Future Trends in Bioenergy

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I. ABSTRACT

The air we breathe, the water we drink, and the very essence of life as we know it is under threat. As the global population continues to surge and energy demands reach unprecedented levels, we stand at a crossroads, desperately seeking a path toward sustainability. This is where solutions like bioenergy come to the rescue. Bioenergy can be harnessed through various processes, including combustion, fermentation, and anaerobic digestion. The sustainable provision of future energy needs can be significantly aided by biomass. Numerous regional and national bioenergy organizations have conducted extensive research and comprehensive assessments to evaluate the feasibility of utilizing biomass crops and other potential feedstocks for biomass energy. These assessments have encompassed cost-supply evaluations, environmental impact analyses, life cycle assessments, and assessments of externalities. Additionally, stakeholders in the bioenergy sector have collaborated to establish consensus recommendations and guidelines to promote sustainable bioenergy development. A consistent outcome derived from these collective endeavors is the recognition that replacing annual agricultural crops with native perennial biomass crops holds significant potential[1]. By doing so, not only can we decrease our reliance on fossil fuels and address the associated ecological challenges, but we can also contribute to the restoration of natural ecosystem functions within cultivated landscapes. This, in turn, contributes to the preservation of natural biodiversity. Bioenergy is presently the largest global contributor to renewable energy and has significant potential to expand in the production of heat, electricity, and fuels for transport. Looking toward the future, several innovative trends are shaping the field of bioenergy, paving the way for sustainable and efficient energy production. [4]

In this chapter, we will look at the role of bioenergy in climate mitigation over the next century and evaluate why it might be seen as a legacy fuel in the later decades of the 21st century.

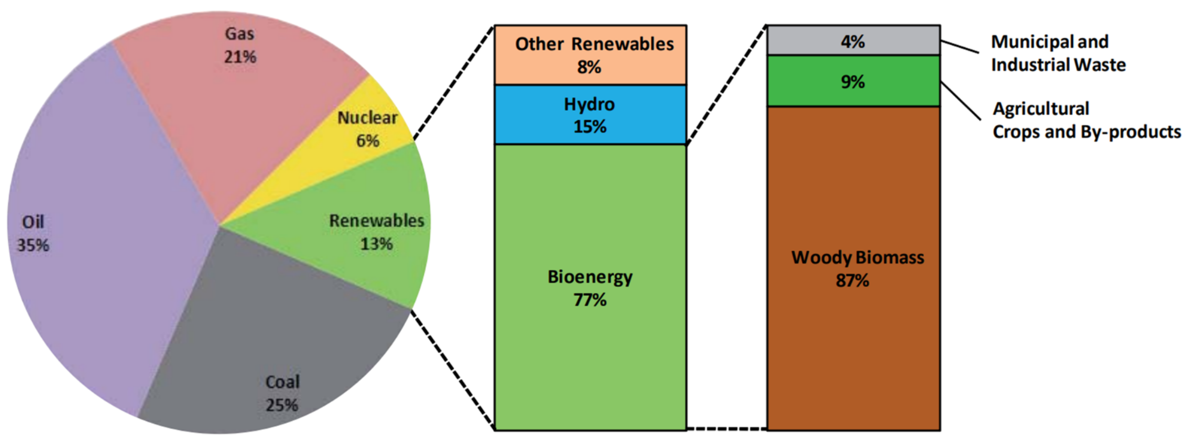
II. INTRODUCTION

Bioenergy refers to the production of energy from organic matter, also known as biomass. This renewable energy source utilizes biological materials such as plants, wood, agricultural residues, and organic waste to generate heat, electricity, or transportation fuels. Bioenergy can be harnessed through various processes, including combustion, fermentation, and anaerobic digestion. Currently, the primary sources of biomass for generating electricity and heat are forestry, agricultural, and municipal residues and wastes. A small portion of sugar, grain, and vegetable oil crops are also utilized for producing liquid biofuels. However, there is considerable untapped potential to expand biomass utilization by harnessing the substantial volumes of unused residues and wastes.

To further enhance biomass usage, there is an opportunity to cautiously expand the utilization of conventional crops, taking into account factors such as land availability and the demand for food. In the medium term, the production of lignocellulosic crops (both herbaceous and woody) on marginal, degraded, and surplus agricultural lands holds promise as a substantial biomass resource. Looking ahead, aquatic biomass, specifically algae, could also play a significant role in contributing to the biomass supply in the long run.

Extensive research has focused on investigating the environmental impacts of conventional crop production, surpassing the level of scrutiny given to lignocellulosic crop production. However, in general, lignocellulosic crops are anticipated to cause fewer and less severe impacts associated with agronomic inputs. This is due to their reduced reliance on fertilizers, agrochemicals, and their perennial nature. Moreover, the cultivation of bioenergy crops can yield positive effects, such as enhancing soil structure and fertility in degraded lands.

However, the availability of water downstream may be significantly reduced if sparsely vegetated regions are transformed into high-yielding lignocellulosic plants. This, in turn, can lead to deteriorating conditions in water-scarce regions. The environmental impacts associated with bioenergy crop production vary depending on local conditions, with the type of land use that the energy crops replace (known as reference land use) being a critical parameter influencing the outcomes.



Share of bioenergy in the world primary energy mix. Source: based on IEA, 2006; and IPCC, 2007. [1]

The potential for energy crops in the long term is contingent upon several factors. One crucial aspect is the availability of land, which is influenced by the development of the food sector. This includes factors such as the growth in food demand, changes in population diet, and improvements in crop productivity. Additionally, the accessibility of land can be constrained by limitations such as water scarcity and the need for environmental protection.

Another significant factor that determines the long-term potential of energy crops is the selection of specific crops for energy production. The choice of energy crops plays a vital role in determining the achievable biomass yields on the available land. This decision directly impacts the overall amount of bioenergy that can be feasibly deployed by the year 2050.[7] Thus, to determine the exact extent of bioenergy deployment in 2050, it is essential to consider factors such as land availability, food sector development, water resources, nature conservation, and selecting appropriate energy crops with high biomass yield potential.

III. DOMAINS OF BIOENERGY

A. Biofuels: Energy for transportation

Biofuels are a category of renewable resources that can be transformed into liquid fuels, specifically intended for transportation purposes. Among the different biofuels available, we find cellulosic ethanol, biodiesel, and renewable hydrocarbon fuels that can be seamlessly integrated into existing fuel systems. Ethanol and biodiesel are currently the most widely used biofuels [9]. These biofuels can be employed in various modes of transportation, including road vehicles and airplanes. By utilizing renewable transportation fuels that exhibit functional equivalence to conventional petroleum fuels, we can effectively reduce the carbon intensity associated with our vehicles and airplanes. [2] [11]

B. Biopower: Energy for heat and electricity

Biopower technologies encompass the conversion of renewable biomass fuels into heat and electricity, employing methodologies similar to those utilized with fossil fuels. The process of harnessing the energy contained within biomass for biopower production can be achieved through three primary approaches: combustion, bacterial decomposition, and conversion into gaseous or liquid fuels. By utilizing these methods, biopower has the potential to substitute carbon-based fuels traditionally burned in power plants, consequently leading to a reduction in the carbon intensity associated with electricity generation. In contrast to certain intermittent renewable energy sources, biopower offers the advantage of enhancing the flexibility of electricity generation and bolstering the electric grid's reliability. [2]

C. Bioproducts: Everyday commodities made from biomass

Biomass represents a highly versatile energy resource comparable to petroleum. In addition to its conversion into biofuels for transportation purposes, biomass holds the potential to serve as a renewable substitute for fossil fuels in the production of various bioproducts. These bioproducts encompass a wide range of materials, including plastics, lubricants, industrial chemicals, and other products that currently rely on petroleum or natural gas as their source. Following the model of petroleum refineries, integrated biorefineries have emerged, enabling the simultaneous production of both biofuels and bioproducts. This co-production approach offers enhanced efficiency, cost-effectiveness, and integration in harnessing biomass resources in the United States. Moreover, the revenue generated from bioproducts adds value to the equation, improving the economic viability of biorefinery operations and rendering biofuels more competitive in terms of cost. [2]

BIOFUELS	**BIOPOWER**	**BIOPRODUCTS**
Renewable resources for transportation.	Converts biomass into heat and electricity	Used to produce various bioproducts.
Cellulosic ethanol and biodiesel are common biofuels.	Uses combustion, decomposition, or conversion methods.	Include plastics, lubricants, and chemicals.
Carbon intensity in vehicles and planes.	Replaces carbon-based fuels in power plants.	Integrated biorefineries produce biofuels and bioproducts.
Ethanol and biodiesel integrate into existing fuel systems.	Biopower improves flexibility and reliability of the electric grid.	Biorefineries enhance efficiency and cost-effectiveness.

Table 1: Major differences between biofuels, biomass and bioproducts [2]

IV. BIOMASS CONVERSION TECHNOLOGIES

There are several bioenergy pathways that may be employed to transform unprocessed biomass fuel into an end product. A variety of conversion methods have been created that are tailored to the various physical characteristics and chemical make-up of the feedstock as well as the energy service needed (heat, electricity, or gasoline for transportation). Upgrading technologies for biomass feedstocks (e.g. pelletisation, torrefaction, and pyrolysis) are being developed to convert bulky raw biomass into denser and more practical energy carriers for more efficient transport, storage and convenient use in subsequent conversion processes.

To generate power from biomass, many methods either exist or are being developed. Co-combustion (also called co-firing) in coal-based power plants is the most cost effective use of biomass for power generation. Utilizing biomass for combined power and heat, whether in co-firing with coal or independently, along with district heating networks and biochemical processing of waste biomass, proves to be among the most efficient and cost-effective applications for reducing greenhouse gas emissions.

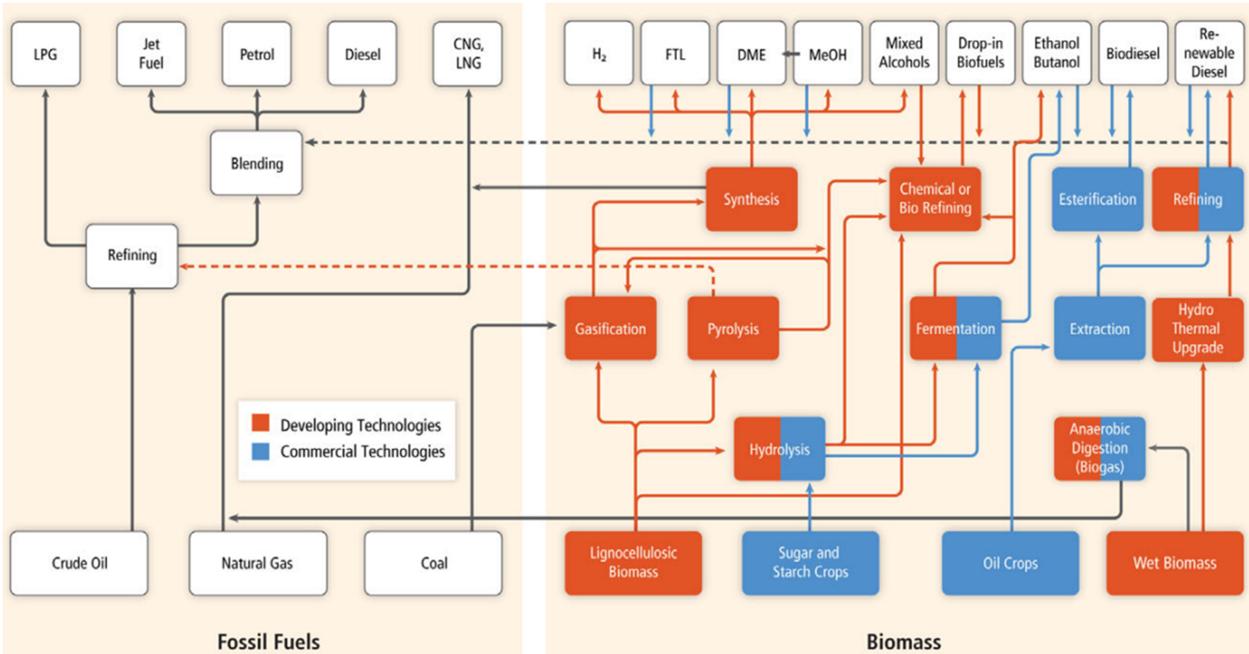


Figure 2: Production pathways to liquid and gaseous fuels from biomass and, for comparison from fossil fuels [33]

In summary, a range of conversion technologies enable the transformation of biomass into useful energy forms, with hybrid biomass-fossil fuel systems being increasingly adopted. Biomass utilization for combined power and heat, along with district heating networks and biochemical waste processing, offers effective and affordable means to reduce greenhouse gas emissions.

V. LAND INTENSIVE BIOENERGY

Land-intensive bioenergy refers to the production of energy through the use of biomass, such as plants and organic materials, which requires significant amounts of land. This form of energy production involves cultivating crops specifically for the purpose of converting them into biofuels or using agricultural residues, forest residues, or dedicated energy crops as feedstock for bioenergy production. These bioenergy systems often involve the cultivation of high-yielding energy crops, such as corn, sugarcane, soybeans, or switchgrass, which can be converted into biofuels like ethanol or biodiesel. These energy crops require substantial land areas for their cultivation, as well as additional land for processing and storage facilities.

While land-intensive bioenergy has the potential to provide a renewable and alternative source of energy, there are several considerations and challenges associated with its implementation. One major concern is the competition for land between bioenergy production and other land uses, such as food production or conservation. Increasing the cultivation of energy crops on a large scale could lead to land-use conflicts, deforestation, or the conversion of valuable ecosystems, potentially impacting biodiversity and ecosystem services. [4]

The technical bioenergy potential refers to the amount of biomass that can be utilized for bioenergy using existing technologies. It represents a portion of the theoretical potential, which is the maximum biomass that can be obtained based solely on biophysical limitations. Estimating the technical bioenergy potential lacks a standardized methodology, leading to varying estimates in different studies. Many recent studies adopt the "food/fiber first principle," focusing on biomass sources that do not conflict with food or fiber production. Additionally, deforestation is typically excluded from these estimations, resulting in an estimate known as the "environmentally sustainable bioenergy potential" that considers a comprehensive range of environmental restrictions. [10]

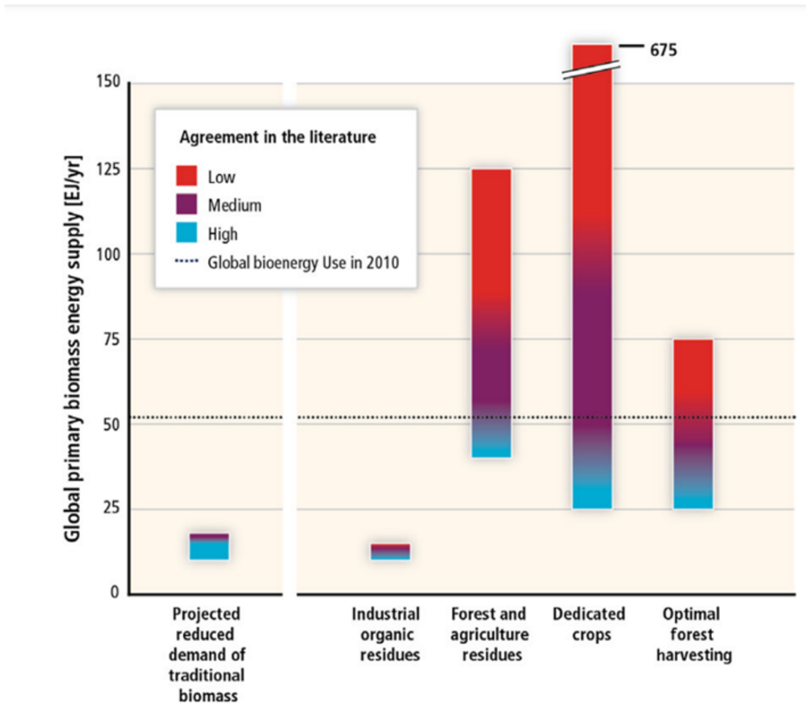


Figure 3: Technical Primary Biomass Potential for Bioenergy on a Global Scale by Main Resource Category in 2050. The worldwide technical primary biomass potential for bioenergy is depicted in the figure along with the estimation ranges for each main resource type. From blue (all researchers believe that this level can be obtained), through purple (medium agreement), to red (few researchers agree that this level can be attained), the color grading is meant to qualitatively demonstrate the degree of agreement in the estimations. Additionally, lowering the need for conventional biomass by improving its efficiency might free up the conserved biomass for alternative energy uses, which would have a significant positive impact on sustainable development [34]

According to resource categories, the above figure estimates the potential for technological bioenergy worldwide in 2050. Using a food/fiber first approach, a variety of limits involving resource limitations and environmental issues, but no explicit cost considerations, ranges were determined by evaluating a large amount of research.

Generation	Feedstocks	Description
1st Generation	Traditional food crops (e.g., corn, sugarcane, vegetable oils)	Biofuels produced from edible crops, such as ethanol from corn or sugarcane and biodiesel from vegetable oils. They have raised concerns regarding food competition and resource usage.
2nd Generation	Non-food biomass feedstocks (e.g., agricultural residues, dedicated energy crops, forestry residues)	Biofuels derived from non-food sources using advanced conversion technologies. These feedstocks aim to address sustainability issues associated with first-generation biofuels.

3rd Generation	Algae	Biofuels produced from photosynthetic microorganisms, specifically algae. Algae-based biofuels offer high productivity and can be grown on non-arable land and wastewater, reducing resource conflicts with food production. Commercial-scale production of algae-based biofuels is still under development.

Figure 4: Descriptive table of 1st, 2nd and 3rd generation biofuels; [32]

VI. FUTURISTIC APPROACHES

Bioenergy, as a renewable and carbon-neutral energy source, plays a crucial role in addressing the challenges of energy security and climate change mitigation. Advanced biofuels derived from non-food feedstocks, such as algae and cellulosic biomass, are gaining traction for their potential to offer higher energy yields and reduced carbon emissions. Synthetic biology and genetic engineering techniques are revolutionizing bioenergy production by designing microorganisms for enhanced biofuel synthesis. Algae-based bioenergy, waste-to-energy conversion, and microbial electrochemical systems are also emerging as futuristic avenues.

Furthermore, the integration of bioenergy into circular economy models and the concept of bioenergy with carbon capture and storage showcase promising paths for a greener and more sustainable future. [4] These trends underscore the ongoing advancements and possibilities in bioenergy, offering solutions that contribute to a cleaner and more resilient energy landscape.

A. Advanced Biofuels

Biofuels are widely recognized as a highly promising solution for reducing carbon dioxide (CO_2) emissions in the transportation sector. However, the utilization of conventional plant-based biofuels like biodiesel and bioethanol has been limited, accounting for only around 4% of total transportation fuel consumption in 2016. This is primarily due to significant challenges such as insufficient availability of raw materials, limited CO_2 mitigation potential, blending limitations, and inadequate cost competitiveness.

To address these limitations, advanced biofuels have emerged as a promising alternative. These advanced biofuels, including drop-in fuels, microalgal fuels, and electrofuels, offer potential solutions to meet the increasing demand for biofuels. Particularly, advanced biofuels derived from inedible biomass sources hold significant promise. By utilizing these advanced biofuels, it is possible to overcome the constraints associated with conventional plant-based biofuels and effectively meet the growing biofuel demand.

Step	**Description**
Feedstock selection	- Choose non-food feedstocks like lignocellulosic biomass, algae, and waste materials - Consider factors such as availability, sustainability, cost-effectiveness, and local conditions.
Pretreatment	- Break down complex structures of feedstock. - Use physical, chemical, or biological processes. - Increase accessibility of cellulose, hemicellulose, and lignin.

Biomass Conversion	- Convert pretreated biomass into biofuel intermediates - Employ biochemical or thermochemical processes. - Transform feedstock into sugars, syngas, or bio-oil.
Fuel production	- Refine intermediate products to produce advanced biofuels. - Additional steps like purification, upgrading, esterification, or hydrogenation may be involved. - Enhance quality, stability, and compatibility.
Quality Control	- Implement quality control measures throughout the production process. - Test for fuel properties, impurities, contaminants, and performance characteristics.
Distribution/Utilization	- Distribute and use advanced biofuels in existing transportation infrastructure. - Can be blended with fossil fuels or used as pure biofuels. - Suitable for road vehicles, ships, and airplanes.

Table 3: General overview of advanced biofuel production [32]

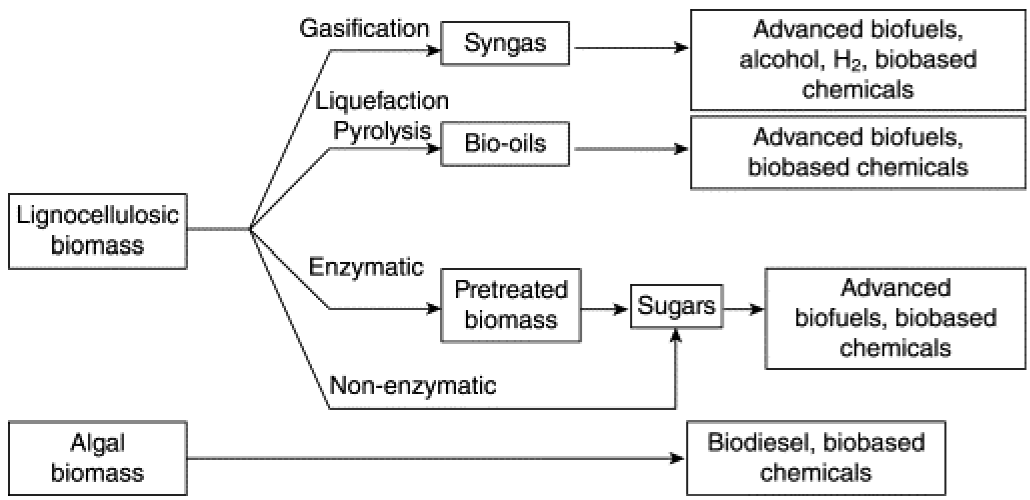


Figure 6: Courtesy: ScienceDirect: [30]

B. Microbial Electrochemical Systems (MES)

Microbial Electrochemical Systems (MES) are an innovative technology that harnesses the power of microorganisms to convert organic matter into electricity or hydrogen through electrochemical reactions. This field holds great promise for sustainable bioenergy production and environmental applications [12]. MES consists of an anode, where microorganisms oxidize organic substrates, and a cathode, where reduction reactions occur. The electron transfer between the anode and cathode can be facilitated by either direct electrical connection or through a mediator [18]. MES offer numerous advantages, including the ability to treat organic waste while simultaneously generating energy, the potential for decentralized systems, and the ability to operate using a wide range of organic feedstocks[15][16][17]. Research in this area focuses on improving system efficiency, understanding microbial communities and metabolic pathways, and exploring novel electrode materials and reactor designs [24]. MES technology has applications in wastewater treatment, bioelectricity generation, and biohydrogen production.

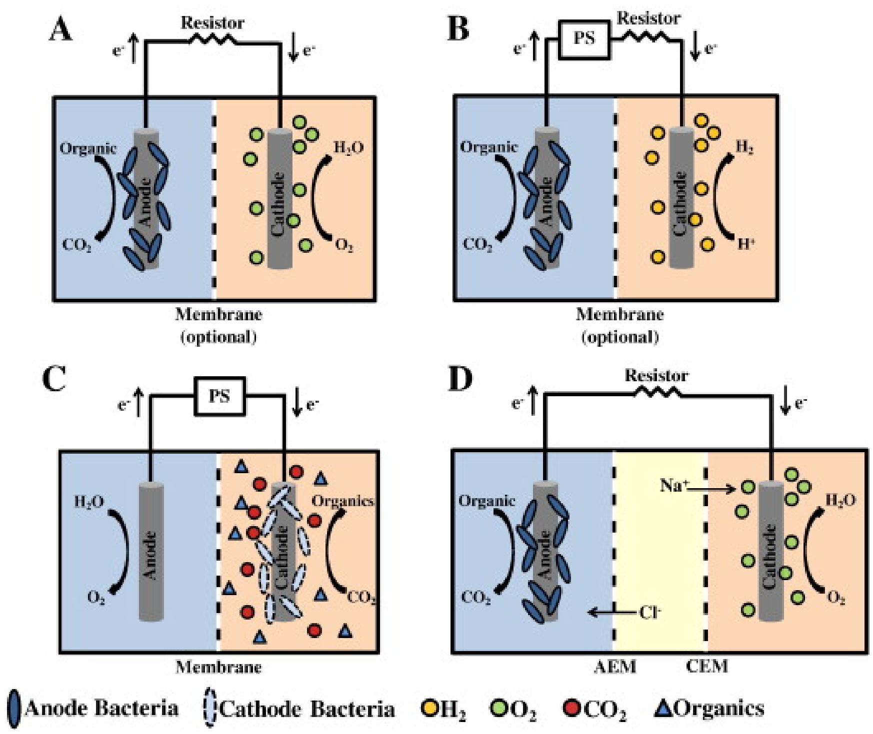


Figure 6: Basic principles in four typical MESs (left chamber: anode; right chamber: cathode). (A) Electricity generation in air-cathode microbial fuel cells (MFCs); (B) hydrogen generation with external power supply in microbial electrolysis cells (MECs); (C) chemical production by microbial electrosynthesis (MES); (D) middle chamber desalination in microbial desalination cells (MDCs). [15]

C. Bioenergy with carbon capture and storage - BECCS

Bioenergy with carbon capture and storage (BECCS) is a technology that combines the use of biomass for energy generation with the capture and storage of carbon dioxide (CO2) emissions. It is considered a negative emissions technology, as it has the potential to remove CO2 from the atmosphere and help mitigate climate change [19][20]. BECCS works by utilizing organic materials such as crop residues, dedicated energy crops, or organic waste as biomass feedstock. This biomass is then converted into energy through processes like combustion, gasification, or fermentation. During this energy generation process, CO2 emissions are captured using carbon capture and storage (CCS) technologies. The captured CO2 is then transported and stored in appropriate geological formations, ensuring its safe and permanent containment.

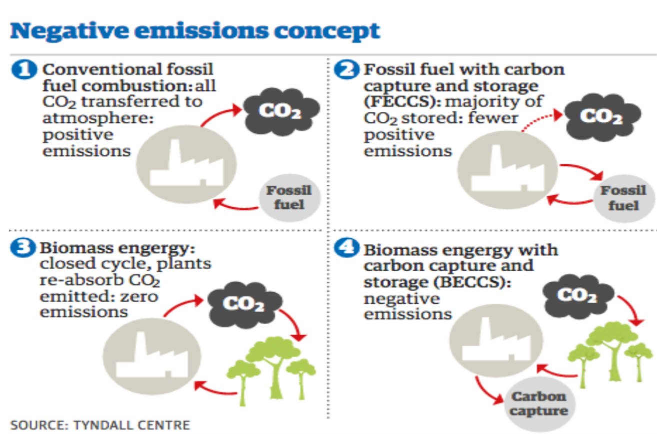


***Figure** 7: Visualization of negative emission concept*

BECCS offers several advantages, including its ability to sequester carbon and reduce greenhouse gas levels, as well as its utilization of renewable energy sources derived from biomass. This technology is regarded as a potential solution for achieving negative emissions and meeting climate targets. The IPCC Fourth Assessment Report has identified BECCS as a key technology for achieving low atmospheric carbon dioxide concentrations. [19]

In regions where biomass feedstock is predominantly cultivated, such as agrarian economies like India, the trade in biomass could potentially contribute significantly to the Gross Domestic Product (GDP). This highlights the economic potential associated with the biomass industry.However, the implementation of BECCS faces notable challenges, both technological and institutional in nature. These challenges primarily revolve around the extensive land, water, and fertilizer requirements necessary to meet the energy demands through biomass cultivation. The scale of these requirements poses significant hurdles to the widespread adoption of BECCS.

To overcome these challenges, it is crucial for governments to allocate subsidies for research and development (R&D) in the field of BECCS. Such investments would facilitate advancements in carbon capture technologies, making them more affordable and accessible for widespread implementation [23].

D. National Bio-Energy Programme

India possesses significant biomass potential, capable of generating over 750 million metric tonnes annually. This abundance of biomass offers a substantial opportunity for the production of bioenergy. Since the 1980s, the Ministry of New & Renewable Energy in India has been actively promoting bioenergy utilization by harnessing surplus biomass, cattle dung, and various forms of biowaste generated within the country. A notable initiative of the ministry is the provision of central financial assistance to facilitate the establishment of bioenergy projects. This support mechanism has considerably enhanced project viability by reducing costs or offering interest subsidies on loans.

The National Bioenergy Programme represents a comprehensive endeavor to encourage bioenergy adoption and foster an investor-friendly ecosystem founded on the principles of the circular economy. Another vital program is the Waste to Energy Programme, which focuses on harnessing energy from urban, industrial, and agricultural waste and residues. By leveraging the wastes produced by these sectors, the program aims to establish large-scale biogas, bio-CNG, and power plants. It is important to note that municipal solid waste to power projects are excluded from this particular program [22].

Furthermore, the Biomass Programme, which encompasses the Scheme to Support Manufacturing of Briquettes & Pellets and the Promotion of Biomass (non-bagasse) based cogeneration in Industries, aims to facilitate the establishment of power generation projects using pellets, briquettes, and non-bagasse biomass. These initiatives are aimed at diversifying the sources of power generation and promoting sustainable practices within the industrial sector.

E. Synthetic Bioenergy and Genetic Engineering

Synthetic bioenergy and genetic engineering represent cutting-edge fields that hold significant promise for revolutionizing the production of sustainable energy. Through the integration of advanced biotechnological tools and techniques, researchers are leveraging the power of genetic manipulation to enhance bioenergy production processes. This overview explores the concepts, applications, and potential benefits of synthetic bioenergy and genetic engineering in driving a greener and more sustainable energy future [24].

Genetic Engineering in Bioenergy Production:

Genetic engineering techniques play a vital role in improving the efficiency, yield, and environmental sustainability of bioenergy production. By altering the genetic makeup of microorganisms and plants involved in bioenergy pathways, researchers can enhance their ability to convert biomass into valuable biofuels and chemicals.

Enhanced Microbial Biofuel Production:

One area where genetic engineering has made significant contributions is in the production of biofuels from microbial hosts. Microorganisms such as bacteria and yeast can be genetically modified to efficiently convert biomass feedstocks into advanced biofuels like ethanol, butanol, and biodiesel. Genetic engineering enables the optimization of metabolic pathways, increasing the yield and reducing the production costs of biofuels[12][13].

Metabolic Engineering of Plants for Biomass Production:

Genetic engineering techniques also facilitate the modification of plants to enhance their suitability for bioenergy production. Researchers can manipulate plant genomes to increase biomass yield, alter cell wall composition for easier bioconversion, and improve stress tolerance for cultivation in diverse environments. These genetic modifications in energy crops offer the potential for sustainable and high-yielding biomass feedstocks [26].

F. Synthetic Biology for Bioenergy

Synthetic biology, an interdisciplinary field that combines engineering principles with biology, offers powerful tools for designing and constructing biological systems for bioenergy production. By utilizing standardized genetic parts and engineering principles, synthetic biology enables the construction of tailor-made microbial systems for efficient and customizable bioenergy pathways.

Advanced Feedstocks for Bioenergy:

Genetic engineering plays a critical role in diversifying feedstock options for bioenergy. Researchers are exploring the use of non-food feedstocks such as algae, lignocellulosic biomass, and waste materials [27]. Algae-based bioenergy, for instance, holds great potential due to its high growth rates and lipid content. Genetic engineering allows the modification of algae to enhance biomass productivity, lipid accumulation, and the production of specific biofuel precursors [14][28].

Beyond bioenergy production, genetic engineering has broad applications in environmental remediation and waste treatment. Microorganisms can be engineered to efficiently degrade organic pollutants and convert waste streams into valuable energy products. Genetic engineering enables the development of specialized microbial communities capable of pollutant degradation, facilitating sustainable waste management practices [29].

Synthetic bioenergy and genetic engineering have the potential to transform the landscape of sustainable energy production. By harnessing the power of genetic manipulation, researchers can optimize bioenergy pathways, develop advanced feedstocks, and enhance the efficiency of biofuel production. As these fields continue to advance, the potential for scalable and environmentally friendly bioenergy solutions grows. Leveraging the tools of synthetic biology and genetic engineering, we are paving the way for a future where bioenergy plays a pivotal role in meeting global energy demands while reducing carbon emissions and promoting a sustainable future [24].

VII. SUBSEQUENT ADVANCEMENTS

A. Advanced feedstocks

Currently, the dominant feedstocks utilized for generating heat and electricity from biomass consist of forestry and agricultural residues, along with diverse organic wastes. Traditional crops like sugar, grain, and vegetable oil are commonly employed for the production of liquid biofuels. However, looking towards the future, lignocellulosic crops, including perennial herbaceous and woody varieties, hold significant potential to become the primary biomass resource. Algae, while holding promise for the longer term, are still relatively unexplored as a feedstock due to the current stage of their development [27].

B. Waste to energy conversion

Municipal solid waste (MSW) represents a highly diverse and often heavily polluted feedstock, requiring robust technologies and strict emission controls. These factors contribute to relatively high costs associated with waste-to-energy facilities. Various technologies are available for MSW treatment, with the selection depending on the level of separation achieved among different waste fractions. However, the generation of electricity from MSW tends to be economically uncompetitive without appropriate waste management strategies and incentives. As a result, despite its considerable potential in many countries, MSW remains largely untapped as an energy resource.

C. How does bioenergy differ from other renewable alternatives?

In contrast to other renewable energy options, biomass offers the advantage of being capable of producing carbon-based fuels that closely resemble fossil fuels, which are widely used in present-day energy technology. Additionally, biomass represents a form of solar energy stored within organic matter, thereby addressing the intermittency issues associated with direct solar energy. This characteristic makes biomass highly suitable for both heat and power generation, especially in the transport sector where it currently serves as the primary renewable alternative to gasoline and diesel fuels.

However, it is important to note that biomass feedstock acquisition incurs a cost, unlike other renewable energy resources such as wind, hydro, geothermal, wave, and sunlight, which are naturally available and do not require specific input costs. [8]

VIII. WAY FORWARD AND FUTURE PROSPECTS

In the later part of the 21st century, bioenergy is expected to emerge as a significant legacy fuel, playing a crucial role in the global energy landscape. As the world continues to grapple with the challenges of climate change, resource depletion, and energy security, bioenergy offers a sustainable and renewable alternative to traditional fossil fuels.The evolution of bioenergy technologies, coupled with advancements in feedstock production and conversion processes, has paved the way for its prominence as a legacy fuel. The utilization of biomass, whether from agricultural residues, dedicated energy crops, or algae, offers the potential to generate carbon-neutral or even carbon-negative energy. This aligns with the overarching goal of reducing greenhouse gas emissions and mitigating climate change [21].

Moreover, the versatility of bioenergy allows for its application across multiple sectors, including electricity generation, heat production, and transportation. The ongoing development of biofuels, such as advanced bioethanol and biodiesel, is progressively transforming the transport sector by offering renewable alternatives to gasoline and diesel [11][13]. While bioenergy's journey towards becoming a legacy fuel is promising, challenges remain. Sustainable feedstock availability, technological advancements, and the need for comprehensive environmental regulations are areas that require attention. Additionally, striking a balance between bioenergy production and food security is crucial, ensuring that bioenergy does not compromise global food production or lead to undesirable land-use changes.

Bioenergy holds immense potential as a legacy fuel in the later 21st century. Its renewable nature, capacity for carbon neutrality, and versatile applications make it an attractive option for sustainable energy generation. With continued research, innovation, and policy support, bioenergy can contribute significantly to the transition towards a cleaner, more resilient, and secure energy future.

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