Clean Energy Technologies Journal
Web page info: https://cetj.yildiz.edu.tr
DOI: 10.14744/cetj.2023.0009

CLEAN ENERGY TECHNOLOGIES JOURNAL

Review Article

Artificial photosynthesis a novel and sustainable renewable energy source: In the perspective of Saudi Arabia

Muhammad SALEEM[1], Mehmood ALI[2], Muhammad Adil BIN SALEEM[3,*], Muhammad Taha BIN SALEEM[4]

[1]*Department of Civil Engineering, Jubail Industrial City 31961, Jubail Industrial College, Kingdom of Saudi Arabia,*
[2]*Department of Environmental Engineering, NED University of Engineering and Technology, Karachi, 75270 Pakistan,*
[3]*Department of Mechanical Engineering, Jubail Industrial City 31961, Jubail Industrial College, Kingdom of Saudi Arabia*
[4]*Department of Mechanical Engineering, King Fahad University of Petroleum & Minerals, 5069 Dhahran 31261, Kingdom of Saudi Arabia*

ARTICLE INFO

Article history
Received: 31 July 2023
Revised: 07 December2023
Accepted: 12 December 2023

Keywords:
Renewable Clean Energy; Artificial Photosynthesis; Vision 2030 Saudi Arabia; Material Limitations; Feasibility; Catalytic Routes

ABSTRACT

In the present era, energy is one of the key players in the sustainable development of a country from the economic, social, and environmental point of views. Saudi Arabia is one of the major oil producers in the world. Therefore, Saudi Arabia is using conventional fossil fuels as the main source of electrical energy generation. However, in order to diversify its economic sources and address environmental issues, the country has planned in Vision 2030 to exploit renewable energy resources. The objective of this study is to analyse the various sources of renewable energy in Saudi Arabia and evaluate the novel artificial photosynthesis technique in more detail. Evidence and data were reviewed from various articles, books, and conference proceedings to support this study. To conclude reviewing this technology, novel artificial photosynthesis techniques were narrowed down to prove how they can be one of the fossil fuel alternatives. Various suggestions have been given to prevent setbacks and to find alternative methods to overcome limiting factors.

Cite this article as: Saleem M, Ali M, Bin Saleem MA, Bin Saleem MT. Artificial photosynthesis a novel and sustainable renewable energy source: In the perspective of Saudi Arabia. Clean Energy Technol 2023;1(2):90–104.

INTRODUCTION

Despite the growing attention towards renewable energy resources in recent years, fossil fuels are still the major source of global energy use. Around 84% of global primary energy comes from fossil fuels [1]. The three leading fossil fuels for energy consumption are coal, petroleum and natural gas of which coal is the cheapest and the most polluting, and oil the most abundantly used. Consequently, there has

Highlights

- Saudi Arabia is gradually shifting towards the renewable energy sources.
- Saudi Vision 2030 intends to generate up to 60 gigawatts from renewable sources.
- Present research provides the viability of APS as an alternative energy source.
- Suggestions to overcome the limitations of APS execution highlighted in detail.

***Corresponding author.**
*E-mail address: i_am_saleem@yahoo.com

Published by Yıldız Technical University Press, İstanbul, Turkey

been a rapid incline in pollution and global warming. In order to counter the impact of pollution, world's ministers of environment gathered at the United Nations Environment Assembly (UNEA) in 2017 to propose an 'Implementation Plan' that will help cut down use of non-renewable energy resources and help transition towards renewable energy resources [2].

Saudi Arabia has the second-largest proven crude oil reserves which in fact give it great influence in the global oil market. However, globally the overexploitation of non-renewable reserves to fulfil the rising demands will diminish the depleting reserves and could be detrimental to the energy security of the country. As reported in some studies, "Middle Eastern countries' major exporters of oil and natural gas, will not be able to supply and meet energy demands by the next 50 years" [3]. The Kingdom of Saudi Arabia already developed the layout plan for future energy demand and supply in the national Vision 2030 that targets to accelerate the efforts toward achieving sustainable development goals. It has a strategic framework to reduce Saudi Arabia's dependence on oil, diversify its economy and protect the environment [4].

In the charter of Vision 2030, the renewable energy plan has been drawn and targets to ensure renewable energy progression that is one of the main priorities to achieve sustainable growth in the country [4]. The present study highlights the current situation of pollution and renewable energy at the global level and in the Kingdom, as well as the strategies and actions postulated in the Kingdom's Vision 2030 to cultivate a renewable energy sector in the region. In addition to famous renewable energy sources including wind, solar and geothermal, the novel artificial photosynthesis (APS) option is discussed.

The main objective of this research is to prove the viability of APS as a secondary alternative to fossil fuels, as this topic has not been addressed in the past for this region and may pave the route to a novel approach to provide relief to the current energy scenario in the country. The steps of an APS process are explained and solutions to potential limitations are included in the paper. The effectiveness and efficiency of this process will be discussed, and major pros and cons are considered. A concise explanation of the use of renewable energy and fossil fuels is also given to set a background. The upshot of the study includes whether APS could be one of the renewable energy options in the country's hybrid energy plan.

This study has been performed by utilising data from various research studies, recent journal articles and periodicals including Scopus, Web of Science, ERIC and ScienceDirect. It was made sure that the data referred to and used is from within the past decade or so. For detailed insight and background information, some data from an even earlier duration was also used. In the concluding section, the barriers facing the implementation of artificial photosynthesis as a viable option in the Kingdom of Saudi Arabia have been addressed and recommendations for improvement to develop the renewable energy sector are also discussed. The solar energy conversion efficiency has improved from 1% to 10% during the last decade and current studies expect even higher conversion in future devices [5]. The present study will be beneficial to energy planners, researchers and technological personnel for further exploration and advancement.

FOSSIL FUELS AND ENVIRONMENT

Fossil fuels can be defined as: "Fossil fuel, any of a class of hydrocarbon-containing materials of biological origin occurring within Earth's crust that can be used as a source of energy" [6]. In simple terms, decomposing plants and animals found in the Earth's crust, composed of mainly hydrogen and carbon, that can be burned for energy. Some of the fossil fuels include coal, petroleum, natural gas, tar sands, bitumens, oil shales, and heavy oils. Their extraction is mainly based on two methods: mining and drilling, which also has adverse environmental effects on our biosphere.

Fossil Fuel Extraction and Effects on the Environment

Mining is usually done to extract solid fossil fuels such as coal and oil shales by digging or scraping the buried resources. In the mining process, the location is first deforested, then the topsoil is removed and saved for later reclamation. Fissile fuel extraction is done by various techniques, including mountaintop mining, underground mining, and hydraulic fracturing [7]. Mountaintop removal is usually done to access coal or oil shale deposits. This is a more damaging type of surface mining in which all of the overburden is removed with explosives, exposing the coal seam. The large mass of the mountaintop is removed and placed into a nearby valley, and the coal is then removed [8]. Underground mining is a method used to access deeper fuel deposits. Liquid and gaseous fossil fuels such as natural gas and oil are extracted by drilling methods. Once the deposit is identified, a shaft or a tunnel is used to access the reserve. After that, ore is extracted by drilling, blasting, or using other extraction methods. By drilling a hole or an exit, these oils and gases are forced to flow out. Hydraulic fracturing is done in order to expand cracks or gaps in the earth's crust containing fuel deposits. This is done by injecting water, chemicals, and sand with high pressure into the cracks, driving fuel towards the outside, and making it an easier task to extract them. In the hydraulic fracturing process, cracks and fractures are widened by injecting fluids, and proppant at high pressure. Proppant is a solid material, typically sand, treated sand or manufactured ceramic materials. Hydraulic fracturing fluids commonly contain chemical additives in water and proppant that will help to open and enlarge fractures within the rock formation [9].

All of these methods can be a hazard to the environment and the health of the workers. The processes of explosion and digging release many pollutants to the surrounding environment and community, and result in the alternation of the ecosystem. Associated air pollutants such as particulate matter, nitrogen oxides, and sulphur dioxide do not only raise health concerns, but they also have effects on all ecosystems. Air pollution contributes to issues such as water and soil acidification, chemical bioaccumulation in the food web and eutrophication. These processes create vast amounts of wastewater, emit greenhouse gases such as methane, release toxic air pollutants and generate noise. Studies have shown these gas and oil operations can lead to loss of animal and plant habitats, species decline, migratory disruptions and land degradation [10].

Although fossil fuels are cheap with well-developed machinery to extract them and are much more reliable in terms of energy efficiency, they pose a great threat to our environment and us. Nicoles (2022) says fossil fuels are the main cause of global warming. 'Fossil fuels are the main driver of global warming. When they are burned, they release vast amounts of harmful byproducts called greenhouse gases (CO_2, SO_2, and NO_x) and toxic pollutants (polycyclic hydrocarbons, mercury, and volatile chemicals) responsible for global warming and have multiple adverse effects on human health [11]. The greenhouse gases released into the atmosphere trap huge amounts of heat causing drastic changes in the weather patterns due to climate change and global warming. The inevitable price of using fossil fuels is not limited to these and spans health, economic, and social problems. Environmental concerns are increasing at an alarming rate [12]. As reported by recent studies (Figure 1) with all the measures, global CO_2 emissions from fuel consumption are increasing at an alarming rate [13].

Oil rig accidents can be caused by extreme weather, equipment malfunction, poor maintenance, or lack of safety equipment, which can result in fires and explosions. In 2010, a British petroleum oil spill occurred where an explosion sank the oil rig, causing a major oil leak when the oil well disconnected that went on for over four months. The central cause of the explosion aboard the drilling rig was a failure of the cement at the base of the 18,000-foot-deep well that was supposed to contain oil and gas within the wellbore. The accident resulted in killing about 34,000 birds and hundreds of other sea creatures in its wake (Figure 2) [13].

In 1952, a major environmental disaster occurred called 'The London's Killer Fog' where over 12,000 people were killed as soot covered the city buildings and thick black clouds covered the sky due to toxic fumes and smoke from the over burning of coal to fight the harsh winters cold. The cause of the disaster was the over burning of coal, and according to later investigations, on each day during the

Figure 2. The BP deep-water horizon oil rig explosion, Gulf of Mexico in 2010 [13].

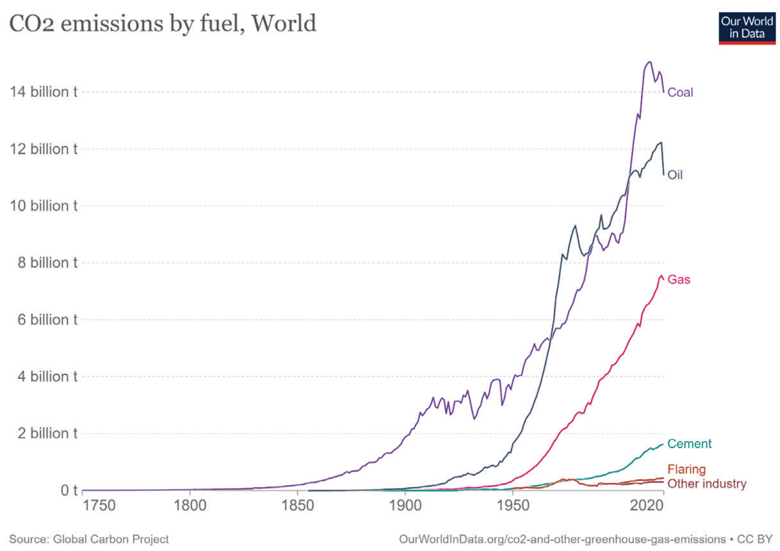

Figure 1. Global CO_2 emissions from fuel consumption [1].

foggy period, 1,000 tonnes of smoke particles, 2,000 tonnes of carbon dioxide, 140 tonnes of hydrochloric acid and 14 tonnes of fluorine compounds were emitted [13]. This event gave a lesson to the public and the government and as a result, the British government passed and implemented the Clean Air Act in 1956. The act established smoke-free areas throughout the city and restricted the burning of coal in domestic fires as well as in industrial furnaces [14]. Despite the disastrous incidents due to fossil fuels, there are still many polluting fossil fuel plants around the world that need to be stopped or replaced with a renewable energy source. Cutting down the use of fossil fuel and other major polluting energy sources is imperative.

POTENTIAL RENEWABLE ENERGY RESOURCES

A Renewable energy resource is one that can be used unlimited times as it is restored naturally [15]. Most renewable energy resources are considered sustainable. However, some renewable energy resources, if used up too fast or if they are harmful to the environment, could result in the resource becoming unsustainable. This means that the rate of use exceeds the rate of renewal [16].

Solar energy, wind energy, biofuel, hydropower, and geothermal energy are some of the most common renewable energy resources that may be referred to as unlimited energy resources. According to a report, renewable energy has the potential to reduce energy-related CO_2 emissions by 90% [17]. Researchers are also making continuous efforts to explore other renewable sources of energy, such as biodiesel, bioethanol, bioelectricity, biohydrogen, and biohythane [18, 19].

As shown in Figure 3, there has been an impressive increase in renewable energy use in recent years. However, governments must take further action to ensure a major and swift transition towards renewable energy [20].

Wind Energy

Wind power is another form of renewable energy with old roots. It was used by humans to power their vessels across the open seas with the help of sails. It also had many applications in farming. The first recorded use of wind power in agriculture goes back to the 17th century BC when the Babylonians employed it in their irrigation systems. The earliest iterations of the windmill were used in Egypt in the 1st century. According to the Flagship report of April 2020 by International Energy Agency (IEA), during the year 2020, use of renewable energy in various sectors augmented globally by 1.5% as compared to what it was in the year 2019. Furthermore, more than 60 GW of wind power projects and about 100 GW of solar PV were installed during the year 2019 [21].

Solar Energy

Solar energy, in simple terms, is the energy from the sun due to nuclear fission that may be harvested by technological means for our use. Solar energy is harvested in two main ways: Photovoltaics (PV) and Concentrated Solar Power (CSP).

Photovoltaics

Solar energy is absorbed by PV cells in solar panels and in turn produces electricity. Energy Efficiency & Renewable Energy (2022) explains 'When the sun shines onto a solar panel, energy from the sunlight is absorbed by the PV cells in the panel. This energy creates electrical charges that move in response to an internal electrical field in the cell, causing electricity to flow' [22]. A schematic diagram in Figure 4 shows the PV system working principle.

Concentrated Solar Power

In Concentrated Solar Power (CSP), mirrors are used to force sunlight energy at a focal point making it concentrated

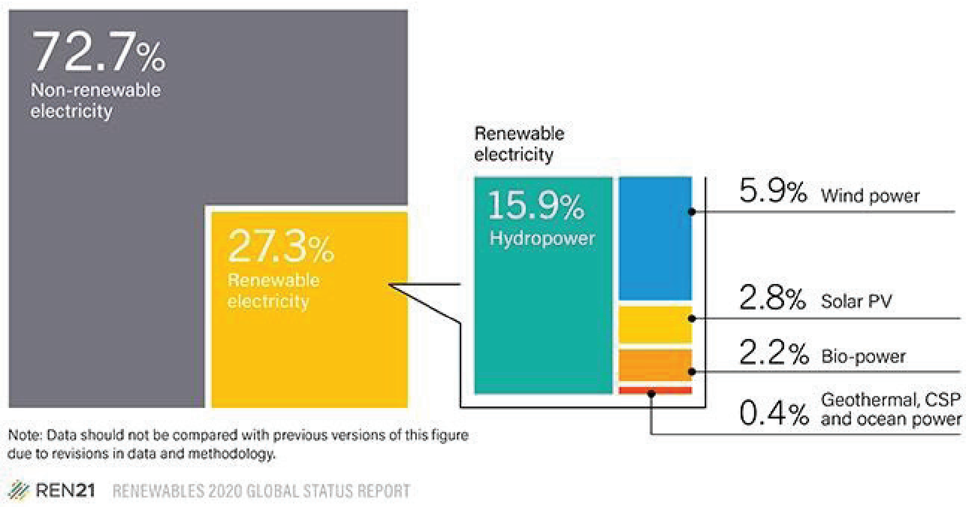

Figure 3. Estimated renewable energy share of global electricity production in 2019 [20].

Clean Energy Technol J,, Vol. 1, No. 2, pp. 90–104, December, 2023

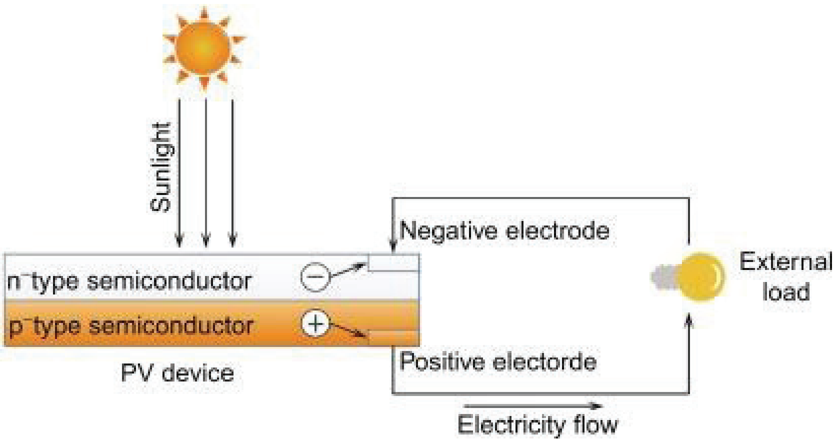

Figure 4. Schematic diagram visual of PV system working principle [23].

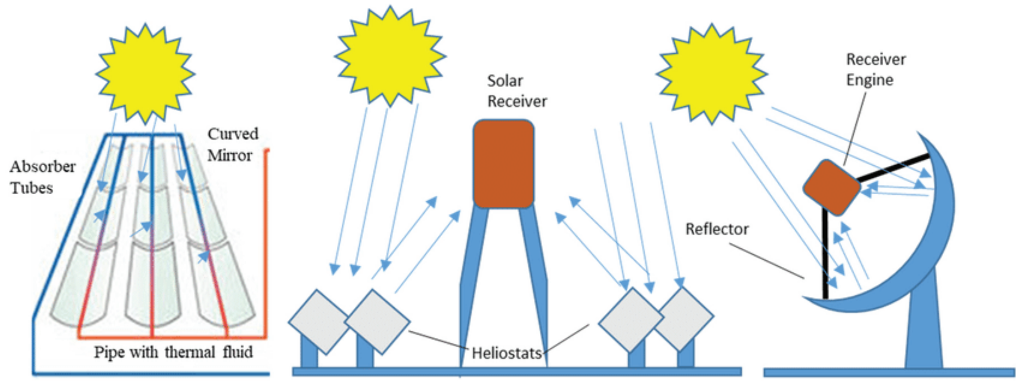

Figure 5. Pathway of implementing CSP to harness sunlight [25].

enough to produce heat which can be utilised in various ways to generate electricity. Figure 5, depicts the various methods that can be used to harness solar energy using CSP such as: trough systems, power tower systems and parabolic dish systems [24].

Geothermal Energy

Geothermal energy is one of the renewable energy resources that can be utilised as an alternative source. The earth core is about 2,900 kilometres beneath the Earth's surface and the temperature of the inner core is estimated to be about 6,000 degrees Celsius (°C). However, the temperatures in the mantle range from about 200 °C near the mantle-crust boundary to about 4,000 °C near the mantle-core boundary. This energy can be harvested from feasible locations on the earth's surface [26]. Geothermal energy provides sustainable baseload energy that can be used for district heating/cooling, water desalination, and even electricity generation.

The normalised cost of electricity from geothermal power projects averaged between USD 0.049 and USD 0.085 per kWh during the years 2010 to 2020 [27]. Geothermal energy is one of the contributors in covering rising energy demands in several countries, including New Zealand, Iceland, Kenya, El Salvador, and the Philippines. In fact, geothermal provided 90% of the energy share of heating demand in Iceland [28].

The geological structure and deep structural conditions of the Saudi Arabian land are promising for the development of geothermal energy resource plans to provide alternative renewable energy in the region. Most of the feasible locations for geothermal energy harvesting are along the Red Sea due to high heat-flow from deep in the Earth. Two of the most suitable locations in the Kingdom's Giga Projects indicated by studies are the Red Sea Development Project (near Al-Wajh) and NEOM [29].

The geothermal energy option is capital-intensive, which requires a higher initial investment than some other energy sources. Like wind and solar energy options, this option is only feasible in certain locations. Furthermore, air and water pollution are two major environmental issues linked with geothermal energy technologies. In addition to that, the safe disposal of hazardous waste, siting and land subsidence makes feasibility limited. Most geothermal power plants also require a large amount of water for cooling or other purposes [30].

Natural Photosynthesis

Natural photosynthesis has been the source of energy for all life on Earth either directly or indirectly as plants, algae, and some bacteria are mostly the only living organisms able to get their energy directly from the sun. BiologyOnline (2021) defines photosynthesis in technical terms as: 'The synthesis of complex organic material using carbon dioxide, water, inorganic salts, and light energy (from sunlight) captured by light-absorbing pigments, such as chlorophyll and other accessory pigments' [31]. Life on earth has always been in perfect sync as energy is cycled through at almost perfect efficiency. Energy in fossil fuels has indirectly come from the photosynthesis process. Photosynthesis is the chief example of an efficient renewable energy source.

Natural photosynthesis process takes place in an organelle called chloroplast. This process can be segmented into two main parts: Light dependent reaction, which takes place in the Thylakoid membrane, and light independent reaction or Calvin cycle, that takes place in the stroma as illustrated in Figure 6. Thylakoid membrane contains photosystem II, photosystem I, carriers or cytochromes, various attached enzymes including NADP reductase, and ATP synthase. As light shines on a leaf, specifically PS II on the thylakoid membrane, 2 electrons from a manganese atom are released and are transported from one cytochrome to another down their energy level. This releases heat energy which helps draw in protons from the stroma into the thylakoid lumen. The build up of proton gradient causes the movement of protons through ATP synthase. In a process called chemiosmosis, each 3 protons cause an ATP molecule to form, from ADP and an inorganic phosphate (P_i), as they move out of ATP synthase [32].

Meanwhile, energy from the sunlight activates water splitting enzymes adjacent to PS II causing water to be broken down into oxygen, protons, and electrons. Oxygen is released through stomata as a waste product. The electrons replace the lost electrons of manganese in PS II. The protons move to NADP reductase producing NADP-reduced or NADPH. The first stage of photosynthesis is complete and the products of the light dependent reaction are ATP, as an energy carrying vessel, and NADP reduced. These move to the light independent reaction or Calvin cycle [33].

The Calvin cycle occurs in the stroma of the chloroplast where CO_2 and the products of light dependent reaction are utilised. This cycle consists of four main steps: carbon fixation, reduction, carbohydrate formation, and regeneration [34]. Ribulose 1,5-bisphosphate (RuBP), also known as Rubisco, is an enzyme that catalyses the CO_2 fixation as it binds with it and an unstable carbon compound forms. The unstable compound goes under the splitting process forming glycerate phosphate (GP) acid. Subsequently, the reduction phase begins as NADP-reduced and ATP help reduce GP to phosphoglyceraldehyde (PGAL). NADP and

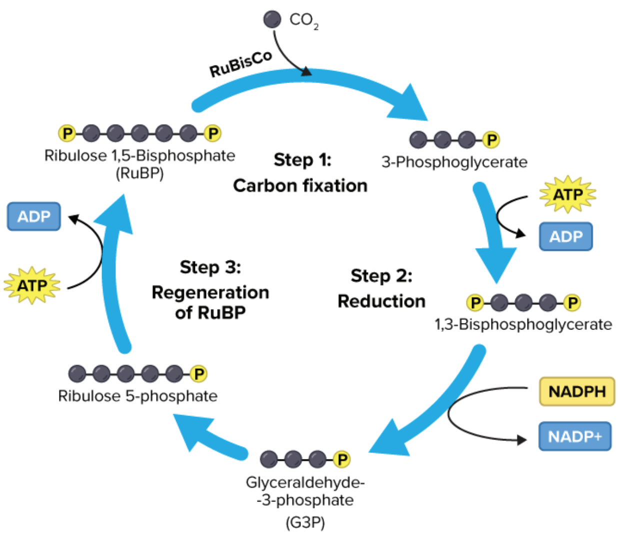

Figure 7. An overview of the Calvin cycle [35].

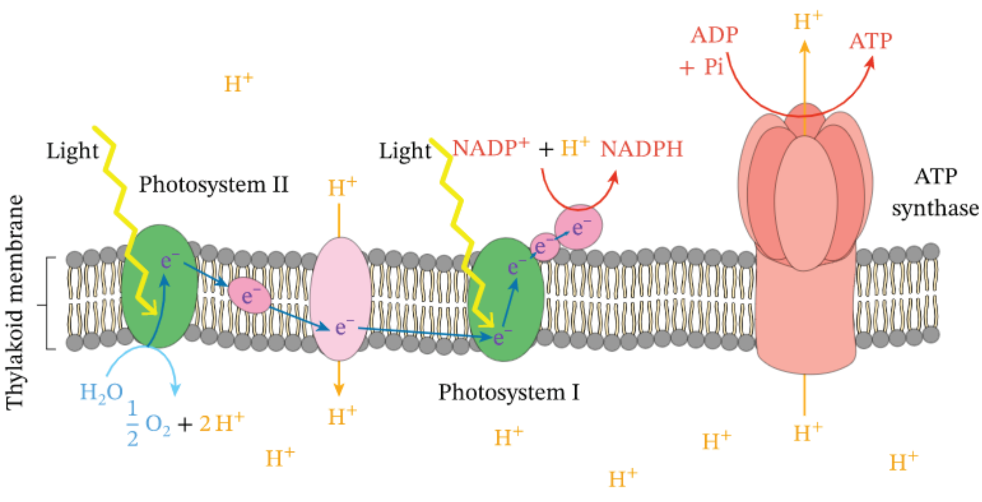

Figure 6. Light dependent reaction on a section of thylakoid membrane [33].

ADP are formed as reduction phase ends. One of the PGAL molecules forms glucose, amino acids, glycerol, fatty acids, etc. The other PGAL molecule carries forward to the regeneration phase as RuBP is produced again. Thus, continuing the Calvin cycle. An overview of the Calvin cycle is illustrated in Figure 7 [35].

The ultimate product of photosynthesis is the following reaction:

$$6H_2O + 6CO_2 + (\text{sunlight}) \rightarrow C_6H_{12}O_6 + 6O_2 \quad \text{Equ (1)}$$

Artificial Photosynthesis

As our society advances, its need for a much more efficient, less polluting, and more reliable energy source rises. That's where APS comes, which mimics the very natural process of photosynthesis that occurs in plants that supply all life on Earth with solar energy in various forms. In simple terms, the basic idea behind APS is to mimic the process that natural organisms use and mould it to fit our energy needs [36]. It is a device which enables us to capture and store solar energy in the form of a fuel like hydrogen or methanol rather than producing glucose.

Artificial Photosynthesis Process

Similar to how in the solar PV system the semiconductors in solar panels absorb solar energy and transform it into electrical energy, in APS, the semiconductors absorb solar energy and store it in "the carbon-carbon bond or the carbon-hydrogen bond of liquid fuels like methane or butanol." [37].

APS mimics natural photosynthesis; however, currently suggested materials utilised in artificial photosynthetic systems are not efficient, have less durability, are relatively uneconomical, and are sometimes toxic. A challenge in APS is to use cheap and environmentally friendly compounds as in natural photosynthesis. Although many intelligent strategies must be encouraged and tested, learning from natural systems is indispensable [38].

The overall components of an APS system are the electricity supply to the system (ideally using PV panels), dry agriculture or liquid fuel production, hydrogen production, and carbon dioxide fixation [39]. PV cells are used to harvest solar energy to produce electricity which then powers the water splitting, fuel production, and CO_2 reduction process. The main process of APS is hydrogen production through water splitting using solar energy. Solar energy conversion consists of light harvesting, charge separation, and catalysis. Silicon junctions in the PV cells harvest solar energy. This produces current for several photochemical reactions to occur in the solar cell producing photovoltage which initiates the water-splitting process in the presence of catalysts, such as cobalt oxide and manganese, forming hydrogen and oxygen. It also produces electrons that will be used in dry agriculture and liquid fuel production in the later stages of the process. Hydrogen is a valuable source of fuel for various purposes, including electric transport. If enough hydrogen fuel supply is established for electric transport, a major polluting factor can be crossed out from the long list of pollutants [40].

Dry agriculture or liquid fuels such as hydrocarbon methanol can be produced using CO_2 which will also act as a CO_2 fixation process. Electrons, CO_2, and a section of hydrogen yield are used to produce ideal liquid fuels such as methanol. Naturally, living organisms convert inorganic carbon in the form of CO_2 to organic compounds that are used for energy storage. This process is done by photosynthesis and in some organisms by chemosynthesis. These processes can be biomimicked as water and carbon dioxide can be used in the presence of sunlight to produce hydrogen, oxygen, and hydrocarbon fuels or other organic compounds. This whole process serves as a carbon fixation process, and hydrogen and liquid fuel or dry agriculture production [41].

Device Prototype

A simple prototype for an APS device has been proposed by various professional researchers. The main process of APS can be graphically represented as shown in Figure 8.

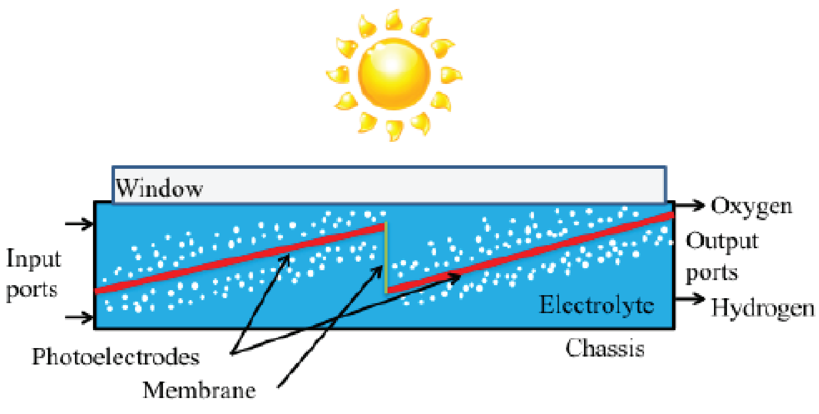

Figure 8. A graphical representation of the main process of artificial photosynthesis [42].

As seen in the diagram above, the input ports allow input of water. The photoelectrodes are responsible to act as the reaction surface where water is broken down into hydrogen and oxygen. The catalysts for this reaction are found on the photoelectrodes. These catalysts are efficient, increase the rate of reaction kinetics, and have a selective nature for the specific output of hydrogen and oxygen [42]. Using sunlight, the photoanode and photocathode generate voltage to carry out water splitting. The output ports allow storage or use of the resulting products. The oxygen is let out while hydrogen is either stored as fuel or taken to a liquid fuel production segment. The membrane separates the electrolyte mixtures; water is on the left while hydrogen and oxygen on the right of the membrane [43].

Limitations of Artificial Photosynthesis

As seen in the dark reaction or Calvin cycle of the natural photosynthesis process, ribulose bisphosphate acts as a very important molecule for carbon fixation. Although possible substitutes have been used, it's still a challenge for scientists to produce a molecule which is more or on par, in terms of efficiency, with ribulose bisphosphate. Another drawback, which can be considered a major one, is that due to the nature of this form of energy source, it's impossible to implement it worldwide. The most efficient and dependable regions worldwide are selective. Although not globally, thankfully many regions such as gulf countries including Saudi Arabia (Figure 9) receive the needed amount of sunlight for this method to be viable [44].

The conversion efficiency of solar to chemical energy, although industrially feasible, seems low for it to be a major viable energy source. The efficiency is still quite high being at least 10% or higher [36]. However, the efficiency scaling up is still a major problem. In natural photosynthesis, organic catalysts that are unstable are used but have a peculiar characteristic of self-healing. This characteristic can't be achieved in any artificial catalyst used by us. Substitute metal oxides and various other catalysts can be used but they lack the same efficiency [45].

Some Quantitative Facts

In reality, natural photosynthesis is an inefficient process and usually has an efficiency below 1%, with some exceptions such as sugarcane in tropical climates [46]. However, APS utilises the most energetically efficient primary events of light capture, charge separation and charge transfer. According to studies, more than 40% solar light is absorbed by n-type semiconductors, which makes APS a promising technique [46]. To date, the efforts to commercialise APS have been fruitful, and it will soon be a viable alternative fuel source. Some researchers used photovoltaic-coupled electrolysers incorporating the workings of both a solar cell and an electrochemical cell in two steps. In that configuration, APS has demonstrated the most efficient conversion as high as 30% [46].

Comparison of Artificial Photosynthesis with Other Technologies

Although artificial photosynthetic technology has demonstrated the potential of applying this tool in various applications other than fuel production, there are still areas which require keen investigation to come up with viable solutions to make this technology practical. Among them the issues of cost and yield in fuel production are of prime importance to be resolved. A large number of studies have been done in the past as shown in Table 1, to achieve better

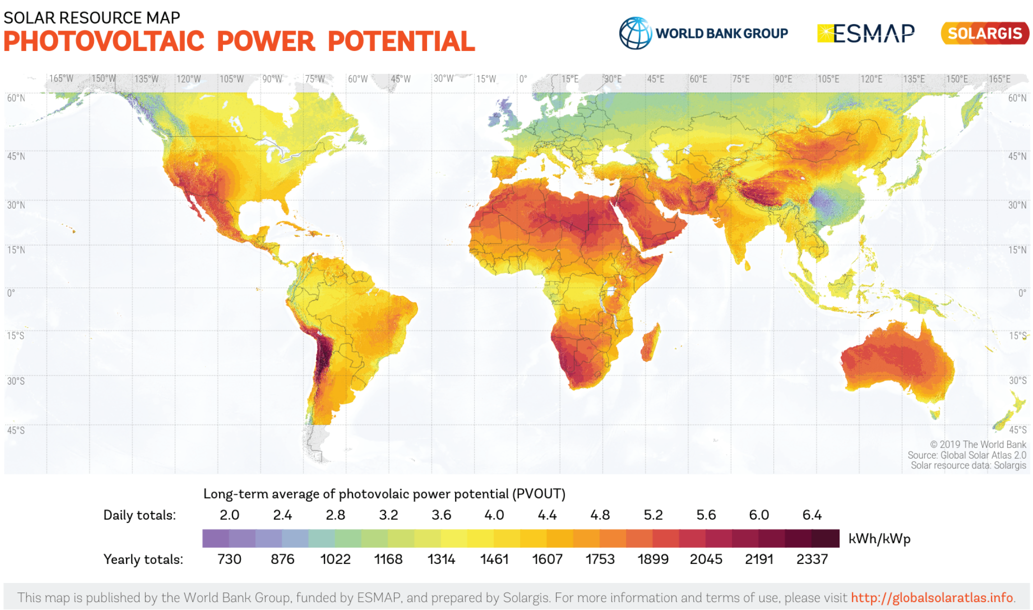

Figure 9. Global photovoltaic power potential in 2019 [44].

Clean Energy Technol J,, Vol. 1, No. 2, pp. 90–104, December, 2023

yield and conversion efficiencies [39], however, researchers are still hopeful to bring the technology to a commercial level [47]. As shown in the Table 1, various PV cell materials were tested, and among them TiO_2 hydrogenated-crystals gave a conversion efficiency of more than 26% during hydrogen production. These materials and light sources are among the controlling parameters. These studies demonstrated optimistic and encouraging results in terms of conversion efficiencies and the yields.

Comparison and Trend in Cost of Renewable Energy

According to the International Renewable Energy Agency (IRENA), in 2019, the energy produced from renewable sources was comparable in price to that of fossil fuels [57]. IRENA set targets to implement renewable energy by gradually replacing conventional energy sources. Accordingly, IRENA stated that by the necessary investment and implementation, renewable energy sources could effectively supply 86% of the world's projected energy needs by the year 2050 [58, 59].

At present, the cost of renewable hydrogen production is 8 to 9 times higher than when it is produced by natural gas steam methane reforming, which is only \$ 1.39/kg H [58]. Table 2 shows the cost comparison of various fossil and renewable energy sources. The estimates depend on the location, such as availability of solar flux in the solar energy option and availability of fuel reserves in the case of oil and gas options.

As shown in Figure 10, the temporal variation of capital cost of various renewable energies is declining with the advancement in materials and technology. Among them, the decrease in cost of solar photovoltaic systems is significant, mainly due to the development of more advanced materials and reduction in fabrication and installation costs. Similarly, a significant reduction is expected with the increase in conversion efficiency as well as the decrease in fabrication cost of APS setups. The trend is encouraging and demands an active contribution of researchers to come up with a viable economic and practical option for APS. Furthermore, with the increase in the cumulative energy capacity, the installed cost per watt also reduces [60]. It is also expected that for APS, depending on whether it is a standalone or hybrid system, significant reduction in the cost is anticipated [61]. Therefore, in the pace of switching from conventional energy sources to innovative and any possible renewable energy sources during the year 2020, the U.S. Department of Energy (DOE) announced a 5-year funding plan of \$100 million towards research on APS. This investment by the DOE shows the expectations and commitment of the country in the area of APS. Studies in the past and the present study concludes that this technology has the potential to be a part of the energy mix in relieving the world's current energy dilemma [62].

Table 2. Cost comparison of various fossil and renewable energy sources [59, 63, 64, 65].

Renewable Energy Type	Cost (\$/kW-hr)
Coal & Oil	0.05-0.15
Natural Gas	0.043-0.06
Nuclear	0.093-0.12
Concentrated Solar Power	0.108-0.34
Wind onshore	0.038-0.10
Wind offshore	0.106-0.13
Solar Photovoltaic	0.036-0.381
Solar Thermal	0.12-0.165
Geothermal	0.04-0.09
Biomass	0.09-0.108
Hydroelectric	0.039-0.05

Table 1. Comparison of research on APS in terms of conversion efficiencies and the yields

Type of Fuel Produced	PV Cell Material	Light Source	Conversion Efficiency (%)/ Production Rate (mmole/hr)	Reference
Hydrogen	Boron-doped p-Si microwires	100 mW/cm^2, ELH-type W-halogen	9.6	[48]
Hydrogen	p-InP with TiO_2 passivation and Ru cocatalyst	100 mW/cm^2	14.0	[49]
Hydrogen	Black hydrogenated TiO_2 crystals	Visible and infrared light	26.1	[50
Hydrogen	ZnO-ZnS nanowires	100 mW/cm^2	Production rate of H2: ~ 4.29	[51]
Hydrogen	Boron-doped g-C_3N_4 with Pt and $Co(OH)_2$ cocatalyst	Simulated solar illumination	Production rate of H2: 0.033	[52]
Hydrogen	3D macropore carbon-vacancy g-C_3N_4	300 W Xe lamp	Production rate of H2: 0.065	[53]
Methane	g-C3N_4/TiO_2 with MnOx and Au cocatalyst	Visible light: $\lambda > 420$ nm, 300 W Xe lamp	Production rate of CH4: 0.14	[54]
Methane	Carbon quantum dot/protonated	Visible light: $\lambda > 400$ nm, 500 W	Production rate of CH4: 0.037	[55]
Methane	TiO_2@$ZnIn_2S_4$/ Ti_3C_2 MXene	300 W Xe lamp, $200 < \lambda < 800$ nm	Production rate of CH4: 0.011	[56]

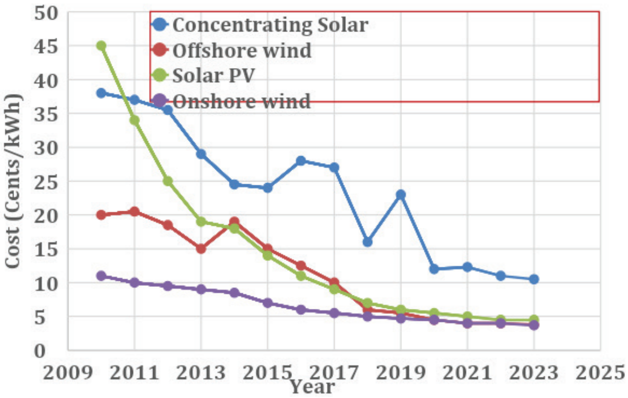

Figure 10. Temporal variation in renewable energy cost [66, 67, 68].

An exact and complete economic estimation for the overall operation of an APS plant, involving operational site selection, plant construction, acquisition of raw materials and energy, distribution of products, and balancing of income/expenditure is not easy. However, based on current information about material and process efficiency, a simple model estimate for the production feasibility can be demonstrated. Estimates presented in a previous study can be utilised to customise cost based on location, material and conversion efficiency.

It is estimated that 7900 tonnes of H_2 can be generated annually by 1 km^2 of solar flux region with a solar to hydrogen efficiency of 10%. If an H_2 to methane conversion efficiency of 70.8% as an average is considered, 11,200 tonnes methane per year can be produced by providing 71,100 tonnes of water and 43,500 tonnes of CO_2 annually with an expenditure of 1.23 × 1013 J year^{-1} of electric energy for the filter pumps as the major part of ancillary energy. The produced amount of energy is corresponding to 17.789 MW annually [69].

DISCUSSION

Present studies show that APS is a promising option leveraging sunlight to drive chemical reactions. The photo-electric cells can be used to perform both hydrogen evolution reactions and oxygen evolution reactions–mimicking the natural photosynthetic processes after capturing and storing solar energy as chemical energy in the form of hydrogen [70]. The process is promising; however, it is necessary to design more efficient materials with a careful balance between light absorption, charge separation, and redox reaction kinetics to achieve optimal performance. Overcoming the stated dares compels continual research and progress [71].

Detailed review shows that some researchers have developed biomimetic approaches, complexes that mimic the structure and function of the active sites in hydrogenases and photosystems to catalyse the hydrogen evolution reaction and oxygen evolution reaction, respectively. These catalysts are targeted to utilise the same contrivances which are used in the natural process. This approach significantly increases the efficiency of these reactions. This biomimetic approach has been utilised to develop catalysts that convert CO_2 into biofuels, other useful chemicals and effectively enhance the selectivity of the process which will help to produce the required specific product. The design and development of such biomimetic systems is difficult and challenging. At present, it is required to mimic the complexity of APS as accurately as possible, which should be a stable and efficient assimilation of components. Furthermore, these designs have to be scaled up for real life applications. Although these limitations may seem overwhelming, most of these limitations have viable substitutions and aren't limited by possibility. Trial and error is an important part in the advancement of any technology. With increased advancement in technology, many of these setbacks can be overcome. Present study shows that the present pace of development will lead to a robust process, and it holds enormous prospective for the imminent future of artificial photosynthesis. It is also evident that probing into the light capture mechanisms, charge separation pathways, catalytic routes, and formation of final products provided significant developments in APS [70].

Energy and Related Pollution Situation in Saudi Arabia

The Kingdom of Saudi Arabia is the owner of the second largest crude oil reserves in the world. Fossil fuel combustion is one of the chief causes of greenhouse gases emissions in the country. It is mainly due to the fact that almost all of Saudi Arabia's domestic energy demand was met by utilising fossil fuels [71]. According to studies, the country's CO_2 emissions reached 18 tons per capita annually [72]. According to the World Bank report, the annual greenhouse gas emission levels have been persistently growing, on average, over the last couple of decades [71]. Recent studies reported that the per-capita annual CO_2 emissions from 1969 to 2020 have increased by around 3.65% [73]

Renewable Energy and Vision 2030 Plan of Saudi Arabia

As per the plan of Saudi Vision 2030, Saudi Arabia is fully committed to becoming a renewable energy state [4]. Saudi Vision 2030 considers renewable energy more than oil and mineral resources as one of the pillars for the growth of the country's economy. The Kingdom is ambitious to achieve self-reliance by focusing on the numerous and significant branches of the Saudi economy. Plans according to the Vision 2030 give priority to localising the manufacturing and fabrication related equipment in the local industries [4].

In order to handle the current emission and pollution levels of the country, active actions towards renewable alternatives have been started to fulfil its growing energy demand. Saudi Vision 2030 and its implementations in the roadmap show the robust potential of various renewable energy sources as alternatives to fossil fuels in Saudi Arabia [74]. According to the plan, the target is to achieve 27.3 GW of renewable power capacity by 2023 and 58.7GW by 2030. However, at its current rate of renewables development (an average of 0.1 GW/year, between 2010-2021), it will lead to a shortfall of 25.8 GW towards its 2023 target [74]. In fact, efforts towards achieving the targets started earlier by implementation of the first 2 MW PV system installed on the roof of King Abdullah University of Science and Technology (KAUST) in Saudi Arabia during the year 2010 [75], and 10 MW solar power plants in Al-Oyainah and Al-Khafji. Similarly, a 500 kW photovoltaic plant with a capacity of 864 MWh/year was commissioned on Farasan Island during October 2011 [76].

In the year 2012, a thermal solar plant was inaugurated at Princess Noura University for Women (PNUW), the largest of its kind in the world. Covering an area of 36,160 m^2, it has a power capacity of up to 25 MW [75]. A 10 MW PV carport system was constructed by Saudi Aramco at their headquarters in Dhahran [75]. During the year 2012, a solar park of 3.5 MW was built by Aramco King Abdullah Petroleum Studies and Research Centre in Riyadh [77]. A solar village project of 1.5 MWh/d of electric energy was built near Al-Jubailah, Al-Uyaynah and Al-Higera [78]. According to the plan, three strategic renewable energy projects have already been started; a 300 MW solar PV plant at Sakaka, a 2,400 MW wind energy plant in Midyan, and another with the same capacity in Dumat Al-Jandal [79].

Mix Renewable Energy Sources Plan of Saudi Arabia

Although information about the implementation of renewable energy in the Kingdom is available, limited information is available about the possibility of APS as one of the components of the energy plan. This study is contributing to filling the gaps in the present literature about the key solutions to the major limitations, which are becoming the main obstacles in the implementation of APS and the contribution of this option during the energy transformation in the Kingdom.

This study also sought to explore the existing literature about the success in transforming from conventional to renewable energy by utilising different renewable energy options (wind, solar and geothermal), including APS in general and specifically in the Kingdom, which is planned according to the vision 2030 of the Kingdom. The main idea of the research is to evaluate the possibility of APS as an alternative source of renewable energy in the country. The current study also identified the key limitations and obstacles in adopting this renewable energy option during the pace of transforming the energy scenario of Saudi Arabia.

In the present scenario and future plans based on the Saudi Vision 2030 and their implementations, the road map shows potential for renewable energy options; however, APS needs a strategic plan to achieve feasibility comparable to the other options at present. Furthermore, there is a need to develop an efficient molecular catalysis which will advance the achievement of a viable APS system [5]. It is recommended that photosynthesis may be developed in conjunction with wind, solar and geothermal sources of renewable energy as a mix.

CONCLUSIONS

Every country should take steps to understand and manage their greenhouse gas emissions by preparing annual greenhouse gas inventories and setting long-term targets to reduce emissions from fossil fuel burning. Several options exist to transition away from a fossil fuel economy. Solar, biomass, wind, geothermal, and APS could be sources of renewable energy in the country's energy mix plan. To conclude, the implementation of APS technology in most sunlight rich regions such as Saudi Arabia was proved to be an efficient, environmentally friendly, and viable addition to other renewable energy resources. With an almost unlimited supply of water for hydrogen fuel production, sunlight, carbon dioxide abundance, and various efficient catalysts such as manganese and cobalt oxide, APS is proven to be an ever-present renewable energy resource. Although it has high potential, APS needs more active research to enable its addition into the vastly implemented renewable energy methods such as wind and solar power. This research and review article provides initial review and is limited to the knowledge available in the literature. The limitations were studied, and alternative methods were adopted. It is suggested to conduct extensive research to produce simple liquid fuels, such as methanol, hydrogen and dry agriculture for initial prototype implementation. As APS provides an additional option to get renewable and sustainable energy, researchers are sure that in the future this option will stand along with the present day renewable energy options. At present, researchers are trying to search various sources of renewable energy that can provide some relief to the accelerating demand of energy to tackle the situation before any energy crises.

According to the Saudi Vision 2030, the country intends to fully commit itself to becoming a renewable state [4]. The kingdom initially set itself a primary target of producing 9.5 GW of renewable energy [71], with plans of generating up to 60 GW by the year 2030, 40 GW of which would be solar power with the other 20 GW consisting chiefly of wind power and other renewable sources [80]. The kingdom has allocated around $117 billion into this ambitious endeavour [81]. According to the Saudi Vision 2030, the country has developed plans and implementation of plans are in progress to adopt renewable energy options including wind and solar energy; however, APS requires more research to achieve feasibility like that possessed by other renewable energy options. It is recommended that photosynthesis be developed as a renewable energy source in conjunction with wind, solar and geothermal energy options in the country. Furthermore, by directing the research towards prevailing limitations and concentrating on the design of materials, catalysis reactions, interface engineering, and optimised design of reactors, the feasible way for the advancement of efficient and sustainable artificial photosynthesis systems can be achieved. It is strongly expected that the cost of APS technology will become affordable over time. Sustained efforts on this track will be helpful in achieving the full potential of artificial photosynthesis as an auspicious possibility for a secondary source of renewable energy generation. The authors concluded by mentioning the requirements for more flexible policy options which will help to accelerate the adoption of renewable energy in the country [82].

Funding: There is no funding source for this study.

Acknowledgments: The authors would like to acknowledge all the motivation and support provided by the Jubail Industrial College, Saudi Arabia, KFUPM, Saudi Arabia, and NED University of Engineering & Technology, Pakistan.

Conflicts of Interest: The authors declare that there is no conflict of interests regarding the publication of this paper.

REFERENCES

[1] Ritchie H, Roser M, Rosado P. CO_2 and Greenhouse Gas Emissions. Our World in Data. 2020. Available at: https://ourworldindata.org/emissions-by-fuel. Accessed April 9, 2023.

[2] United Nations Environment Programme. A Global Response to Pollution. 2022. Available at: https://www.unep.org/beatpollution/global-response-pollution Accessed on Apr 3, 2022.

[3] Shields-Menard SA, Amirsadeghi M, French WT, Boopathy R. A review on microbial lipids as a potential biofuel. Bioresour Technol 2018;259:451–460.

[4] Arabia S. Saudi Arabia Vision 2030. Gazette. Riyadh Tuesday; Available at: https://semiocast.com/downloads/Semiocast_Twitter_debate_on_Saudi_Arabia_Vision_2030_20160516.pdf Accessed on Apr 26, 2016.

[5] Kathpalia R, Verma AK. Artificial Photosynthesis as an Alternative Source of Renewable Energy: Potential and Limitations. Physiology. London: IntechOpen; 2023. [CrossRef]

[6] Kopp OC. Fossil Fuel. Encyclopædia Britannica. 2021 June 1. Available at: https://www.britannica.com/science/fossil-fuel. Accessed April 5, 2022.

[7] Union of Concerned Scientists. The Hidden Costs of Fossil Fuels. 2016 August 30. Available at: https://www.ucsusa.org/resources/hidden-costs-fossil-fuels. Accessed on April 6, 2022.

[8] Holzman DC. Mountaintop removal mining: digging into community health concerns. 2011;119:A509. [CrossRef]

[9] Hou B, Chang Z, Fu W, Muhadasi Y, Chen M. Fracture initiation and propagation in a deep shale gas reservoir subject to an alternating-fluid-injection hydraulic-fracturing treatment. Spe J 2019;24:1839–1855. [CrossRef]

[10] Yu H, Zahidi I. Environmental hazards posed by mine dust, and monitoring method of mine dust pollution using remote sensing technologies: An overview. Sci Total Environ 2023;864:161135. [CrossRef]

[11] Nicoles E. Fossil Fuels Pros and Cons. solarreviews. 2022 February 22. Available at: https://www.solarreviews.com/blog/fossil-fuels-pros-and-cons. Accessed Apr 6, 2022.

[12] Osman AI, Chen L, Yang M, Msigwa G, Farghali M, Fawzy S, et al. Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. Environ Chem Lett 2023;21:741–764. [CrossRef]

[13] Rinkesh. Top 15 Worst Environmental Disasters Caused by Humans. Conserve Energy Future. 2022. Available at: https://www.conserve-energy-future.com/worst-environmental-disasters-caused-by-humans.php. Accessed Apr 8, 2022.

[14] Kenny J. The evolution of environmental concern in Europe. Res Handb Environ Sociol 2021;79-96. [CrossRef]

[15] Banton C, Potters C, Rathburn P. Renewable Resource. Investopedia. 2021 Oct 30. Available at: https://www.investopedia.com/terms/r/renewable_resource.asp. Accessed Apr 5, 2022.

[16] Donev J, Jenden J, Lloyd E, Stenhouse K, Strange M, Suarez LV, Yyelland B. Renewable and Sustainable Energy. Energy Education. 2021 December 20. Available at: https://energyeducation.ca/encyclopedia/Renewable_and_sustainable_energy. Accessed Apr 5, 2022.

[17] Darwish AS, Al-Dabbagh R. Wind energy state of the art: present and future technology advancements. Renew Energy Environ Sustain 2020;5:7. [CrossRef]

[18] Wong WY, Lim S, Pang YL, Shuit SH, Chen WH, Lee KT. Synthesis of renewable heterogeneous acid catalyst from oil palm empty fruit bunch for glycerol-free biodiesel production. Sci Total Environ 2020;727:138534. [CrossRef]

[19] Sasidhar KB, Kumar PS, Xiao L. A critical review on the two-stage biohythane production and its viability as a renewable fuel. Fuel 2022;317:123449. [CrossRef]

[20] Najafpour MM, Shen JR, Allakhverdiev SI. Natural and artificial photosynthesis: fundamentals, progress, and challenges. Photosynth Res 2022;154:229–231. [CrossRef]

[21] Xie Y, Khoo KS, Chew KW, Devadas VV, Phang SJ, Lim HR, et al. Advancement of renewable energy technologies via artificial and microalgae photosynthesis. Bioresour Technol 2022;363:127830. [CrossRef]

[22] Sharma S, Ghoshal SK. Hydrogen the future transportation fuel: From production to applications. Renew Sustain Energy Rev 2015;43:1151–1158. [CrossRef]
[23] Zhang T, Yang, H. Building-Integrated Photovoltaics (BIPV). Handbook of Energy Efficiency in Buildings (pp. 443-506). Amsterdam: Elsevier; 2018.
[24] Walczak KA, Hutchins MJ, Dornfeld D. Energy system design to maximize net energy production considering uncertainty in scale-up: A case study in artificial photosynthesis. Procedia CIRP 2014;15:306–312. [CrossRef]
[25] Wang Y, Seo B, Wang B, Zamel N, Jiao K, Adroher XC. Fundamentals, materials, and machine learning of polymer electrolyte membrane fuel cell technology. Energy and AI 2020;1:100014. [CrossRef]
[26] Solargis. Photovoltaic Electricity Potential. Available at: https://solargis.com/maps-and-gis-data/download/world. Accessed May 3, 2022.
[27] Mengele AK, Rau S. Learning from Nature's Example: Repair Strategies in Light-Driven Catalysis. JACS Au 2022;3:36–46. [CrossRef]
[28] Lan G, Fan Y, Shi W, You E, Veroneau SS, Lin W. Biomimetic active sites on monolayered metal-organic frameworks for artificial photosynthesis. Nature Catalysis 2022;5:1006–1018. [CrossRef]
[29] Qiu B, Du M, Ma Y, Zhu Q, Xing M, Zhang J. Integration of redox cocatalysts for artificial photosynthesis. Energy Environ Sci 2021;14:5260-5288. [CrossRef]
[30] Boettcher SW, Warren EL, Putnam MC, Santori EA, Turner-Evans D, Kelzenberg MD, et al. Photoelectrochemical hydrogen evolution using si microwire arrays. J Am Chem Soc 2011;133:1216–1219. [CrossRef]
[31] Lee MH, Takei K, Zhang J, Kapadia R, Zheng M, Chen Y-Z, et al. p-Type InP nanopillar photocathodes for efficient solar-driven hydrogen production. Angew Chem Int Ed 2012;51:10760–10764. [CrossRef]
[32] Chen X, Liu L, Yu PY, Mao SS. Increasing solar absorption for photocatalysis with black hydrogenated titanium dioxide nanocrystals. Science 2011;331:746–750. [CrossRef]
[33] Chen HM, Chen CK, Liu RS, Wu CC, Chang WS, Chen KH, et al. A new approach to solar hydrogen production: a ZnO-ZnS solid solution nanowire array photoanode. Adv Energy Mater 2011;1:742–747. [CrossRef]
[34] Zhao D, Wang Y, Dong C-L, Huang Y-C, Chen J, Xue F, et al. Boron-doped nitrogen-deficient carbon nitride-based Z-scheme heterostructures for photocatalytic overall water splitting. Nat Energy 2021;6:388–397. [CrossRef]
[35] Wang X, Li Q, Gan L, Ji X, Chen F, Peng X, et al. 3D macropore carbon-vacancy g-C3N4 constructed using polymethylmethacrylate spheres for enhanced photocatalytic H2 evolution and CO2 reduction. J Energy Chem 2021;53:139–146. [CrossRef]
[36] Shah R, Matsil E, Massoud G. Artificial Photosynthesis as a Renewable Energy Source. Retrieved April 8, 2022, from ALTENERGYMAG. Available at: https://www.altenergymag.com/article/2021/04/2021-top-article-artificial-photosynthesis-as-a-renewable-energy-source/34878 Accessed on Dec 19, 2023.
[37] Chouhan N, Liu RS, Zhang J. Photochemical water splitting: materials and applications.1st ed. New York: CRC Press; 2017. [CrossRef]
[38] Najafpour MM, Shen JR, Allakhverdiev SI. Natural and artificial photosynthesis: fundamentals, progress, and challenges. Photosynthesis Res 2022;154:229–231. [CrossRef]
[39] Xie Y, Khoo KS, Chew KW, Devadas VV, Phang SJ, Lim HR, et al. Advancement of renewable energy technologies via artificial and microalgae photosynthesis. Bioresour Technol 2022;363:127830. [CrossRef]
[40] Sharma S, Ghoshal SK. Hydrogen the future transportation fuel: From production to applications. Renew Sustain Energy Rev 2015;43:1151–1158. [CrossRef]
[41] Thornton DCO. Primary production in the ocean. In: Advances in Photosynthesis-Fundamental Aspects. Intech; 2012. p. 563–588.
[42] Walczak KA, Hutchins MJ, Dornfeld D. Energy system design to maximize net energy production considering uncertainty in scale-up: A case study in artificial photosynthesis. Procedia CIRP 2014;15:306–312. [CrossRef]
[43] Wang Y, Seo B, Wang B, Zamel N, Jiao K, Adroher XC. Fundamentals, materials, and machine learning of polymer electrolyte membrane fuel cell technology. Energy AI 2020;1:100014. [CrossRef]
[44] Solargis. Photovoltaic Electricity Potential. 2022. Available at https://solargis.com
[45] Mengele AK, Rau S. Learning from Nature's Example: Repair Strategies in Light-Driven Catalysis. JACS Au 2022;3:36–46. [CrossRef]
[46] Lan G, Fan Y, Shi W, You E, Veroneau SS, Lin W. Biomimetic active sites on monolayered metal-organic frameworks for artificial photosynthesis. Nature Catalysis 2022;5:1006–1018. [CrossRef]
[47] Qiu B, Du M, Ma Y, Zhu Q, Xing M, Zhang J. Integration of redox cocatalysts for artificial photosynthesis. Energy Environ Sci 2021;14:5260–5288. [CrossRef]
[48] Boettcher SW, Warren EL, Putnam MC, Santori EA, Turner-Evans D, Kelzenberg MD, et al. Photoelectrochemical hydrogen evolution using si microwire arrays. J Am Chem Soc 2011;133:1216–1219. [CrossRef]
[49] Lee MH, Takei K, Zhang J, Kapadia R, Zheng M, Chen Y-Z, et al. p-Type InP Nanopillar Photocathodes for Efficient Solar-Driven Hydrogen Production. Angew Chem Int Ed 2012;51:10760–10764. [CrossRef]

[50] Chen X, Liu L, Yu PY, Mao SS. Increasing solar absorption for photocatalysis with black hydrogenated titanium dioxide nanocrystals. Science 2011;331:746–750. [CrossRef]

[51] Chen HM, Chen CK, Liu RS, Wu CC, Chang WS, Chen KH, Tsai DP. A new approach to solar hydrogen production: a ZnO-ZnS solid solution nanowire array photoanode. Adv Energy Mater 2011;1:742–747. [CrossRef]

[52] Zhao D, Wang Y, Dong C-L, Huang Y-C, Chen J, Xue F, et al. Boron-doped nitrogen-deficient carbon nitride-based Z-scheme heterostructures for photocatalytic overall water splitting. Nat Energy 2021;6:388–397. [CrossRef]

[53] Wang X, Li Q, Gan L, Ji X, Chen F, Peng X, et al. 3D macropore carbon-vacancy g-C3N4 constructed using polymethylmethacrylate spheres for enhanced photocatalytic H2 evolution and CO2 reduction. J Energy Chem 2021;53:139–146. [CrossRef]

[54] Raziq F, Sun L, Wang Y, Zhang X, Humayun M, Ali S, et al. Synthesis of large surface-area g-C3N4 comodified with MnOx and Au-TiO2 as efficient visible-light photocatalysts for fuel production. Adv Energy Mater 2018;8:1701580. [CrossRef]

[55] Ong W-J, Putri LK, Tan Y-C, Tan L-L, Li N, Ng YH, Wen X, Chai S-P. Unravelling charge carrier dynamics in protonated g-C3N4 interfaced with carbon nanodots as co-catalysts toward enhanced photocatalytic CO2 reduction: A combined experimental and first-principles DFT study. Nano Res 2017;10:1673–1696. [CrossRef]

[56] Wang K, Li X, Wang N, Shen Q, Liu M, Zhou J, Li N. Z-Scheme Core-Shell meso-TiO2@ZnIn2S4/Ti3C2 MXene enhances visible light-driven CO2-to-CH4 selectivity. Ind Eng Chem Res 2021;60:8720–8732. [CrossRef]

[57] Nguyen PA, Abbott M, Nguyen TLT. The development and cost of renewable energy resources in Vietnam. Utilities Policy 2019;57:59–66. [CrossRef]

[58] Vimmerstedt L, Akar S, Mirletz B, Sekar A, Stright D, Augustine C, et al. Annual Technology Baseline: The 2022 Electricity Update. National Renewable Energy Lab. (NREL), Golden, CO (United States); June 28, 2022. [CrossRef]

[59] Sens L, Neuling U, Kaltschmitt M. Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines-Development by 2050. Renewable Energy 2022;185:525–537. [CrossRef]

[60] Weigt H. Germany's wind energy: The potential for fossil capacity replacement and cost saving. Appl Energy 2009;86:1857–1863. [CrossRef]

[61] Kim S, Kim KH, Oh C, Zhang K, Park JH. Artificial photosynthesis for high-value-added chemicals: old material, new opportunity. Carbon Energy 2022;4:21–44. [CrossRef]

[62] Shah WUH, Hao G, Yan H, Zhu N, Yasmeen R, Dincă G. Role of renewable, non-renewable energy consumption and carbon emission in energy efficiency and productivity change: Evidence from G20 economies. Geosci Front 2023;101631. [CrossRef]

[63] Eia U. US Energy Information Administration Annual Energy Outlook 2020 with projections to 2050. US Department of Energy: Washington, DC, USA; 2020.

[64] Kabeyi MJB, Olanrewaju OA. Electricity Generation Costs by Technology. Natural Gas 2022;81:4. [CrossRef]

[65] Alam MM, Aktar MA, Idris NDM, Al-Amin AQ. World energy economics and geopolitics amid COVID-19 and post-COVID-19 policy direction. World Dev Sustain2023;2:100048. [CrossRef]

[66] Gielen D, Gorini R, Wagner N, Leme R, Gutierrez L, Prakash G, et al. Global energy transformation: a roadmap to 2050. International Renewable Energy Agency (IRENA), Abu Dhabi; 2019.

[67] Holechek JL, Geli HM, Sawalhah MN, Valdez R. A global assessment: can renewable energy replace fossil fuels by 2050? Sustainability 2022;14:4792. [CrossRef]

[68] Diallo A, Kitzing L. Selection bias in multi-technology auctions: How to quantify and assess efficiency implications in renewable energy auctions. Energy Policy 2024;184:113864. [CrossRef]

[69] Setoyama T, Takewaki T, Domen K, Tatsumi T. The challenges of solar hydrogen in chemical industry: how to provide, and how to apply? Faraday Discussions 2017;198:509–527. [CrossRef]

[70] Machín A, Cotto M, Ducongé J, Márquez F. Artificial photosynthesis: Current advancements and future prospects. Biomimetics 2023;8:298. [CrossRef]

[71] Ding P, Jiang T, Han N, Li Y. Photocathode engineering for efficient photoelectrochemical CO2 reduction. Materials Today Nano 2020;10:100077. [CrossRef]

[72] World Bank. Available at https://databank.worldbank.org/source/world-development-indicators. Accessed on Dec 5, 2023.

[73] Murshed M. The impacts of fuel exports on sustainable economic growth: The importance of controlling environmental pollution in Saudi Arabia. Energy Rep 2022;8:13708–13722. [CrossRef]

[74] Power Technology News. Saudi Arabia to fall short of its 2023 and 2030 Renewable Target. Available at https://www.power-technology.com/comment/saudi-arabia-renewable/. Accessed on Jun 7, 2023.

[75] Pazheri FR. Solar Power Potential In Saudi Arabia. Int J Eng Res Appl 2014;4:171–174.

[76] Alamri HR, Rezk H, Abd-Elbary H, Ziedan HA, Elnozahy A. Experimental Investigation to Improve the Energy Efficiency of Solar PV Panels Using Hydrophobic SiO2 Nanomaterial. Coatings 2020;10:503. [CrossRef]

[77] Al Shidi H, Sulaiman H, Amoatey P. Shifting to renewable energy to mitigate carbon emissions: initiatives by the states of gulf cooperation council. Low Carbon Economy 2016;7:123–136. [CrossRef]

[78] Bhutto AW, Bazmi AA, Zahedi G, Klemes JJ. A review of progress in renewable energy implementation in the gulf cooperation council countries. J Clean Prod 2014;71:168–180. [CrossRef]

[79] Saudi Press Agency. Riyadh,. Available at: https://www.spa.gov.sa/viewfullstory.php?lang=enand-newsid=2020780 Accessed on Jan 9, 2020.

[80] Al Zohbi G, AlAmri FG. Current situation of renewable energy in Saudi Arabia: Opportunities and challenges. J Sustain Dev 2020;13:98. [CrossRef]

[81] Saleem M, Ali M. Sustainable energy measures in Saudi Arabia based on renewable energy sources: present actions and future plans. In Proceedings of the 4th International Conference on Energy, Environment and Sustainable Development (EESD 2016), Mehran University of Engineering and Technology, Jamshoro, Pakistan, November 1-3, 2016.

[82] Al-Sarihi A, Mansouri N, Al-Otaibi S. GCC Renewable Energy Development Amid COVID-19 Pandemic. In: Kozhanov N, Young K, Qanas J, editors. GCC Hydrocarbon Economies and COVID. Springer; 2023. p. 57–89. [CrossRef]