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INTERNATIONAL COOPERATION FOR SELECTIVE CONVERSION OF CO_2 INTO METHANOL UNDER SOLAR LIGHT

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PROJECT SUMMARY

This report is part of the deliverables from the project "METHASOL" which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101022649.

Methanol is an appealing energy vectors, with attractive volumetric and gravimetric energy values, storable in liquid phase at ambient conditions of pressure and temperature, and that can be used as fuel directly or converted into chemicals or gasoline. However, its production lacks a sustainable route. Thus, the METHASOL project aims to produce methanol through a sustainable and cost-effective process based on the selective visible light driven gas phase CO_2 reduction, with a solar to methanol energy conversion efficiency of 5%. During 42 months, METHASOL will gather 14 partners from EU/Associated MS, China and the USA, including some of the world's most recognized researchers on artificial photosynthesis, to achieve a ground-breaking combination of a CO_2 reduction reaction (CO_2RR) system based on Metal-Organic Framework (MOF) and a graphitic Carbon Nitride (g-CN) for photocatalytic oxygen evolution reaction (OER), through a Z-scheme heterojunction. Following the definition of the system specifications (WP1), a first set of materials for OER and CO_2RR will be synthesised and their photocatalytic activity and stability will be screened (WP2). The most promising materials will be further analysed thanks to experimental characterisation and modelling (WP3), leading to guidelines used for designing an enhanced CO_2RR and OER materials (WP4). The best systems will then be integrated through a Z-scheme heterojunction, either with or without a mediator, and tested in tailored reactors operating in the gas phase under different conditions (WP5). A complete sustainability analysis will be conducted (WP6) to ensure the clean production of methanol. The cooperation between European and Chinese research entities will be consolidated to last beyond the project lifetime through the creation of a common exploitation plan (WP7). Through its ambitious activities on photocatalyst developments for solar to methanol conversion, METHASOL will propose a new path for decarbonizing Europe.

More information on the project can be found at https://www.methasol.eu.

OBJECTIVE AND EXECUTIVE SUMMARY

The objective of this report is to provide an overview of the sustainability criteria for selecting industrial site locations for the production of methanol via carbon dioxide reduction using solar energy. The report will highlight the importance of sustainable production and sustainability assessment in evaluating the environmental, economic, and societal impacts of the production process.

Methanol production via carbon dioxide reduction using solar energy has gained attention as a potential pathway for sustainable methanol production. However, to ensure sustainable production, it is essential to consider the environmental, economic, and societal impacts of the production process. Therefore, this report highlights the importance of sustainable production and sustainability assessment, which involves evaluating the sustainability performance of the production process against sustainability criteria. In addition, the report emphasizes the need to consider sustainability criteria while selecting industrial site locations for methanol production, including environmental responsibility, social equity, and economic viability. The report also discusses the principles of sustainable production and the life cycle approach to ensure that the production process is environmentally responsible, socially equitable, and economically viable throughout its entire life cycle.

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2	MAX-PLANCK-GESELLSCHAFT ZUR FORDERUNG DER WISSENSCHAFTEN EV	MPIKG	Germany
3	Wuhan University of Technology	WHUT	China
4	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	CNRS	France
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13	METHANOL INSTITUTE	MI	United States
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ABBREVIATIONS

CO_2	Carbon Dioxide
H_2	Hydrogen
O_2	Oxygen
CH_3OH	Methanol
H_2O	Water
CO_2RR	CO_2 reduction reaction

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1. INTRODUCTION

Methanol (CH_3OH), a versatile chemical compound used as a building block in various industrial processes, can be produced from carbon dioxide (CO_2) using solar energy, which has gained attention as a potential pathway for sustainable CH_3OH production (Kim et al. 2011). This process involves capturing and utilizing CO_2, a greenhouse gas that contributes to climate change, as a feedstock for CH_3OH production, which can help to prevent greenhouse gas emissions and contribute to the circular economy by utilizing waste CO_2 (Do and Kim 2019). However, like any industrial process, the production of CH_3OH from CO_2 using solar energy requires a careful assessment of its sustainability performance. Sustainability assessment is a systematic approach to evaluating the environmental, social, and economic impacts of a process or product to determine its sustainability performance (Rafiaani et al. 2018). In the case of CH_3OH production from CO_2 using solar energy, a sustainability assessment can provide valuable insights into the potential benefits and challenges of this process in terms of sustainability and guide decision-makers toward more sustainable practices. This report provides an overview of the sustainability assessment of CH_3OH production from CO_2 using solar energy, highlighting the key aspects and considerations involved in evaluating its sustainability performance.

1.1. SUSTAINABLE PRODUCTION

Sustainable production refers to the manufacturing or production of goods and services in a manner that minimizes negative impacts on the environment, society, and economy while maximizing positive contributions to sustainability (Su et al. 2022). It involves adopting environmentally responsible, socially equitable, and economically viable practices throughout the production process, from raw material extraction to product manufacturing, distribution, and end-of-life management (Veleva and Ellenbecker 2001, Krajnc and Glavic 2003).

There are several key principles that guide sustainable production, including:

- **Environmental responsibility:** Sustainable production seeks to minimize the use of natural resources, reduce energy consumption, minimize pollution, and manage waste and emissions in a responsible manner. This includes adopting resource-efficient technologies, using renewable energy sources, promoting circular economy practices such as recycling and upcycling, and minimizing the use of toxic materials.

- **Social equity:** Sustainable production promotes fair labor practices, social inclusion, and respect for human rights. This includes providing safe and healthy working conditions, fair wages, equal opportunities for all workers, and respecting the rights and well-being of local communities and indigenous peoples.

- **Economic viability:** Sustainable production aims to ensure the economic viability and long-term profitability while considering the costs and benefits to society as a whole. This involves optimizing production processes, reducing waste and inefficiencies, and fostering economic development that is inclusive and sustainable in the long term.

- **Life cycle approach:** Sustainable production should take the perspective of the entire life cycle of a product, from raw material extraction, manufacturing, distribution, use, and end-of-life management. It aims to minimize the environmental, social, and economic impacts at each stage of the product's life cycle and promote sustainable practices throughout.

- **Stakeholder engagement:** Sustainable production involves actively engaging stakeholders, including employees, local communities, consumers, suppliers, and other relevant parties, in decision-making processes and considering their perspectives and feedback. This promotes transparency, accountability, and mutual understanding among stakeholders.

Sustainability assessment plays a critical role in evaluating and guiding sustainable production practices. It involves the use of various tools, methodologies, and indicators to measure and assess the environmental, social, and economic impacts of production processes, products, or services against sustainability criteria. This assessment can help identify areas for improvement, set targets, and guide decision-making toward more sustainable production practices that align with sustainability principles.

In conclusion, sustainable production is an approach to manufacturing or production that considers the environmental, social, and economic impacts of goods and services and aims to minimize negative impacts while maximizing positive contributions to sustainability. Sustainability assessment is a valuable tool for evaluating and guiding sustainable production practices, ensuring that production processes are conducted in a manner that is environmentally responsible, socially equitable, and economically viable, contributing to a more sustainable and resilient future.

2. SUSTAINABILITY CRITERIA

The sustainable production of CH_3OH via CO_2 reduction using solar energy involves considerations of environmental, economic, and societal criteria to ensure that the production process is environmentally responsible, economically viable, and socially beneficial (Crivellari et al. 2021). The next sections describe the important aspects to evaluate the sustainability of CH_3OH production via CO_2 reduction using solar energy for the three sustainability pillars: environmental (2.1), economic (2.2.) and social (2.3).

2.1 ENVIRONMENTAL

2.1.1. THE SOURCE OF FEEDSTOCK

The feedstock for CH_3OH production from CO_2 reduction using solar energy typically comes from the CO_2 captured from various sources, such as industrial emissions, flue gases, or directly from the atmosphere using a process called direct air capture (DAC) (Prats-Salvado, Monnerie and Sattler 2021). The captured CO_2 is then combined with hydrogen (H_2) or other reducing agents to undergo a chemical reaction that results in the production CH_3OH.

The sources of feedstock for CH_3OH production from CO_2 reduction using solar energy can include:

- **Renewable hydrogen (H2)**: The renewable hydrogen produced through water electrolysis using electricity generated from solar energy or other renewable energy sources can be used as a feedstock for methanol production (Williams 2018). Water electrolysis splits water into hydrogen and oxygen using an electric current, and the hydrogen can be combined with captured CO_2 to produce methanol.

- **Renewable electricity**: Solar energy, as well as other forms of renewable electricity such as wind, hydro, or geothermal, can be used to power methanol production from CO_2 reduction. Renewable electricity can provide the energy required to convert captured CO_2 into methanol through various catalytic or electrochemical processes (Renewable Methanol Report, Methanol Institute, 2023).

- **Captured CO_2 from air or flue gases**: CO_2 can be captured directly from the air or from the flue gases emitted by industrial processes or power plants. Direct air capture (DAC) technologies use specialized equipment to capture CO_2 from the atmosphere, and the captured CO_2 can then be utilized as a feedstock for methanol production using solar energy (Sollai et al. 2023).

It's important to note that the availability and viability of different feedstocks for methanol production from CO_2 reduction using solar energy can depend on factors such as technological advancements, cost-effectiveness, and regulatory frameworks. The field of methanol production from CO_2 reduction using solar energy is still an area of active research and development, and the availability and suitability of specific feedstocks can vary depending on the specific process, location, and economic factors. Consulting reliable sources, such as scientific literature, technical reports, and reputable publications from Methanol Institute (MI), is recommended for accurate and up-to-date information on feedstocks used in methanol production from CO_2 reduction using solar energy.

2.1.2. THE QUANTITY OF EMISSIONS

Methanol production from carbon dioxide (CO_2) reduction using solar energy is generally considered a low-carbon or even a carbon-neutral process, as it involves utilizing CO_2 as a feedstock and converting it into a value-added product (methanol) using renewable solar energy (Kim et al. 2011). However, it is important to note that the emissions associated with methanol production from CO_2 reduction can vary depending on the specific process, technology, and conditions used.

In general, the emissions associated with methanol production from CO_2 reduction using solar energy can come from several sources, including:

- **Energy source**: The production of solar energy for methanol production may require energy-intensive processes for capturing, converting, and utilizing solar energy. The emissions associated with the production of solar energy can vary depending on the type of solar technology used (e.g., photovoltaic or concentrated solar power), the efficiency of the solar panels, the manufacturing processes, and the geographic location of the solar facility.
- **Feedstock source**: The capture and collection of CO_2 from air or flue gases may require energy-intensive processes such as direct air capture (DAC) or CO_2 separation from industrial emissions (Sollai et al. 2023). The emissions associated with these processes can depend on the specific technology used, energy requirements, and efficiency.
- **Methanol production process**: The process used for converting CO_2 into methanol using solar energy can also generate emissions (Steinberg 1998). This may include the use of catalysts, reactors, and other equipment that require energy and materials for their production and operation.
- **Upstream emissions**: Methanol production from CO_2 reduction may also depend on the production of hydrogen (H_2) as a reducing agent (Boretti 2013). The production of hydrogen can involve emissions if it is sourced from fossil fuels or if renewable hydrogen production processes generate emissions during production.

It is important to note that the quantity of emissions associated with methanol production from CO_2 reduction using solar energy can vary significantly depending on the specific technologies and processes used, as well as the efficiency and scale of the production facility. The goal of methanol production from CO_2 reduction using solar energy is to minimize or eliminate emissions by utilizing renewable energy sources and converting CO_2 into a valuable product.

2.2. TECHNOLOGICAL

2.2.1. ENERGY REQUIREMENTS

The energy requirements for CH_3OH production can vary depending on the specific production process used, as well as the energy sources and feedstocks used.

The production of CH_3OH typically involves the conversion of natural gas or coal into synthesis gas (syngas), which is then catalytically converted into CH_3OH. The energy requirements for this process can be significant, as both the conversion of the feedstock into syngas and the conversion of syngas into CH_3OH require high temperatures and pressures. The energy requirements for the production of CH_3OH from natural gas can vary depending on the efficiency of the conversion process, the purity of the natural gas feedstock, and the energy sources used to power the process. According to the International Energy Agency, the energy required to produce one tonne of CH_3OH from natural gas can range from 28 to 39 gigajoules (GJ) per tonne, depending on the production process and the energy sources used (Renewable Energy Agency, 2013).

The energy requirements for the production of CH_3OH from coal can also vary depending on the quality of the coal, the efficiency of the conversion process, and the energy sources used to power the process. According to the World Coal Association, the energy required to produce one tonne of CH_3OH from coal can range from 29 to 33 GJ per tonne (Khalafalla et al. 2020).

The solar energy requirement to produce CH_3OH from CO_2 reduction by photocatalysis depends on the efficiency of the system. Solar energy can be used to power photocatalytic reactors, and the system's efficiency is typically around 5–15% (Kim et al. 2011). Therefore, the solar energy requirement to produce CH_3OH from CO_2 reduction by photocatalysis is typically around 65–195 kWh per kg of CH_3OH produced (Tountas et al. 2019).

In addition to the energy required for the production process itself, energy is also necessary for the transport and storage of feedstocks and products and the operation of ancillary equipment such as pumps, compressors, and boilers.

2.2.2. AVAILABILITY OF THE RENEWABLE ENERGY

Renewable energy can be used to power CH_3OH production from CO_2 reduction, also known as renewable CH_3OH production (Roode-Gutzmer, Kaiser and Bertau 2019). This process involves using renewable energy sources, such as solar, wind, or hydropower, to power H_2O electrolysis to produce H_2 and O_2. The H2 is then reacted with CO_2 to produce CH_3OH (Monnerie et al. 2020).

The availability of renewable energy sources for renewable CH_3OH production can vary depending on the region and the specific energy source used. For example, areas with abundant solar or wind resources may be able to produce renewable CH_3OH using these sources. Hydropower can also produce renewable CH_3OH in regions with suitable H_2O resources.

Renewable CH_3OH production has the potential to play an essential role in the transition to a low-carbon economy, as it allows for the production of carbon-neutral fuel using renewable energy sources. In addition to its use as a fuel, renewable CH_3OH can also be used as a feedstock for producing chemicals and other products.

However, it is essential to note that the availability of renewable energy sources for CH_3OH production from CO_2 reduction is limited by the intermittency of some renewable energy sources, such as solar and wind.

This can be addressed through energy storage systems, such as batteries or H_2 storage, or other renewable energy sources, such as geothermal or biomass.

Overall, the availability of renewable energy sources for CH_3OH production from CO_2 reduction depends on the specific region and energy source used. Still, renewable CH_3OH production has the potential to be an essential part of a low-carbon future.

Renewable energy, specifically solar energy, can be a viable option for powering the process of CH_3OH production from CO_2 reduction. Solar energy can be harnessed through photovoltaic (PV) panels or concentrated solar power (CSP) systems to generate electricity, which can then be used for the electrolysis of H_2O to produce H_2, and subsequently, CH_3OH from the reduction of CO_2 (Alsayegh et al. 2020).

The availability of solar energy for CH_3OH production from CO_2 reduction using solar would depend on several factors:

- **Geographic location**: The availability of solar energy varies depending on the geographic location of a particular region. Areas with high solar irradiation, such as deserts and regions closer to the equator, generally have higher solar energy potential (Gagnon et al. 2016).
- **Local climate**: Solar energy availability can also be influenced by local weather patterns and climate conditions, such as cloud cover, precipitation, and seasonal variations. Regions with consistent sunlight throughout the year would have higher solar energy availability for methanol production.
- **Solar technology efficiency**: The efficiency of solar technologies, such as PV panels and CSP systems, can also affect the availability of solar energy for methanol production (Alsayegh et al. 2020). Advancements in solar technology have improved the efficiency of solar panels, allowing for higher energy generation from sunlight.
- **Time of day and season**: The availability of solar energy for methanol production would also depend on the time of day and season. Solar energy is available only during daylight hours, and its availability can be affected by factors such as latitude, tilt angle, and orientation of the solar panels.
- **Energy storage capabilities**: Methanol production from CO_2 reduction using solar energy may require energy storage capabilities to store excess solar energy for use during periods of low solar irradiation. The availability of efficient and cost-effective energy storage technologies, such as batteries or other forms of energy storage, would impact the availability of renewable energy for methanol production.
- **Government policies and incentives**: Government policies and incentives that promote the use of renewable energy, such as solar energy, can also affect its availability for methanol production. Supportive policies, such as feed-in tariffs, tax incentives, and renewable energy targets, can encourage the development and utilization of solar energy for methanol production.

A thorough assessment of these factors is necessary to determine the feasibility and availability of renewable energy for methanol production using solar energy in a particular location.

2.2.3. CO_2 SOURCE AS SINGLE STREAM

The availability of CO_2 as a single stream depends on various factors, including the location, type of CO_2 source, and the specific capture technology used. In general, CO_2 can be found in different concentrations in the atmosphere and industrial emissions. The availability of CO_2 as a single stream for CH_3OH production depends on the concentration and accessibility of these sources.

In the atmosphere, CO2 is present in trace concentrations, typically around 400 parts per million (ppm) by volume (Sodiq et al. 2023, Maier 2015). Direct air capture (DAC) technologies are capable of capturing CO2 from the ambient air. Still, the concentration of CO_2 in the atmosphere is relatively low, which means that large volumes of air need to be processed to obtain a significant amount of CO2 as a single stream for CH_3OH production.

On the other hand, industrial emissions from processes such as power plants, cement plants, and other industrial facilities can contain higher concentrations of CO2, making them potentially more suitable as a single stream for CH_3OH production (Khojasteh-Salkuyeh et al. 2021). However, the availability of CO_2 as a single stream from industrial emissions depends on the specific industrial processes, the location and size of the emissions source, and the regulatory and economic factors governing CO_2 emissions capture.

It is important to note that the availability of CO_2 as a single stream for CH_3OH production is subject to environmental regulations, economic feasibility, and sustainability considerations. The capture of CO2 from the atmosphere or industrial emissions requires energy and resources (Sodiq et al. 2023, Khojasteh-Salkuyeh et al. 2021). The overall sustainability and feasibility of the process need to be carefully assessed, considering the factors such as energy requirements, economic viability, environmental impact, and potential competition with other uses of CO_2, such as for carbon capture and storage (CCS) or other applications.

2.3. ECONOMIC

2.3.1. SUNLIGHT POTENTIAL

The amount of sunlight required to reduce CO_2 to CH_3OH through photocatalysis depends on several factors, including the type of photocatalyst used, the intensity and wavelength of the light, and the reaction conditions, such as temperature and pressure.

In general, photocatalytic CO_2 reduction efficiency is relatively low, with reported solar-to-fuel conversion efficiencies ranging from a few percent to about 15% (Zhu et al. 2020). This means that a significant amount of sunlight is required to produce a meaningful amount of CH_3OH.

For example, a recent study reported that the solar energy required to produce 1 kg of CH_3OH through photocatalytic CO_2 reduction using TiO_2 as the photocatalyst was estimated to be around 600-800 kWh (Rehman et al. 2022). This is equivalent to several days of continuous sunlight, depending on the location and time of year.

In addition, solar energy potential varies depending on the location, season, and weather conditions. According to the National Renewable Energy Laboratory (NREL) in the United States, the average solar energy potential for the contiguous United States is about 4-6 kilowatt-hours per square meter per day (kWh/m^2/day) (Gagnon et al. 2016, Average Annual Daily Potential Solar Energy, 2015). However, it can be higher in sunnier regions such as the southwestern states. In other parts of the world, solar energy potential can vary widely, ranging from 3-7 kWh/m^2/day in Europe, 4-6 kWh/m^2/day in China, and 5-7 kWh/m^2/day in parts of the Middle East.

Therefore, while sunlight has the potential to be used as a renewable source of energy for CH_3OH production through photocatalysis, significant improvements in the efficiency of this process are needed to make it economically viable on a large scale.

2.3.2. THE QUANTITY AND MARKET OF PRODUCTS AND BY-PRODUCTS

To production of CH_3OH by photocatalysis involves using light to drive the conversion of CO_2 and H_2O into CH_3OH and O_2 (Alsayegh et al. 2019). The process can also result in the generation of other products and by-products, which can vary depending on the specific process conditions and the efficiency of the photocatalytic reaction.

- **METHANOL (CH_3OH):** Methanol is the main product of CH_3OH production by photocatalysis. It is a colorless liquid that can be used as a chemical feedstock in various industries, including the production of formaldehyde, acetic acid, and other chemicals, as well as a fuel in fuel cells and as a potential renewable energy carrier.
- **OXYGEN (O_2):** Oxygen gas is produced as a by-product of the photocatalytic reaction, as H_2O is split into H_2 and O_2 during the process. Oxygen is a valuable gas with various industrial applications, including in combustion processes, medical applications, and as a feed gas for chemical reactions.
- **Formic acid (HCOOH):** Formic acid is a common by-product of CH_3OH production by photocatalysis. It is produced by the oxidation of CH_3OH under certain reaction conditions or by the decomposition of intermediate species during the photocatalytic reaction. Formic acid can be used as a chemical feedstock and a reducing agent in various chemical processes.
- **Carbon monoxide (CO):** Carbon monoxide is another potential by-product of CH_3OH production by photocatalysis. It can be formed as a result of competing reactions during the photocatalytic process. Carbon monoxide is a toxic gas but can also be used as a reducing agent in certain chemical reactions.
- **Hydrogen gas (H_2):** Hydrogen gas is also a potential by-product of CH_3OH production by photocatalysis. It can be formed as a result of competing reactions during the photocatalytic process, especially when H_2O is used as a source of H_2. Hydrogen is a valuable gas with various applications, including fuel in fuel cells and industrial processes.

The quantity and market of these products and by-products from CH_3OH production by photocatalysis can vary depending on the specific process conditions, the efficiency of the photocatalytic reaction, and the intended end use.

2.3.3. THE DEMAND FOR CH_3OH END-USE

The demand for CH_3OH as an end-use product varies depending on regional and global market dynamics, economic conditions, government policies, and technological advancements. Here are some general statistics on the demand for CH_3OH in various end-use applications:

- **Formaldehyde and Resins:** CH_3OH is a critical raw material for the production of formaldehyde, which is used in the production of resins, plastics, textiles, and other products. According to a report by Grand View Research, the global formaldehyde market was valued at USD 11.5 billion in 2020 and is projected to reach USD 16.2 billion by 2028, growing at a CAGR of 4.5% from 2021 to 2028 (Grand View Research).
- **Fuels and Energy:** CH_3OH is used as a fuel or fuel additive in various applications. According to a report by Future Market Insights, the global CH_3OH market for fuels and energy was valued at USD

26.8 billion in 2020 and is expected to reach USD 45.6 billion by 2031, growing at a CAGR of 5.1% from 2021 to 2031 (Future Market Insights).

- **Chemicals and Solvents:** CH_3OH is used as a raw material or solvent to produce a variety of chemicals. According to a report by Markets and Markets, the global CH_3OH market for chemicals and solvents was valued at USD 21.1 billion in 2020 and is projected to reach USD 26.3 billion by 2025, growing at a CAGR of 4.5% from 2020 to 2025 (Markets and Markets).
- **Plastics and Polymers:** CH_3OH is used as a building block in the production of various plastics and polymers. According to a report by Transparency Market Research, the global CH_3OH market for plastics and polymers was valued at USD 16.6 billion in 2019 and is projected to reach USD 27.7 billion by 2027, growing at a CAGR of 6.5% from 2020 to 2027 (Transparency Market Research).
- **Pharmaceuticals:** CH_3OH is used as a solvent and raw material in the production of pharmaceuticals. However, specific statistics on demand for CH_3OH in the pharmaceutical industry are not readily available.

It's important to note that these statistics are estimates and can vary depending on various factors such as region, market dynamics, and economic conditions. Demand for CH_3OH in different end-use applications may also be influenced by factors such as technological advancements, environmental regulations, and market trends.

2.4. SOCIAL

2.4.1. SOCIAL AND HEALTH BENEFITS

Safety and health considerations are important aspects of CH_3OH production from CO2 reduction using solar energy. Here are some social benefits related to safety and health:

- **REDUCED EMISSIONS AND AIR POLLUTION:** The production of CH_3OH from CO_2 reduction using solar energy does not emit harmful pollutants into the air, as solar energy is a clean and renewable source of energy. This can lead to improved air quality and reduced exposure to air pollutants, which can have positive impacts on human health, particularly for communities located near CH_3OH production facilities.
- **Lower risks of accidents and incidents:** Solar-powered CH_3OH production processes typically involve fewer risks of accidents and incidents compared to traditional CH_3OH production methods that rely on fossil fuels. Solar energy does not involve combustion or the use of flammable gases, reducing the risks of explosions, fires, leaks, and other accidents associated with fossil fuel-based processes. This can contribute to a safer working environment for workers and reduce the risks to nearby communities.
- **Reduced transportation risks:** The production of CH_3OH from CO_2 reduction using solar energy can be located close to the source of CO2 emissions, such as industrial facilities or power plants, reducing the need for transporting large amounts of CO_2. This can help minimize the risks associated with transportation, such as accidents, spills, and emissions during transportation, thereby reducing potential health and safety risks to workers and local communities.
- **Safer handling of materials:** Solar-powered CH_3OH production processes typically require the handling of fewer hazardous materials compared to traditional methods. CH_3OH is a relatively safe and easily manageable chemical, and using solar energy in the production process can reduce the need for handling and storage of hazardous materials, such as fossil fuels or toxic catalysts. This

can minimize the risks of exposure to hazardous materials and contribute to a safer working environment.

- **Health co-benefits of renewable energy:** Solar energy, as a renewable and clean energy source, can have positive health co-benefits. Reduced air pollution from using solar energy can lead to improved respiratory health, lower rate of respiratory diseases, and improved overall health and well-being of nearby communities. Additionally, the local production of CH_3OH from CO_2 reduction using solar energy can contribute to economic development, job creation, and improved socio-economic conditions, which can also positively impact health and well-being.
- **Emergency preparedness and resilience:** Solar-powered CH_3OH production processes can enhance emergency preparedness and resilience, as they are less vulnerable to external disruptions, such as power outages or fuel supply disruptions, compared to fossil fuel-based processes. This can help ensure the continuous operation of CH_3OH production facilities even during emergencies or natural disasters, contributing to the improved safety and resilience.

In conclusion, CH_3OH production from CO_2 reduction using solar energy can offer social benefits related to safety and health, including reduced emissions and air pollution, lower risks of accidents and incidents, reduced transportation risks, safer handling of materials, health co-benefits of renewable energy, and improved emergency preparedness and resilience. These social benefits can contribute to a safer and healthier environment for workers, nearby communities, and society.

2.4.2. STAKEHOLDER ENGAGEMENT

Stakeholder engagement is a crucial aspect of implementing CH_3OH production from CO_2 reduction using solar energy, as it entails actively involving and collaborating with various stakeholders who have an interest or are affected by the production process. Based on the Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 , the social aspects are listed.

Here are some key considerations for stakeholder engagement:

- **LOCAL COMMUNITIES**: Engaging with local communities is essential to understand their concerns, needs, and expectations related to CH_3OH production from CO_2 reduction using solar energy. This can involve conducting community outreach programs, public consultations, and information sharing to ensure that the local communities are informed about the project, its benefits, and any potential impacts. Involving local communities in the decision-making process and addressing their concerns can help to build trust, promote transparency, and ensure that the project aligns with the social, cultural, and economic values of communities.
- **Workers and labor unions**: Engaging with workers and labor unions is essential to ensure that their rights, safety, and well-being are considered in the CH_3OH production process. This involved discussing employment opportunities, working conditions, occupational health and safety, and fair compensation. Involving workers and labor unions in the planning, implementing, and monitoring of the CH_3OH production process can help create a positive working environment, promote social equity, and foster long-term relationships based on mutual understanding and respect.
- **Government and regulatory agencies**: Engaging with government and regulatory agencies is essential to comply with relevant laws, regulations, and policies related to CH_3OH production, environmental protection, and safety. This can involve obtaining necessary permits, licenses, and approvals, as well as consulting with government agencies on the project's technical,

environmental, and social aspects. Engaging with government and regulatory agencies proactively and collaboratively can help ensure compliance, promote accountability, and foster a positive relationship based on cooperation.

- **NGOs and civil society organizations**: Engaging with non-governmental organizations (NGOs) and civil society organizations can provide valuable insights, perspectives, and expertise on environmental, social, and health aspects of CH_3OH production from CO_2 reduction using solar energy. This can involve consultations, workshops, and collaborative initiatives to understand and address concerns related to environmental sustainability, human rights, public health, and social justice. Involving NGOs and civil society organizations in the implementing CH_3OH production process can contribute to transparency, accountability, and responsible decision-making.
- **Industry partners and supply chain stakeholders:** Engaging with industry partners, suppliers, and other stakeholders in the supply chain is important to ensure the responsible sourcing of materials, equipment, and services for CH_3OH production. This can involve discussions on sustainability criteria, ethical practices, and the environmental performance of suppliers and contractors. Collaborating with industry partners and supply chain stakeholders can help promote responsible business practices, foster innovation, and create a more sustainable value chain for CH_3OH production.
- **Academic and research institutions**: Engaging with academic and research institutions can provide access to scientific expertise, research findings, and technological advancements in CH_3OH production from CO_2 reduction using solar energy. This can involve collaborations on research and development, innovation, and knowledge sharing to enhance the technical and environmental performance of the production process. Collaborating with academic and research institutions can contribute to evidence-based decision-making, technological advancements, and continuous improvement in the CH_3OH production process.

In conclusion, stakeholder engagement is critical for implementation of the CH_3OH production from CO_2 reduction using solar energy. It involves actively involving and collaborating with various stakeholders to ensure their concerns, needs, and expectations are considered in the decision-making process. Effective stakeholder engagement can help build trust, promote transparency, ensure compliance with regulations, foster responsible business practices, and contribute to a more sustainable and socially responsible CH_3OH production process.

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