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Posted Date: September 4th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9541332/v1

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Additional Declarations: No competing interests reported.

Performance Analysis of a Solar-Hybrid System for Sustainable Hydrogen Production via Biomass Reforming

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This study investigates the thermochemical conversion of carbonaceous materials and biomass via solar-driven gasification for the production of high-calorific gaseous fuels. Particular emphasis is placed on intensifying hydrogen generation through the application of concentrated solar radiation. Thermodynamic assessments reveal that while steam gasification of biomass is energetically unfavorable at low temperatures, the process facilitates complex parallel reaction pathways within the 700–900 °C range, significantly enhancing syngas quality. By integrating concentrated solar energy as an external thermal source, the system achieves autothermal operation, eliminating reliance on fossil fuels for reaction maintenance or steam superheating. This integration enhances overall process efficiency and demonstrates a potential reduction in energy consumption by up to 40%. Furthermore, the study elucidates the reaction mechanisms governing the interactions between coal, biomass-derived carbon, and oxidizing agents under high-temperature solar conditions. Design and operational principles of helioreactors, along with the kinetics and pathways of hydrogen formation, are critically analyzed. Utilizing a solar furnace system, the reforming of CO_2–CH_4 mixtures into hydrogen-rich gas streams is facilitated. Additionally, the incorporation of thermal energy storage in molten salts ensures process stability and continuity, thereby advancing the overall sustainability and reliability of the solar-biomass gasification system.

Keywords: Solar gasification, biomass conversion, helioreactors, thermal energy storage, syngas quality, hydrogen production.

1. Introduction

In recent years, there has been a growing emphasis on the exploration and application of alternative energy sources and fuels. Within the spectrum of renewable and non-conventional energy technologies, solar energy stands out as one of the most promising options due to its abundance, sustainability, and potential for diverse applications in energy conversion process [1-5].

Solar-driven coal gasification processes offer significant practical advantages by reducing the consumption of organic fuel traditionally required to maintain reaction temperatures and to generate and superheat steam, achieving energy savings of up to 40% [6]. Accordingly, current research emphasizes the valorization of waste materials through their gasification in solar furnaces, aiming at the production of high-calorific combustible gases [7, 8].

Hydrogen production from diverse feedstocks fundamentally relies on heat supply and the use of oxidizing agents [9]. Water serves as the principal and virtually inexhaustible source of hydrogen, forming the basis of nearly all production methods, including those derived from fossil fuels and other carbon-containing materials. Hydrogen can be directly obtained from water via electrolysis, thermal decomposition, thermochemical cycles, and related processes, typically resulting in a high-purity product with minimal impurities [10, 11].

Most industrial hydrogen production processes are based on the partial oxidation of fuels (gasification and reforming). These processes generate process gases that primarily contain H_2,

CO, and CO_2, from which hydrogen is subsequently separated and purified in later stages [1, 4].

Considering the anticipated future shortage of natural gas and the high costs associated with its extraction, it is deemed appropriate to replace it with solid fuels in applications where it is currently used for hydrogen production [10-12].

There are two fundamentally distinct gasification methods, based on either internal or external heat supply to facilitate the conversion of coal into gas. In the internal heat supply approach, combustion and gasification of the solid fuel occur within a single apparatus [13, 14]. Heat for the gasification process, similar to natural gas reforming, is provided by partial combustion of the fuel in the gasifier [13, 15]. This category includes industrially established processes developed abroad, such as the Lurgi, Winkler, and Koppers-Totzek methods [9, 16].

For a long time, humans have harnessed solar energy stored in chemical bonds by burning biomass as fuel or consuming it, utilizing the energy contained in sugars and starches, as well as extracting fossilized biomass, particularly in the form of coal [5, 16] All fossil fuels consumed by humanity—coal, oil, and natural gas—originate from ancient biomass. Over millions of years, plant residues on Earth have been converted into fuel. Today, biomass-derived fuels can be employed for a wide range of applications, from heating residential buildings to producing automotive fuels. Biomass accumulates its inherent solar energy during plant growth, indicating that solar radiation is the primary source of its internal energy [10]. Undoubtedly, biomass remains one of the most widespread and versatile energy resources on the planet. It provides not only food but also energy, construction materials, paper, textiles, pharmaceuticals, and chemicals. Humans have utilized biomass since the discovery of fire [17, 18]. Currently, biomass fuels are applied for various purposes, including residential heating, electricity generation, and vehicle fuels. Moreover, additional biomass sources can also be identified. The primary methods for harvesting biomass include the following sources [13, 15]:

- agricultural production residues;
- organic industrial wastes, including those from forestry, wood processing, hydrolysis, pulp and paper, food, and meat and dairy industries
- wastewater sludge;

The main types of biomass include:

- wood residues;
- agricultural residues
- Pulp and paper industry wastes (such as spent liquors, pressed bark, and others)

Wood is undoubtedly one of the most well-known examples of biomass. The combustion process releases the energy that the wood accumulated by capturing solar radiation [18,19]. However, in addition to wood, various other types of biomass are utilized, including agricultural residues (such as corn stalks, rice straw and husks, and nut shells), wood waste (including sawdust, logging residues, and wood chips), paper waste, green waste from urban areas, energy plantations (fast-growing trees such as poplar or willow), as well as methane collected from municipal solid waste (MSW) landfills and urban wastewater treatment facilities. Livestock waste is also employed for this purpose [20, 21].

Biomass is one of the most important renewable energy sources for the future of our planet. For approximately 75% of the population in developing countries, biomass serves as a primary energy source [10, 14]. The growth in population and per capita energy consumption, coupled with the depletion of fossil fuel resources, is expected to drive a rapid increase in biomass demand in these regions. It is highly likely that biomass will remain a key energy resource in developing countries throughout the twenty-first century [19].

Researchers worldwide continue to advance studies in the development of environmentally friendly biofuels. Recently, in the state of Florida, USA, production of cellulosic ethanol from wood chips is expected to commence. This production method is anticipated to be more cost-effective compared to the preparation of biodiesel from cereal crops. The new biofuel facility constructed in Florida is projected to produce 135 million liters of ethanol annually [14, 22].

In recent years, biofuels have become an integral part of the global energy system,

primarily because they do not degrade the environment and can, in fact, contribute to its improvement [12-14].

In Finland, a country recognized for its leading position in environmental protection, the use of environmentally friendly energy sources has virtually become a matter of national policy. With approximately 70% of its territory covered by forests and lacking domestic oil and gas reserves, Finland places considerable emphasis on the utilization of alternative energy sources. Currently, 35% of the country's energy is generated from wood processing residues [14-17]. The share of energy derived from these residues reached 65% in 2015 and is projected to increase to 80% in the future [21, 23].

Among European countries, Sweden, Denmark, and Austria lead in biofuel production, followed by `Germany, Norway, Finland, and the United Kingdom. In France, plans are underway to produce environmentally friendly fuels from sugar beet and other agricultural crops. In several European countries, diesel biofuels are produced from residues remaining after the extraction of corn and sunflower oils. In Belgium, fuel stations selling gasoline blended with 15% biofuel derived from sugar beet and cereal crops are already in operation [14, 21].

In recent years, biofuels, which have become an integral part of the global energy system, also contribute to preventing environmental pollution [24, 25].

Some forms of "raw" biomass are suitable for long-term storage. However, due to its relatively low energy density, transporting biomass over long distances is generally impractical. Consequently, significant efforts have recently been made to identify appropriate methods for its utilization [20, 21].

Methods of energy production from biomass are based on the following processes:

- Direct combustion of biomass
- Thermochemical conversion to produce enriched fuels (including pyrolysis, gasification, and liquefaction)
- Biological conversion (such as anaerobic digestion and fermentation)

We will provide a more detailed analysis of specific methods for utilizing biomass: gasification and pyrolysis [11, 16]. Gasification is the most advanced process for the chemical conversion of coal. Industrial applications of the Lurgi, Winkler, and Koppers-Totzek gasification processes are well established [6, 7]. The primary objective of these processes is to convert coal into gas, which can be used as fuel for energy generation or as a feedstock for chemical processing [18, 23]. Pyrolysis is the simplest and most ancient method of converting one type of fuel into another with optimal efficiency [3, 4]. Various forms of high-energy fuels are obtained by heating dry wood and straw. This process has long been used for the production of charcoal. Pyrolysis involves heating the raw material—often ground or shredded before being placed in a reactor—under conditions of near-complete absence of air, typically at 300–500°C, until volatile fractions are fully removed [15, 26]. Charcoal possesses roughly twice the energy density of the original material and burns at significantly higher temperatures. Depending on moisture content and process efficiency, producing one ton of charcoal requires 4–10 tons of wood. If volatiles are not collected, charcoal retains about two-thirds of the energy of the original feedstock [16, 27]. Pyrolysis can also be conducted in the presence of small amounts of oxygen (gasification), water (steam gasification), or hydrogen (hydrogenation) [10, 28]. One of the most valuable products in such cases is methane, which can serve as fuel for electricity generation using high-efficiency gas turbines [25, 29]. Advanced pyrolysis technologies allow for the collection of volatile substances, and temperature control enables adjustment of their composition. Liquid products can be used as liquid fuels; however, they contain acids and must be purified before use [22, 23].

Currently, conventional pyrolysis is considered the most attractive technology due to the relatively low temperatures employed, which result in lower emissions compared to direct

combustion [2, 29]. This provides an environmental advantage, particularly in the processing of certain waste types. Efforts are also being made to employ small pyrolysis units for recycling plastic waste and used tires, materials whose storage or disposal has become an increasing concern worldwide [3, 8, 30].

The twenty-first century presents humanity with serious challenges, including the depletion of non-renewable fuel resources and the intensive pollution of the environment with anthropogenic emissions. Therefore, energy and environmental issues must now be considered in close conjunction [23, 24]. One of the main energy resources capable of saving significant amounts of valuable fuels is inexhaustible solar energy [25]. The feasibility of using solar energy to address specific tasks is evident. High levels of concentrated radiant energy in parabolic solar reflectors, reaching up to (20–26) × 10^6 kcal/m²·h, have allowed their effective application in melting refractory materials, determining the thermophysical properties of various materials at temperatures of 2000–3000°C, performing thermal oxidation of gaseous nitrogen, and synthesizing refractory oxides based on aluminum, zirconium, and other elements [24, 31].

In the context of scientific and technological progress, the pursuit of advanced technical solutions and cutting-edge technologies for utilizing solar energy to produce alternative fuels—such as hydrogen and other combustible gases—in areas remote from energy supply networks, through the gasification of solid fuels and hydrocarbon residues, is of undeniable interest [22-27].

Energy storage is a necessary component of most currently developed systems aimed at utilizing renewable energy sources [4, 30]. Any endothermic reaction driven by solar radiation, accompanied by chemical bond or molecular structure rearrangement, can be used for energy storage [14, 25]. Under the influence of ionizing radiation, molecular structural rearrangements occur in organic substances. Noble metals supported on acidic oxides are the most active catalysts for selective ring -opening reaction, but these catalysts are very sensitive to poisoning by several compounds in organic feedstocks [31, 32]. Given this problem, the implementation of new technologies will be required. An ionizing rays can break down the accumulated carbonaceous deposits on the catalyst surface. This process restores active sites, increases catalytic activity and lowers the activation energy required for the reaction [32, 33]. The authors have been investigated the chemical transformations of organic compounds using ionizing radiation. Experimental and kinetic studies have shown that γ-radiation effectively decomposes organic matter, with the rate of the process depending on the absorbed dose [34, 35].

Despite the significant challenges associated with the technological application of solar energy, mainly due to the limited performance of heliothermal installations over large surfaces, the use of solar energy in heliogasification processes allows savings of up to 35% of solid fuel while providing the necessary reaction rate and gas production efficiency through external radiant energy supply [7, 15, 36].

Moreover, the integration of solar energy with the production of hydrogen-rich combustible gas is particularly promising, as hydrogen acts as an energy buffer, smoothing out the stochastic fluctuations of solar radiation [24]. Such solar-to-gas conversion schemes are of great interest, not only for energy storage but also for practical use in providing heat and gas supply for autonomous local needs [24, 37].

Recent studies have explored the role of advanced functional materials in enhancing the efficiency and stability of renewable energy systems. Tl- and Ag-based chalcogenide compounds have been investigated for supercapacitor and sensor applications, demonstrating that their

electrical and dielectric properties are significantly influenced by both radiation effects and structural disorder [38-43]. At low temperatures, their conductivity behavior can be effectively described using Mott's variable range hopping model, highlighting a strong correlation between material structure and functional performance [44-48]. Moreover, radiation-resistant polymer composites, such as high-density polyethylene (HDPE) modified with suitable additives, have been proposed to mitigate solar radiation effects in energy systems [49-52]. These materials serve both protective and functional roles, contributing to improved system stability, durability, and overall efficiency [42, 51].

An effective method for accumulating and long-term storage of solar energy is through the use of upgraded solid fuels, in which energy is stored in the form of combustible hydrogen-rich gases [11, 53]. In the context of scientific and technological progress, the exploration of advanced technical solutions and cutting-edge technologies for utilizing solar energy to produce alternative fuels—such as hydrogen and other combustible gases—remains of significant interest, particularly in regions remote from conventional energy supply networks, through the gasification of solid fuels and hydrocarbon feedstocks [54-57].

Therefore, the present study aims to investigate the production of hydrogen and hydrogen-rich combustible gases from biomass using solar-driven thermochemical processes, with a focus on optimizing technological parameters, maximizing energy efficiency, and demonstrating the practical applicability of the developed methods and apparatus for sustainable energy generation.

Method:

The intensification of existing technologies and the development of fundamentally new methods for processing agricultural residues into liquid or gaseous fuels require a comprehensive understanding of the decomposition patterns of plant biomass under various physicochemical factors, primarily temperature, pressure, and catalysts. Gaseous products were obtained under identical conditions in a specially designed flow-through system (Fig. 1) within a pilot-scale setup and analyzed using gas chromatography with a "Gazochrom-3101" chromatograph, intended for rapid determination of the products of thermal decomposition of various carbon-containing substances. Analysis results were recorded using a KSP-4-909 strip recorder.

Results and discussion:

In studies focused on novel conversion methods, different models and designs of heliogas generators were examined for conducting thermochemical transformations of hydrocarbon feedstocks, solid fuels, and plant biomass at high temperatures using concentrated solar energy. One of the most effective processing approaches is the thermochemical conversion of hydrocarbon feedstocks via concentrated solar radiation in the focal zone of a solar furnace.

The utilization of plant residues with solar energy to produce alternative fuels—hydrogen and hydrogen-rich gases—carries substantial environmental and economic significance. A key consideration in using solar energy for gasification is the selection of carbon-containing material. Accordingly, experimental studies were conducted on the gasification of brown coal from the Kansk-Achinsk Basin (KAB) and residues of major biomass types (agricultural crops), including grapevine and cotton stems, in a solar furnace. Biomass primarily consists of cellulose, hemicellulose, and lignin. For example, the primary conversion of cellulose occurs according to the following reaction:

$$(\mathrm{C}_6H_{10}O_5) + aH_2O \rightarrow CH_4 + (5-a)CO + aCO_2 + (3+a)H_2 \quad (1)$$

Secondary conversion occurs according to the following reactions:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (2)$$
$$CO + H_2O \rightarrow CO_2 + H_2 \quad (3)$$

Thus, by selecting appropriate conditions, the cellulose conversion process can be carried out according to the following reactions:

$$C_6H_{10}O_5 + H_2O \rightarrow CH_4 + 4CO + CO_2 + 4H_2 \ (a = 1) \quad (1.1)$$
$$C_6H_{10}O_5 + 2H_2O \rightarrow CH_4 + 3CO + 2CO_2 + 5H_2 \ (a = 2) \quad (1.2)$$
$$C_6H_{10}O_5 + 3H_2O \rightarrow CH_4 + 2CO + 3CO_2 + 6H_2 \ (a = 3) \quad (1.3)$$

A key feature of the proposed biomass conversion process is the execution of the endothermic reaction using concentrated solar heat. To enhance the efficiency of the thermal decomposition of agricultural residues such as cotton, tobacco, and grape stems with concentrated solar radiation, it is necessary to assess the feasibility of using high-temperature heliothermal installations for this purpose.

The suitability of solar energy for conducting the thermal decomposition of agricultural residues is evident. The high concentration of solar rays achieved by parabolic reflectors enables their application in technological processes such as the gasification of solid fuels for the production of combustible gases.

For the design calculations of the solar energy installation, the following input data were adopted:

a) Meteorological data (for Baku):

1. Annual sunshine duration: Ɛ = 2500 h/year
2. Maximum direct solar radiation incident on a perpendicular surface:
3. Number of working days: 150–180 days/year
4. Maximum design wind speed: V = 25 m/s

b) Optical parameters:

1. Integral reflectivity coefficient of parabolic mirrors: R = 0.8–0.9
2. Focal length: f = 0.637 m
3. Aperture angle: U = 60°

c) Thermotechnical parameters:

1. Achievable temperature limit: ~3000°C
2. Maximum thermal load in the focal zone: (83.5–125.4) × 10^6 kJ/m²·h
3. Heating zone dimensions at temperatures of at least 2000°C

The energy distribution curve and the focal plane of the paraboloid are described by a specific formula (Fig. 1)

$$E_0 = 2926\ kJ/m^2 \cdot h = 0{,}82 kVt/m^2$$

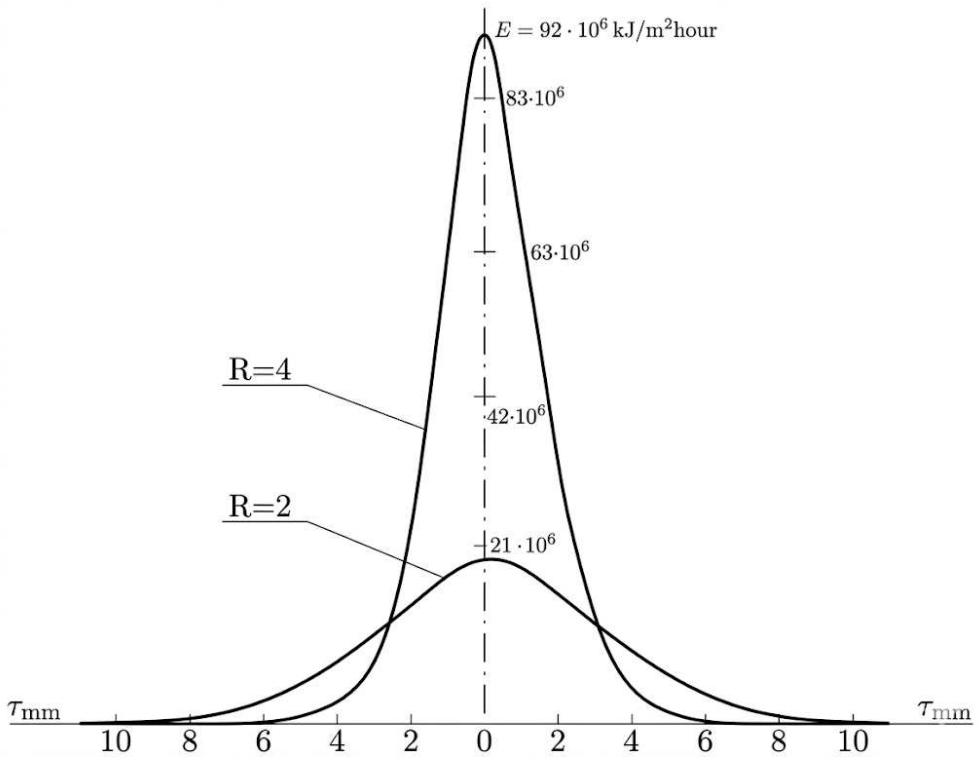


Fig. 1. Calculated curves for energy distribution in the focal plane.

Mirror parameters:

- Diameter: D = 1.5 m
- Aperture angle: U = 61°
- Focal length: f = ρ/2 = 639 mm
- Reflectivity: $R_3 = 0.8$
- Incident energy: $E_0 = 29$ kJ/m²·h
- h – spotlight class

The energy at a point in the focal plane is given by: $E = 83.5 \times 10^6 \cdot \exp(-11.88 \times 10^4)$.

The power of the flux reflected from the mirror is determined according to the corresponding formula [57].

$$Q = E_0 F_3 R_3 = E_0 c785 D^2 R_3 = 4138 \frac{kJ}{h} = 1{,}15\ kVt$$

Assuming an emissivity coefficient of ξ = 1, an absorption coefficient of A_s=0.5, and a minimum reaction temperature of t = 2000°C, the required thermal load can be determined.

$$A_S E_{min} = \sigma(\frac{t_{min}}{100})^4;\ E_{min} = \frac{\sigma}{A_S}(\frac{t_{min}}{100})^4 = 4.6 \cdot 10^6$$

At the central point of the temperature spot, the following value is achieved:

$$t_{max} = 100 \cdot \sqrt[4]{A_S E_{max} 1\sigma\xi} \approx 3000^{\circ} C$$

A_S – the average equilibrium temperature for the working area of the spot is [58]:

$$T_{cp} = \frac{t_{max} + t_{min}}{2}$$

Load ratio

$$\xi = \frac{E_{min}}{E_{max}} = 0{,}07$$

η- relative amount of energy utilized

$$\eta = 1 - \xi = 0.93$$

The image radius containing 93% of the total reflected energy

$$\zeta = \sqrt{\frac{1}{4343} \cdot \sqrt{lg \frac{1}{1-\eta}}} \approx 5.5\ mm$$

Thus, the diameter of the area in which temperatures exceed 2000°C is approximately 11 m. Experimental studies of the heliogasification process of solid fuels were conducted on a laboratory-scale setup with a mirror diameter of D = 1.5 m (the technical specifications of which were described above).

For these purposes, a multifunctional heliothermal installation (HTI) was developed, enabling the dynamic production and collection of combustible hydrogen-rich gas.

The main components of the heliothermal installation (HTI) are a parabolic-type concentrator and a helioreactor equipped with a feed system. Additionally, the system includes solar-tracking, cooling, temperature regulation and control systems, a control unit, and other auxiliary components.

The thermochemical reactor is positioned in the focal zone of the concentrator. The intensity of direct solar radiation is J_0 = 700–800 W/m², the power of concentrated solar rays reflected from the mirror is Q = 1.15 kW, and the reaction chamber temperature ranges from 700 to 900°C. Reaction products were analyzed using gas chromatography.

Experiments were conducted at the heliochemical laboratory site on the HTI (Fig.2).

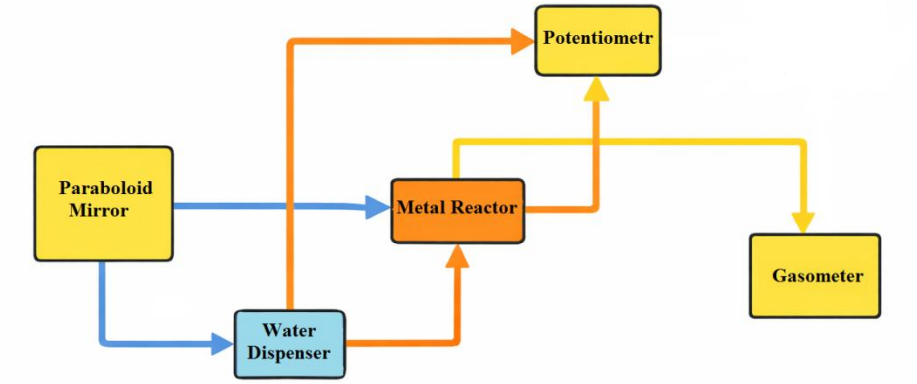


Fig. 2. Scheme for hydrogen production in a metal reactor.

For experiments with brown coals from the Kansk-Achinsk Basin (KAB), samples were taken from the Irsha-Borodino and Berezovsky deposits. In this setup, the helioreceiver of the heliothermal installation consisted of the crushed coal samples with a particle size of 5 mm. The temperature range during the experiments was 700–900°C. Experimental studies demonstrated the feasibility of gasifying brown coals in the heliothermal installation, achieving enhanced performance compared to graphite due to the use of solar energy. Table 1 presents the gasification data for brown coals from KAB.

Table 1

Gasification of KAB brown coals in the heliothermal installation

Raw material	Temperature, °C	Gas outlet, $m^3/h \cdot kg$	Gas composition, % vol.				
			H_2	CO	CO_2	CH_4	N_2
Irsha-Borodinsky angle of the deposit (KAB)	700	1.69	45.0	30.0	20.0	1.5	3.5
	800	2.26	43.0	32.0	11.5	10.0	3.5
	900	3.39	50.0	30.0	2.5	15.0	2.5
Berezovsky Coal. Deposits (KAB)	700	2.07	40.0	28.0	20.0	7.0	5.0
	800	2.83	44.0	27.0	15.0	9.0	5.0
	900	3.20	50.0	24.0	10.0	10.0	5.0

In Azerbaijan Republic, the main agricultural production is based on the cultivation of two major crops – cotton and grapes. The residues from these productions provide a valuable raw material base for their gasification and for the production of combustible household gases. Experimental studies on the gasification of these residues were conducted using a heliothermal installation with a parabolic reflector. The helioreceiver material consisted of crushed grape and cotton stems. The results of these studies are presented in Fig. 3.

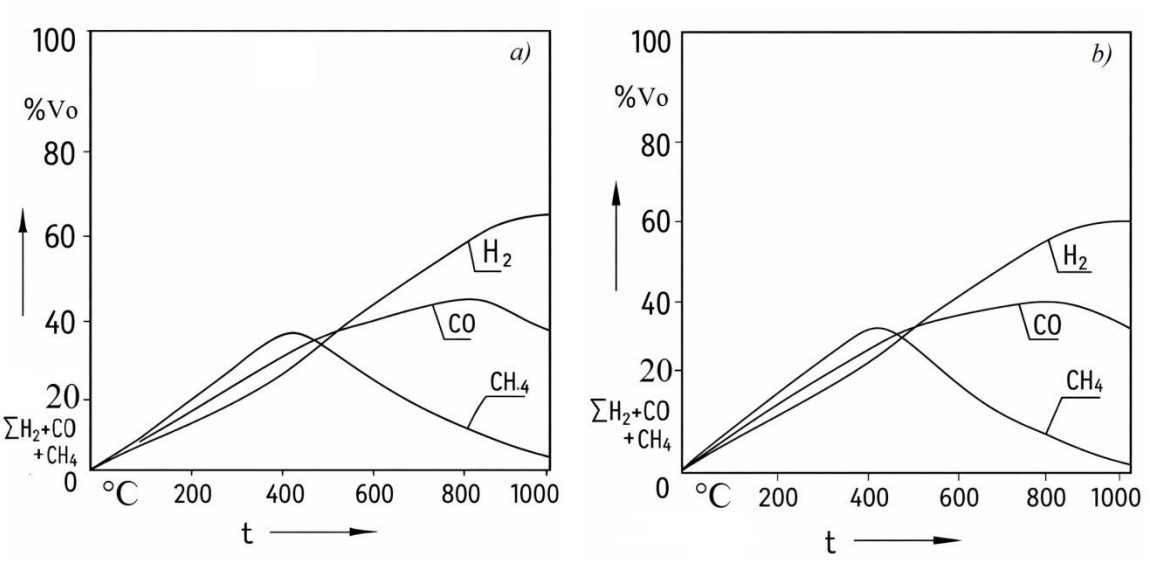


Fig. 3. Composition of gas generated during the thermal decomposition of plant biomass: (a) grape; (b) cotton

As can be seen, in the temperature range of 700–900°C, the gasification processes of these residues proceed efficiently, producing hydrogen-rich combustible gases. A slightly higher hydrogen content was observed for cotton stems compared to grape stems.

Data on the reaction enthalpies for reactions (1.1), (1.2), and (1.3) at temperatures 25, 500, 600, 700, and 727 °C are presented in Table 3. The data indicate that steam conversion of biomass involves comparatively higher energy expenditures. For hydrogen production via methane conversion according to reaction (2), the reaction enthalpy per 1 g of hydrogen is 35 kJ, whereas for hydrogen obtained via reaction (1), it is approximately 23 kJ.

Table2

Heat of reactions ΔH_T^0 kJ/mol

Reactions	Temperature, °C				
	25	500	600	700	727
1.1	249	294	302	313	318
1.2	208	252	266	278	283
1.3	167	219	230	243	247

Table3

Composition of the gas mixture formed by reaction 1. At temperatures of 500-600 °C

Reactions	Amount of water vapor, g/mol	Gas composition, %			
		H_2	CO	CH_4	CO_2
1.1	1	40	40	10	10
1.2	2	54.4	27.3	9.1	18.2
1.3	3	50.0	16.7	8.3	25.0

The calorific value of the generated gas is regulated by the temperature and the H_2O:biomass ratio, which allows obtaining gas with higher energy content within the material's potential limits. In a series of experimental studies, for a standard helioreactor biomass load of up to 0.15 kg, the hydrogen and hydrogen-rich gas yield averaged 80–100 $\times 10^{-3} m^3/h$. The composition of the produced gas closely corresponded to the data presented in Table 4.

Table 4

Energy conversion and efficiency in coal gasification processes using solar energy

Coal processing reactions, kJ	Combustion energy of carbon, kJ	Combustion energy of reaction products, kJ	Accumulated energy 1t of coal and EF
C gasification using steam $C + H_2O = CO + H_2 - 131\ kJ$	$C + O_2 = CO_2 + 393.5$	$CO + 0.5O_2 = CO_2 + 283$ $H_2 + 0.5O_2 = H_2O + 241.8$	$0.94 \cdot 10^6$ γ=33%
$C + CO_2 = 2CO - 175$	$C + O_2 = CO_2 + 393.5$	$2CO + O_2 = 2CO_2 + 566$	$14.37 \cdot 10^6$ γ=43.8%

Due to real-world variations in solar radiation intensity on the helioconcentrator, maintaining precise temperatures (500–700 °C) is challenging. Therefore, thermochemical decomposition experiments of biomass on the solar installation were conducted at 500 ± (30–50 °C) and 700 ± (30–50 °C). Long-term experiments in the flow-through helioreactor demonstrated that within this temperature range, the highest rates of biomass thermal decomposition and the maximum yields of hydrogen and hydrogen-containing gases were observed.

In recent decades, significant achievements have been made in various technological fields using alternative and renewable energy sources. One of these areas is solar-hydrogen energy, which has been extensively studied in laboratories over many years. High-potential solar energy installations have been developed, producing combustible gases (H_2, CH_4, CO) from solid fuels, including coal and agricultural residues. The thermochemical characteristics of hydrocarbon decomposition and the optimization of focal temperatures in the installation's concentration zone have been investigated.

Currently, hydrogen is produced worldwide using a variety of methods. Hydrogen can be produced from a variety of primary energy sources, including fossil fuels, nuclear energy, and renewable resources, as illustrated in Fig. 4.

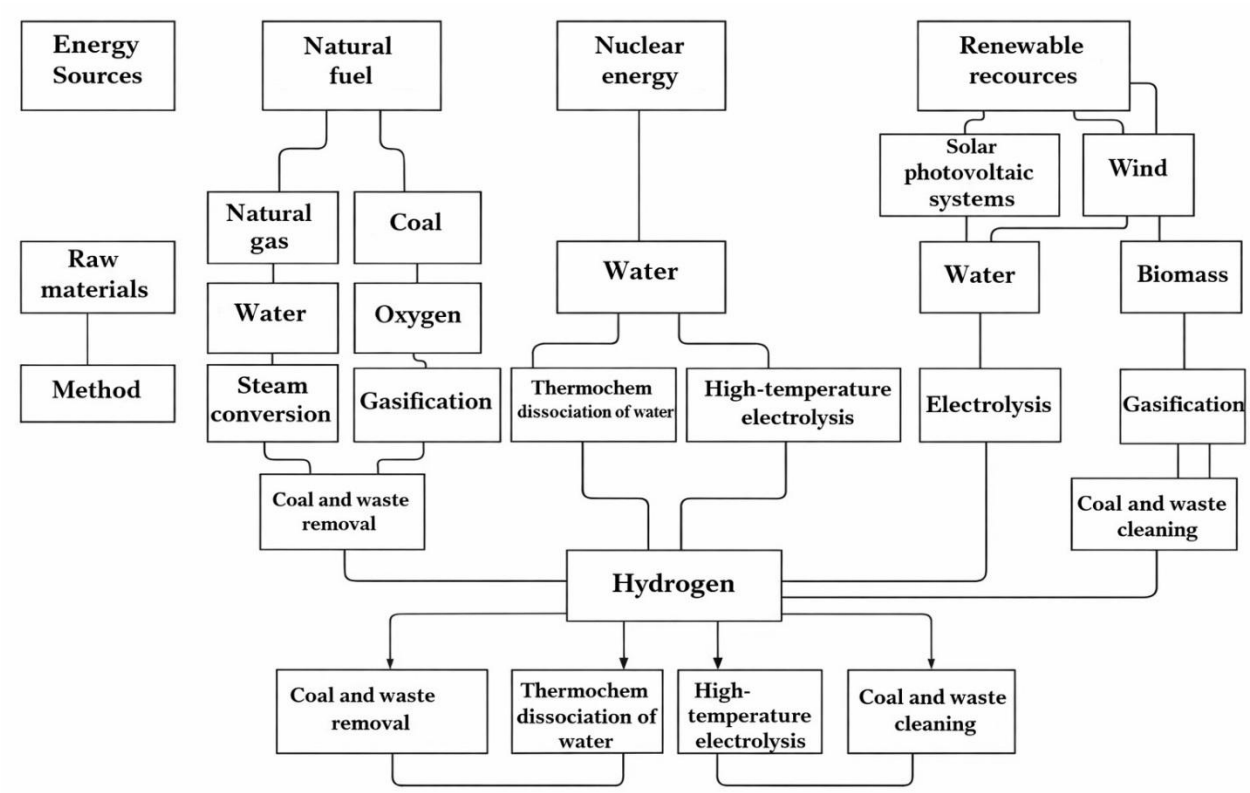


Fig. 4. Schematic diagram of hydrogen production processes based on fossil fuels, nuclear energy, and renewable resources

The most widely used method is methane steam reforming. CH_4 is relatively inexpensive and has a higher C/H ratio compared to other hydrocarbons. Hydrogen can be obtained from CH_4 through its conversion with various oxidizing agents (H_2O, CO_2, CO, O_2) according to the following reactions, with H_2 yield given as a percentage by volume.

$$CH_4 + H_2O \rightleftarrows CO + 3H_2 \longrightarrow 75\%$$

$$CH_4 + CO_2 \rightleftarrows 2CO + 2H_2 \longrightarrow 50\%$$
$$CO + H_2O \rightleftarrows CO_2 + H_2 \longrightarrow 50\%$$

The selection of oxidizing agents is carried out based on the technical and economic performance of the process and the intended application.

The gasification of coal and hydrocarbon-containing materials (with steam) for hydrogen production is performed in a helioreactor or a nuclear reactor using thermochemical cycles. The coal gasification reactions yield hydrogen, with the composition given as a percentage by volume.

$$C + H_2O \longrightarrow CO + H_2 \longrightarrow 50\%$$
$$CO + H_2O \longrightarrow CO_2 + H_2 \longrightarrow 50\%$$
$$C + 2H_2O \longrightarrow CO_2 + 2H_2 \longrightarrow 67\%$$

Steam reforming of heavy hydrocarbon-containing materials:

$$C_nH_{2n+2} + 2nH_2O \longrightarrow nCO_2 + (3n+1)H_2$$
$$CH_4 + 2H_2O = CO_2 + 4H_2 \longrightarrow 80\%$$

Hydrogen production from biomass

$$(C_6H_{10}O_5) + aH_2O \longrightarrow CH_4 + (5-a)CO + aCO_2 + (3+a)H_2$$

$C_6H_{10}O_5$ (cellulose or the elemental unit of biomass) interacts with steam at high temperatures (700–900 °C) to produce synthesis gas (CO, CO_2, H_2, CH_4). This process exhibits a heterogeneous–catalytic character and proceeds via a multi-step mechanism. The heterogeneous catalytic mechanism of steam gasification of $C_6H_{10}O_5$, including pyrolysis, steam–carbon reactions, water–gas shift, and methanation, is illustrated in Fig. 5.

Overall reaction:

$$C_6H_{10}O_5 + aH_2O \longrightarrow CH_4 + CO + CO_2 + H_2$$

$$C_6H_{10}O_5 \longrightarrow C_w + CO + CO_2 + H_2 + CH_4 + \text{volatile components}$$

Here, the parameter *a* represents the amount of steam in the system and directly influences the product distribution. At high temperatures, the macromolecule initially decomposes via a radical mechanism:

$$C_6H_{10}O_5 \longrightarrow C_w + CO + CO_2 + H_2 + CH_4 + \text{volatile components}$$

At this stage:

- C–O and C–C bonds undergo homolytic cleavage
- Active radicals are generated
- A solid carbon phase, known as "char," is formed.

This stage represents the initiation point of gasification.

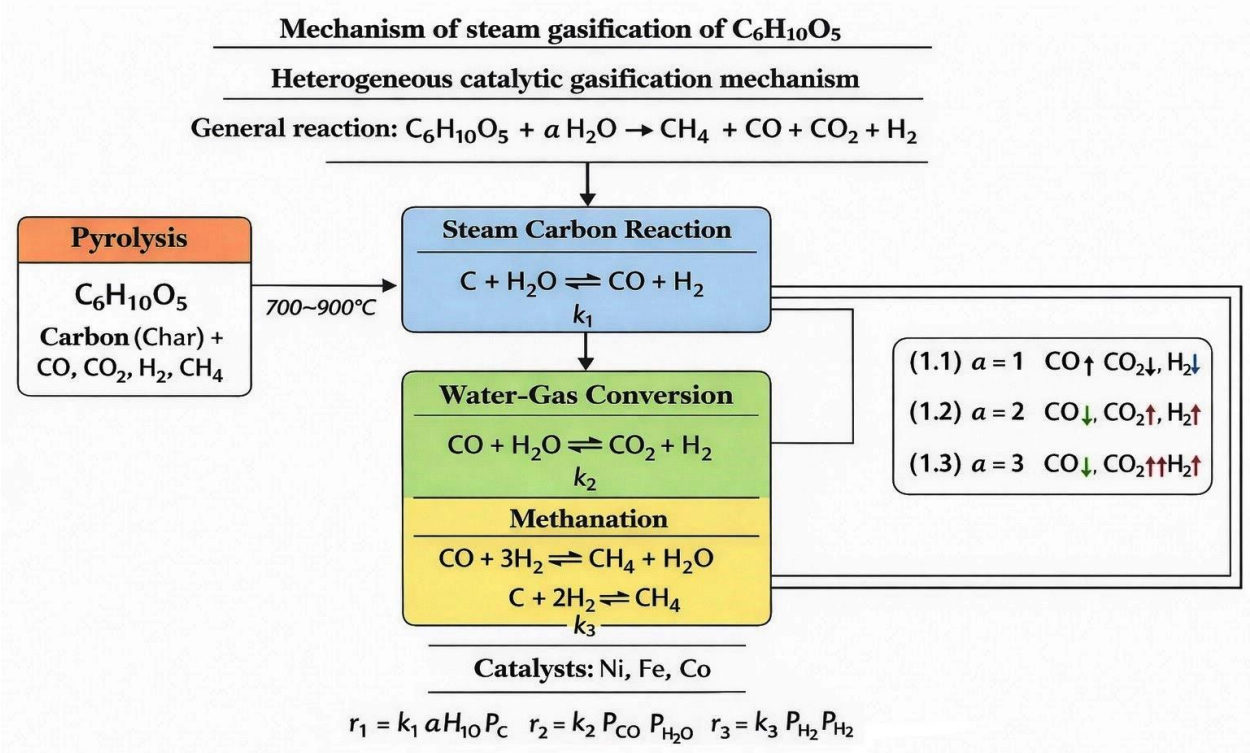


Fig. 5. Schematic diagram of the heterogeneous catalytic mechanism of steam gasification of $C_6H_{10}O_5$, including pyrolysis, steam–carbon reaction, water–gas shift, and methanation.

Main kinetic stage

Main kinetic stage:

$$C_w + H_2O_{(g)} \rightleftharpoons CO + H_2 \quad \Delta H > 0$$

This is an endothermic reaction, and its intensity increases with temperature. Mechanistically, the process proceeds as follows:

1. H_2O is adsorbed on the surface.
2. The H–OH bond is cleaved.
3. OH* binds to an active site.
4. Interaction with surface C* produces CO*.
5. CO desorbs from the surface.
6. H* atoms recombine to form H_2.

Water–Gas Shift Reaction:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \qquad \Delta H < 0$$

This stage:

- Reduces CO concentration,
- Increases CO_2 and H_2 content,
- Alters the thermodynamic equilibrium of the system.

According to Le Chatelier's principle, increasing the amount of water shifts the reaction to the right. The effect of water content (parameter *a*) is as follows:

- **a= 1** (limited water):
  - Steam–carbon reaction proceeds slowly
  - Water–gas shift is limited
  - CO predominates
  - H_2 yield is relatively low

- **a=2** (moderate water):
  - Part of CO converts to CO_2
  - H_2 generation increases
  - CO concentration decreases
  - System approaches equilibrium

- **a = 3** (excess water):
  - Water–gas shift proceeds at maximum rate
  - CO concentration is minimal
  - CO_2 and H_2 reach maximum values
  - Thermodynamically, the system favors more oxidized products

Hydrogen production from biomass (BM) through pyrolysis or steam gasification has been carried out in a helioreactor at temperatures ranging from 600 to 1000 °C. The composition of the resulting gas mixture depends on the potential power of the heliosystem and the BM:H_2O ratio, allowing a hydrogen content of 55–65 vol.% to be achieved.

Among the main methods for hydrogen production, thermochemical and biochemical conversion of biomass is the most promising. Processing forest and agricultural residues through these methods enables efficient hydrogen generation, with the production cost of 1 kg of H_2 currently estimated at $4–7, while experts predict this may decrease to $1–1.5 in the near future.

The calorific value of hydrogen significantly surpasses that of all other conventional fuels. While natural gas has a high calorific value among traditional fuels, hydrogen's calorific value of 28700 kcal/kg is 2.4 times higher than methane (11950 kcal/kg), underscoring its potential as a high-energy carrier for future energy systems. Moreover, hydrogen combustion produces only water, offering notable environmental advantages.

The development of chemical methods for solar energy conversion (CMSEC) is an important modern scientific challenge. The concept of direct chemical conversion of solar energy into fuels was first proposed by Academician N.N. Semenov. Addressing this problem requires an interdisciplinary approach, involving chemists, biologists, physicists, and energy engineers.

CMSEC has two main objectives: (1) conversion of solar energy into electricity, and (2) accumulation of solar energy in fuels in the form of chemical energy. One promising direction is the enhancement of the calorific value of existing organic fuels using solar energy. For instance, the steam gasification of CH_4 or other hydrocarbons increases the energy content: 1 mol of CH_4 has a calorific value of 213 kcal, while its conversion with steam produces 1 mol CO and 3 mol H_2 with a calorific value of 273 kcal, increasing the fuel's energy content by 28 %.

Energy conversion and efficiency of steam gasification processes of coal and methane using solar energy demonstrate the significant potential of solar-driven thermochemical technologies for sustainable fuel production.

Table 5

Energy conversion and efficiency in methane steam gasification processes using solar energy

Reactions	**Combustion energy of methan, kJ**	**Combustion energy of reaction products, kJ**	**Accumulated energy 1t of methan and EF**
Conversion of methane with water vapor $CH_4 + H_2O = 3H_2 + CO - 206$	$CH_4 + 2O_2 = CO_2 + 2H_2O + 802.3$	$3H_2 + 1{,}5O_2 = 2H_2O + 725{,}4$ $CO + 0{,}5O_2 = CO_2 + 283$ ---- ---- 1008.4 kJ	$12.88 \cdot 10^6$ γ=25.7%
Reaction of methane with CO_2 $CH_4 + CO_2 = 2CO + 2H_2 - 247.3$	$CH_4 + 2O_2 = CO_2 + 2H_2O + 802.3$	$2CO + O_2 = 2CO_2 + 566$ $2H_2 + O_2 = 2H_2 + 483.6$ ---- ---- 1049.6 kJ	$15.48 \cdot 10^6$ γ=30.8%

It can thus be noted that Azerbaijan's favorable geographical location and climatic conditions, similar to those of several developed countries, provide a strong basis for the expanded utilization of environmentally friendly biomass and solar energy.

The world's reserves of oil and natural gas are finite, and it is difficult to determine precisely how many years these reserves will last. If current consumption trends continue, global

oil demand is projected to reach 3 billion tons by 2018. Even assuming a significant increase in industrial reserves, geologists estimate that by 2030, approximately 80% of the known oil reserves will be depleted.

Consequently, in recent years, increasing attention worldwide has been directed toward the prospects of hydrogen energy. Hydrogen is a highly efficient and environmentally clean fuel. Currently, large-scale hydrogen utilization has been successfully implemented in industrial chemical processes and rocket technology. Global hydrogen production has exceeded 50 million tons and continues to grow rapidly. With further development, hydrogen could serve as a versatile energy source for local electricity and heat production, household energy supply, energy storage, and transportation, including vehicle fueling. When produced from water using renewable or nuclear energy technologies, hydrogen becomes a renewable fuel that supports sustainable development on a global scale.

Another key advantage of hydrogen as a renewable energy source is its capacity to directly convert the energy released from its reaction with oxygen into electrical current in so-called fuel cells. Hydrogen-based power sources are often regarded as an ideal solution to global energy challenges, as their use eliminates emissions of environmentally harmful substances. These fuel cells can also be employed for transporting and storing energy generated from renewable sources, positioning the “hydrogen economy” as a potentially optimal pathway for civilizational development. However, current technologies for both hydrogen production and electricity generation from it are still far from perfect.

A significant number of recent developments have focused on the domestic use of hydrogen, such as heating, hot water supply, and cooking. Most of these innovations employ catalytic hydrogen combustion, resulting in the creation of a series of highly efficient, cost-effective, and user-friendly devices at the prototype stage. Moreover, the feasibility and potential of new technical solutions for both domestic and industrial thermal systems—including heating systems, refrigerators, air conditioners, and low-potential heat transportation systems—based on hydrogen metal hydride technologies have been demonstrated.

Given the depletion of oil reserves, particular attention has also been directed toward the deep processing of heavy oil fractions to increase the yield of motor fuels and petrochemical products. For the same reason, the development of coal and shale processing technologies, which require substantial amounts of hydrogen, is anticipated. Interest in hydrogen as a motor fuel is driven by these circumstances, highlighting its potential as a clean, efficient, and sustainable energy source for the future. When hydrogen is combusted in an engine, it produces almost exclusively water; in this regard, a hydrogen-fueled engine represents one of the most environmentally friendly options. Hydrogen possesses high energy characteristics: its lower heating value is approximately 120 MJ/kg, which is more than four times higher than that of gasoline (about 25 MJ/kg), meaning that 1 kg of hydrogen is roughly equivalent to 4.5 kg of gasoline.

Hydrogen has a virtually unlimited raw material base, provided it is produced from water. The use of hydrogen as a motor fuel for vehicles can be implemented in several ways: Utilization of pure hydrogen;

Use of hydrogen in combination with conventional petroleum fuels;

Application of hydrogen as a fuel in fuel cells.

Another important feature of hydrogen is the possibility of directly converting the chemical energy of its reaction with oxygen into electricity in an electrochemical generator (ECG) with a high efficiency.

Hydrogen is also used as a heat transfer medium in cooling systems for high-power electric generators, in the production of synthetic gemstones and optical quartz, rare metals, hard alloys, powder metallurgy, and in numerous other industrial sectors.

Conclusion

As global reserves of organic fuels, which serve as energy carriers for non-renewable energy, become depleted, humanity faces the urgent task of identifying and effectively utilizing new energy sources and carriers. Hydrogen has emerged as a primary candidate for this role. An analysis of potential processes for converting solid and liquid fuels into gaseous products indicates that, in order to maintain the autothermal nature of technological steam production and hydrogen generation, the requirements for thermal and electrical energy can, in some cases, exceed half of the initial fuel input. Therefore, the integration of solar energy into the biomass gasification process—unlike traditional technologies based on internal heat supply, which consume approximately 40% of the fuel—enables efficient accumulation and conservation of solar energy in the form of combustible gases.

Both theoretical and practical aspects of using solar energy to produce hydrogen and hydrogen-containing gases from water, coal, or agricultural production waste—such as cotton and grape residues—have been examined. A method has been proposed, and the technological parameters for obtaining hydrogen and carbon monoxide via the thermochemical decomposition of water, coal, or agricultural residues using solar heat have been determined, with thermal loads in the flare area ranging from 84 to 126 × 10^6 kJ/m²·h.

Thermodynamic calculations of the equilibrium compositions of gases produced from the reaction of carbon with water vapor were conducted, and experimental results were found to correspond closely with theoretical predictions. It has been demonstrated that, during the gasification of lignite, grape stems, and cotton stalks using water vapor and solar heat with an intensity of 2933 kJ/m²·h, the volumes of combustible gases obtained are approximately 0.06, 0.18 and 0.105 m³/h, with calorific values of 11812.68, 14565.2 and 12773.2 kJ/m³, respectively.

The developed method and apparatus for producing hydrogen and combustible gases using solar energy can be applied to address various energy challenges in the southern regions of the country. The accumulation of solar energy enables savings of up to 40% of solid fuel, which is particularly significant for preserving the cleanliness of the atmosphere.

Competing Interests

The authors declare that they have no known competing financial or non-financial interests that could have appeared to influence the work reported in this paper.

Availability of Data and Materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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