists and their institutions. The time has come to take bold steps to address the challenge of decarbonization[34].

Socioeconomic Impacts of Decarbonization

The transition towards decarbonization has significant socio-economic impacts that must be considered. While the benefits of decarbonization include improved air quality, reduced greenhouse gas emissions and reduced dependence on finite energy sources, the transition also has the potential to negatively impact communities and industries that are heavily dependent on fossil fuels.

One of the main socio-economic impacts of decarbonization is the potential for job losses in the fossil fuel industry. This includes jobs in the extraction, production and transportation of fossil fuels, as well as jobs in related industries such as manufacturing and engineering. To address this, policies and programs that provide support and retraining for workers in affected industries must be developed. Another impact of decarbonization is the potential increase in energy costs. The transition to low-carbon energy sources can increase the cost of electricity, particularly in the short-term, as the infrastructure and technology required to support the transition are developed. This must be considered when developing energy policy and regulation and measures must be put in place to ensure that the transition is economically viable for communities and businesses.

In addition to the direct impacts, the transition to decarbonization also has indirect impacts on the economy, including changes to trade and investment patterns, changes in energy prices and the development of new industries and technologies.

In conclusion, the transition towards decarbonization has significant socio-economic impacts that must be considered. These impacts include job losses in the fossil fuel industry, potential increases in energy costs and indirect impacts on the economy. Policies and programs that provide support and retraining for workers in affected industries and that ensure that the transition is economically viable must be developed to mitigate these impacts.

We will add some work which has been done in this area in the following sections, further exploring the socio-economic impacts of decarbonization and the strategies and policies that have been developed to address them.

Finding the effects of china's power system decarbonization on society and economy

The study[35] combines a multiplier acceleration model with a multi-regional input-output model to assess how decarbonizing China's power industry will affect the country's economy, employment and greenhouse gas emissions. The results show that increasing the use of clean power will significantly decrease GHG emissions, but without proper socioeconomic policy, this transition may not be beneficial for the economy and employment. In 2050, decarbonization will lead to a decrease in GHG emissions by 89.65%, but it will also result in job losses for 2.04 million workers in the fossil fuel power sector and 19.18 million workers in other sectors such as construction, machinery manufacturing, chemicals and coal mining. The results also show that middle-skilled workers will be the most affected and that males will be impacted more than females. Although the industry of renewable energy is expected to provide 110.69 billion euros to economic growth, the shift is expected to result in a 209.36 billion euro overall economic loss. The study argues that in order to achieve sustained socioeconomic development during the transition to decarbonization, the government and policy makers should concentrate on long-term economic stimulus programs and worker education.

The study analyzes the socio-economic impact of China's power decarbonization efforts in 2030 and 2050. The findings show that while clean power decreases greenhouse gas emissions, without proper socioeconomic policies, this transition may negatively impact the economy and employment. The results also show that renewable power creates new jobs, but also leads to job losses in traditional industries. The results highlight the need for long-term economic stimulus policies and worker education to ensure sustainable socio-economic development during the transition to clean power. The study also touches on the impact of China's decarbonization on the emissions reduction effort globally and the trade-off between decarbonization and socio-economic sustainability goals.

According to the study's findings, decarbonization solutions can successfully lower GHG emissions, which is in line with earlier studies. China, the world's largest coal-fired power producer, will cut its GHG emissions by 41.11% as a result of decarbonization. 86.97% of the world's coal-fired power is generated by the top 10 countries, whose decarbonization will result in a reduction of 37.52% in emissions. In terms of reducing emissions, China comes in third. The minimal impact of emission reduction in Russia is a result of the decarbonization strategy's inclusion of natural gas-fired power as a source of GHG emissions. The study concluded that while electricity decarbonization is a good strategy to cut carbon emissions, it is insufficient to reach carbon neutrality targets and that additional emissions reduction measures, such energy efficiency and carbon sinks, are required in a variety of sectors and businesses.

This study looks at the comprehensive employment impact of replacing fossil fuel electricity with renewable electricity. The indirect effects are found to be much higher than the direct effects in the power sector. China's employment losses from power decarbonization are lower than the global average, but behind most developed countries. Decarbonization brings economic loss, with developed economies experiencing a higher economic loss than developing economies. The study has limitations as it does not consider the emerging new industries from the shift in power structure and the decarbonization process in a dynamic temporal perspective.

The study examined the advantages of China's power grid decarbonization. As a result of decarbonization, GHG emissions can be drastically reduced by 41.11% when compared to 2015. Future socioeconomic development is not hampered by the electricity system's decarbonization; however, job losses may occur. Although China's employment loss is lower than that of most developing nations, it nevertheless disproportionately affects workers with middle-skill levels. When promoting renewable energy and ensuring sustainable socioeconomic growth, policymakers should take the influence on full employment into account. While underdeveloped nations must concentrate on social re-employment initiatives, developed nations should concentrate on economic stimulus measures. It is also emphasized how important it is to incorporate supporting policies with decarbonization measures.

An investigation of canadian support for climate policy

Homeowners in Canada are more likely to accept voluntary decarbonization initiatives like financing and subsidy schemes for low-carbon heating technology (64-82%) than mandatory initiatives like carbon taxes and renewable natural gas mandates (38-49%). Altruistic ideals, concern for climate change, faith in scientists, favorable opinions of heat pumps and higher education are traits that are consistently linked to support for the majority of decarbonization programs. According to cluster analysis, respondents can be categorized into three groups: those who support all decarbonization measures (43%), those who support voluntary policies only (37%) and those who reject all decarbonization policies (20%).

According to the study[36], carbon taxes is opposed by 33% of Canadian homeowners, whereas home decarbonization programs with subsidies are supported by 80-82% of them. The study also discovered that support for certain policies, such as education and subsidies, differs between the decarbonization of heating and personal transportation. Support for the majority of home decarbonization initiatives is consistently correlated with five traits, including altruistic beliefs and favorable opinions of heat pumps. Based on their support for house decarbonization measures, Canadian homeowners were classified into three distinct categories in the study: 43% support all policies, 20% support none and 37% favor just voluntary initiatives. The findings imply that mandatory policies are required to reduce emissions, that confidence in scientists is more consistently associated with support for policies than confidence in the government and that when developing home decarbonization policies, particular relationships between individual characteristics and particular policy types should be taken into account.

A comprehensive analysis of the canadian oil sands' profound decarbonization options

The study[37] looks at the future of Canada's oil sands industry, which is responsible for the third-largest oil reserves in the world, in light of the Paris Agreement's net-zero emissions objective for the nation by 2050. The study examines the effects on oil sands output of several mitigation scenarios with differing global net-zero GHG emission limitations, lower carbon extraction technologies and deployment of direct air capture. According to the findings, under various net-zero emissions scenarios, the use of lower carbon technology and direct air capture increases oil sands production by 20% to 44% by 2050. The development of negative emissions technology, the availability of reduced carbon technologies and global oil demand all play a role in the future of oil sands production.

The Global Change Analysis Model has been used in a study to examine Canada's oil sands production under various decarbonization and technological scenarios (GCAM). The study discovered that Canadian oil sands production is heavily reliant on global demand and technology advancements in ambitious mitigation scenarios. The production of oil sands would be dependent on the availability and viability of Direct Air Capture (DAC) technology if the world achieves net-zero emissions by 2050. Oil sands production might reach 8 EJ in 2050 if DAC is made available. Through the middle of the century, lower carbon extraction technologies can assist lower emissions intensity while maintaining significant output levels. The report emphasizes the erratic nature of the demand for Canadian oil sands in the future and the potential importance of particular technologies in a decarbonized environment.

Conclusion

In conclusion, decarbonization of the oil and gas industry is a critical aspect of mitigating the effects of global warming. The industry has several pathways and strategies to adopt to achieve this goal, including whole economy deep decarbonization, decarbonization roadmaps, decarbonization via local production of hydrogen and decarbonizing remote microgrids. The economic and technological feasibility of these pathways was analyzed, as well as their potential impact on the environment and industry operations. Additionally, CO2-EOR was seen as a potential near-term solution for decarbonization, with the use of renewable energy sources also playing a role in the future of the industry. Political and economic considerations, as well as the socioeconomic impacts of decarbonization, must also be considered. Ultimately, the industry must work towards a decarbonized future, balancing the needs for energy growth with the goals of sustainability and environmental protection.

CRediT authorship contribution statement

Ekrem ALAGOZ: Conceptualization, resources, visualization, review and editing. **Emre Can DUNDAR:** Conceptualization, resources, visualization, review and editing. Yasin OZKAN: Conceptualization, formal analysis, investigation, methodology, resources, visualization, writing the original and revised manuscript.

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