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IMPLEMENTATION AND SUSTAINABILITY OF BIOMASS GASIFICATION USING PLASMA TECHNOLOGIES

S.V. Petrov[1], O.I. Som[2], S.G. Bondarenko[3], O.V. Sanginova[3], M. Ganczarski[4], E. Rój[4]

[1]The Gas Institute of the NASU
39 Degtyarivska Str., 03113, Kyiv, Ukraine
[2]Plasma-Master Co., Ltd.
3 Omelian Pritsak Str., 03142, Kyiv, Ukraine
[3]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
37 Prosp. Beresteiskyi, 03056, Kyiv, Ukraine
[4]Hydrogenium P.S.A. (Simple Joint Stock Company)
3/27 Marii Curie-Skłodowskiej Str., Lublin, Poland, 20-029

ABSTRACT

Waste biomass gasification technologies, especially with a focus on hydrogen production, have the potential for large-scale commercialization. The prerequisites for their development and promotion are innovative approaches to modeling, the use of traditional and new gasification mechanisms consistent with fundamental principles, and the development of new technical solutions on this basis. Ultimately, the goal is to significantly improve the gasification process's technical, economic, and environmental performance. In this context, plasma gasification is a promising renewable energy source from various wastes, including biomass. It contributes to achieving sustainable development goals: affordable and clean energy, climate change mitigation, waste diversion and resource reuse, reinforcing the concept of a circular economy. This paper presents an analysis and assessment of the conditions for increasing gasification processes' reliability, productivity, and quality while reducing costs, including potential barriers to applying plasma technologies. The paper presents new technological solutions to the problems facing gasification, aimed at optimizing energy flows in the gasification reactor, rational use of plasma as a concentrated energy flow, reducing electricity consumption by plasma torches, reducing the power and cost of plasma installations, as well as a radical solution to the problem of reliability of gasification equipment. The economic prospects for the transition to large-scale production, where a reduction in capital and operating costs can be expected, are considered.

KEYWORDS: biomass gasification, plasma gasification, plasmatron, synthesis gas, gasifier, energy efficiency of the gasification process

INTRODUCTION

The technical solution of converting biomass into fuel gas, gasification, is a key technology for producing products with higher value and application potential than the feedstock. The prerequisites for developing this technology are advanced, innovative, cost-effective and highly efficient methods. The strategy for improving the feasibility and sustainability of the biomass gasification process lies in technological advancement and minimizing the socio-environmental impacts [1]. Biomass has an advantage over other renewable energy sources because it depends less on location and climate. Biomass is easily stored and transported and is also available in abundance. This makes it a viable and promising feedstock as an energy source. Currently, biomass provides more than 10 % of the world's energy supply and is among the four largest energy sources in global final energy consumption [2].

Biomass waste gasification has an advantage over other existing methods, such as burial, incineration, etc., because it can convert a wide range of feedstocks into various useful products. Biomass gasification is a complex process that includes feedstock preparation, then a combination of pyrolysis, partial combustion of intermediate products, with final gasification, removal of inorganic residue, purification, and separation of synthesis gas. The gasification medium is important in converting intermediate products — solid carbon and heavy hydrocarbons into low-molecular gases such as carbon monoxide (CO) and hydrogen (H_2). The quality and properties of synthesis gas depend on the composition of the feedstock, size, gasifying agent, temperature, blast distribution in the reactor, and its design. Biomass gasification produces many useful components at the output, including synthesis gas, heat, electricity, green hydrogen, and fertilizers. Syngas can be further processed into methanol, dimethyl ether and other chemical products.

Biomass gasification for hydrogen production offers outstanding advantages regarding renewable energy resources, carbon neutrality, high efficiency and environmental benefits. However, the factors affecting H_2 production from biomass gasification are complex, making it difficult to determine the optimal operating conditions [3].

THE REVIEW AIMS

to evaluate and classify plasma biomass gasification technologies based on the conditions for increasing productivity and quality while reducing costs, including potential barriers.

RESEARCH RESULTS

A common drawback of conventional gasifiers, whether with formation, downward emergence, or combined draft, is that the alternating gas contains tar to a greater or lesser extent, which is too problematic for many modern applications. Resin is considered the most inconvenient problem, which requires power outages, mainly when operating in large-scale conditions. Traditionally, steam reforming at elevated temperatures has been used as a solution. Water vapor gasification is an effective and well-proven method [4, 5]. In this case, the production of coke and resins is small, since steam converts them into CO and H_2 through water shear and reforming. Resins are never desired products and therefore reduce the efficiency of the process. Resin yield can be reduced by thermal cracking, steam reforming, dry reforming, carbonization and partial oxidation, which manifests itself in the following reactions:

$$pC_nH_x \leftrightarrow qC_mH_y + rH_2;$$

$$C_nH_x + mH_2O \leftrightarrow nCO + \left(m + \frac{x}{2}\right)H_2;$$

$$C_nH_x + nCO_2 \leftrightarrow 2nCO + \frac{x}{2}H_2;$$

$$C_nH_x \leftrightarrow nC + \frac{x}{2}H_2;$$

$$C_nH_x + \frac{n}{2}O_2 \leftrightarrow nCO + \frac{x}{2}H_2.$$

The authors of [6–9] found that the yield of H_2 during water vapor gasification is several times higher than that during air gasification. They also reported increased economic efficiency with higher H_2 production using water vapor as a gasification medium. It should be noted that a technological attempt to overcome this problem, which is helpful for further developments, is the concept of multi-stage gasification, which is applied at the Danish Technical University (Denmark) and Karlsruhe Institute of Technology (Germany) [10, 11]. This atypical gasification strategy separates the pyrolysis and gasification of biomass into separate stages with individual control, which are then integrated. Pyrolysis and gasification are carried out in separate zones inside the gasifier. This allows the biomass to be processed into usable products. The main motive for this concept is to obtain high-quality, clean synthesis gas with a low resin content. The permissible resin levels depend on the subsequent application. They are about 50 $mg \cdot Nm^{-3}$, 5 $mg \cdot Nm^{-3}$ and 1 $mg \cdot Nm^{-3}$ for gas engines, gas turbines and fuel cells, respectively [12]. The exhaust gas contains significant amounts of ash and dust in all cases. A vital step between gas production in the gasifier and its utilization is gas treatment. The gas leaving the biomass gasification system is contaminated with resin, alkali metals, particulate matter, nitrogen (N_2), sulfur (S), and chlorine (Cl). According to the studies, gas cleaning was the most challenging issue in biomass gasification until recently [13]. To address this problem, various types of updraft and downdraft gasifiers have been developed, and many physical and catalytic methods for resin separation have been investigated. However, the most efficient and popular method for commercial purposes has yet to be developed. Efficient gasification and gas treatment methods allow the production of high-quality gas, ideally resin-free [14], which reduces the overall biomass consumption and ultimately reduces problems with biomass logistics and pre-treatment.

Plasma is also used in gasification processes in two ways: 1) as a heat source; 2) for cracking resins after standard gasification. Plasma gasification is primarily used for processing toxic organic waste, municipal solid waste, and rubber and plastics. Plasma technology has also attracted interest in syngas production and power generation and has entered the commercially competitive range. The main advantages of plasma gasification are syngas yield with high H_2 and CO content, increased heat content, low CO_2 yield, and low resin content [15–19]. The main limitations are the high capital and operating costs due to the high electricity consumption for plasma generation, resulting in low overall efficiency. For example, a base case scenario for a 680 tons per day waste treatment plant, suitable for a small town or regional business, would cost £97 mln, almost three times the cost of other waste treatment plants (such as incinerators).

The study [20] is indicative. Four biomass types — sawdust, plastic waste and oil obtained from the pyrolysis of waste tires — were investigated in a DC electric arc reactor with a torch power of 100 kW. A small amount of argon with H_2O vapor was used as plasma gas and H_2O as an oxidizing medium. High-quality synthesis gas containing 90 vol.% H_2 and CO for all four types of feedstock was obtained, and the resin content was below the sensitivity of the analysis method (1 mg/nm^3). A higher energy requirement compensates for these circumstances. Despite the high heat content in the output gases recorded for all data sets, the process efficiency was low due to

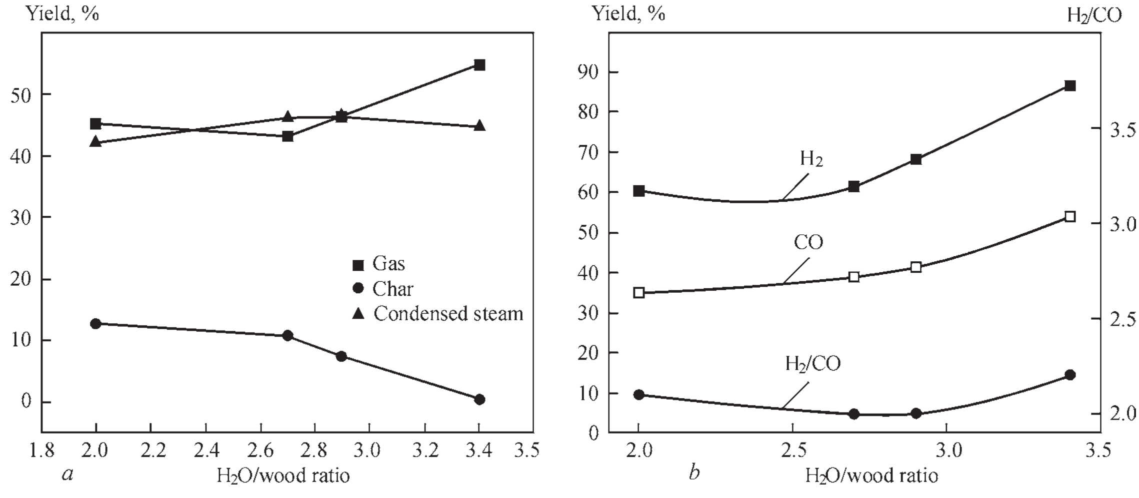

Figure 1. Effect of the H_2O and wood ratio on the product yield: *a* — total mass yield; *b* — yield of H_2 and CO gases, and the H_2/CO ratio

the high energy costs, which is a significant limiting factor for this technology.

Chemical processes modeling and experimental studies [21, 22] have shown that synthesis gas with high H_2 and CO content can be efficiently obtained from biomass waste using water-steam plasma. Timber conversion in a water-steam plasma environment was carried out under the following experimental conditions: wood consumption of 1.2 g/s, steam consumption of 2.63–4.48 g/s, plasma torch power of 49–56 kW. In the range of H_2O/wood ratios of 2.0–3.4, the average mass temperature was maintained at T = 2800 K. Timber was converted entirely into gas, liquid (water vapor), as shown in Figure 1, *a*, *b*. With a plasma torch power of 56 kW and an H_2O/wood ratio of 3/4, the residence time was sufficient to convert wood into gas, liquid, and charcoal. The yield of charcoal in the total mass of reaction products decreased to 0.5 %, and the gas yield increased to 55 %, which ensures a carbon conversion efficiency of up to 97.5 %.

It follows from Figure 1, *a* that the component of the mass balance is condensed incompletely reacted water, which was used as a plasma-forming gas. Thus, optimal organization of the conversion process is required. The amount of charcoal in the mass balance of the reaction products is reduced to 0.5 %, which indicates a great potential of thermoplasma technology for the efficient processing of organic materials. On the other hand, the low yield of carbon monoxide requires making the conversion process more selective. Therefore, special catalysts can be used to reduce the amount of carbon monoxide. Considering the inclusion of hydrogen energy in the energy balance and the comparison of biomass conversion methods into hydrogen from the point of view of the cost of energy consumption in kW·h/kg, technical and economic limitations, and environmental impact, it is crucial to increase efficiency, advance technology, and develop catalysts [23].

Plasma can be formed from air, O_2, water vapor, N_2, Ar, CO_2, or a mixture of these gases. Thus, plasma gasification is a promising source of obtaining renewable energy from solid waste and contributes to achieving sustainable development goals: affordable and clean energy, combating climate change, preventing waste from entering landfills and reusing resources, strengthening the concept of a circular economy. Plasma gasification of waste, unlike traditional incineration, reliably destroys highly toxic dioxins, benzopyrene and furans. High temperature destroys all resins, charcoal and dioxins, producing cleaner synthesis gas than conventional gasification. It should be noted that plasma gasification is the latest technology among modern waste disposal methods. Much work has been done to develop traditional gasification. According to the Council on Gasification and Syngas Technology, there are currently 272 gasification plants with 686 gasifiers in operation worldwide, and another 74 plants with 238 gasifiers are under construction. Most of them use coal as feedstock. Only five commercial plasma gasification plants are used worldwide for waste processing [24]. Recent efforts by developers in the field of plasma gasification are aimed at increasing the efficiency of the process, improving environmental and economic indicators through the development of advanced converter systems, gas cleaning, catalysts, monitoring and control systems, modular plant designs, improved materials and alternative energy sources. Plasma gasification is becoming an up-and-coming technology for waste disposal and energy production.

The Gasification Technologies Council website currently notes that there are operational plasma gasifiers in Japan, Canada, and India. A new 2,000 tons per day MSW plant is being commissioned in Tees Valley, UK, which will be the largest plasma gasifier in the world when completed [25]. The Tees Valley One (TV1) plant, near Billingham, will process pre-treated municipal, commercial, and industrial waste supplied by Impetus Waste Management, diverting it from a nearby landfill. Billed as the "largest gasification plant in the world", it will use plasma gasification technology provided by Canadian company Alter NRG to convert waste into energy for the National Grid. It is expected to generate enough electricity to power 50,000 homes. The plant, which was granted planning permission by Stockton-on-Tees Council in 2011, is estimated to cost $500 mln (£320 mln) and is being funded almost entirely by US company Air Products, with One North East also providing a £260,000 grant in 2010 [25]. However, there have been challenges associated with design and operation. For example, several attempts have been made in South Korea to commercialise plasma waste recycling technology, but none have yet reached the commercialisation stage. However, this has not stopped development. The Korea Fusion Energy Institute, Hyundai Heavy Industries Power System Co., Ltd., and GS Engineering & Construction Co., Ltd. have agreed to develop a commercial plasma gasification furnace [26]. Under the agreement, the three organizations plan to collaborate closely in technology development, research and design of plasma gasification systems, development and manufacture of commercial equipment, and business development and implementation to commercialize plasma gasification technology. The development and construction of a commercial reactor capable of handling 100 tons of waste per day with a 500 kW plasma torch is planned, based on its experience in producing industrial circulating fluidized bed boilers.

It should be noted that there is currently no commercial H_2 production plant using plasma gasification technology from biomass. Significant research is needed to reduce energy consumption and thereby improve efficiency.

In general, hydrogen production technology from biomass gasification has not yet reached a high level of technological maturity. The main novelty of this work is to assess the current state of the art of H_2 production technologies from solid biomass, considering the technological, economic, and environmental indicators and the technical potential of hydrogen production through plasma gasification of biomass. According to the literature review, the normalized cost of hydrogen production can reach an average of 3.15 USD/kg H_2, and the average yield is 0.1 kg H_2/kg biomass biomass [27]. Meanwhile, the economic feasibility of hydrogen production from biomass may be hindered by the high cost, which ranges from 1.21 to 2.42 USD/kg for gasification and from 1.21 to 2.19 USD/kg for pyrolysis. Increasing the hydrogen yield and exploring methods to reduce the temperature are crucial to enhancing biomass gasification's economic viability and sustainability for hydrogen production, with special attention to energy saving [23].

According to the global hydrogen production outlook up to 2050 [28], electricity-based green hydrogen, produced by splitting hydrogen from water using electrolyzers, is expected to be the dominant form of production by mid-century, accounting for 72 % of production. This scenario would require excess renewable energy to power 3,100 gigawatts of electrolyzers. This is more than twice the total installed solar and wind capacity today. Blue hydrogen, produced from natural gas with emissions capture, plays a significant role in the short term (around 30 % of total production in 2030). Still, its competitiveness will decline as renewable capacity increases and prices fall. Making hydrogen projects competitive and economically viable based on excess renewable solar and wind energy to power electrolyzers remains challenging.

Natural gas reforming, coal gasification and water electrolysis are proven technologies for hydrogen production today and are used on an industrial scale worldwide. Steam reforming of natural gas is the most used process in the chemical and petrochemical industries. It is currently the cheapest production method and has the lowest CO_2 emissions of all fossil fuel extraction methods. Water electrolysis is expensive and is only used if high-purity hydrogen is required. With the expected increase in natural gas and coal prices, the gasification process is expected to be the most economical option starting around 2030. Biomass gasification for hydrogen production is still in its early stages today but will likely become the cheapest option for supplying renewable hydrogen in the coming decades. Biomass gasification is currently used in small, decentralized plants at an early stage of infrastructure deployment. In general, the hydrogen production mix is very country-specific. It depends heavily on expected feedstock prices, resource availability, and political support, which also play an essential role, especially for hydrogen from renewables and nuclear energy. Renewable hydrogen is primarily a cost-effective option in countries with a significant renewable resource base and/or a lack of fossil resources, for remote and sparsely populated areas (e.g., islands), or for storing excess electricity from intermittent renewable energy sources. Otherwise, renewable hydrogen should be incentivized or mandatory.

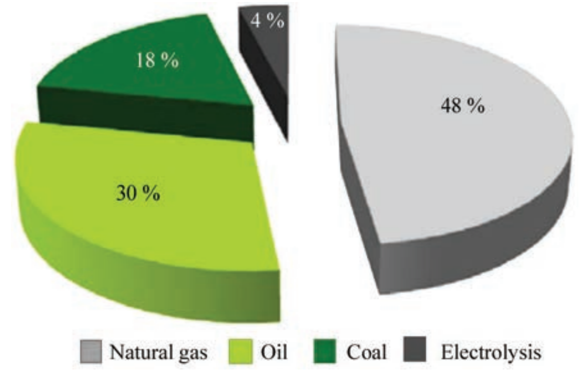

Figure 2. Current raw materials used for H_2 production [30]

In the long term, hydrogen must be produced using processes that avoid or minimize CO_2 emissions. Renewable hydrogen, whether produced by electrolysis from wind, solar energy, or biomass, is undoubtedly an endpoint (especially in climate change mitigation), but is not a prerequisite for introducing hydrogen as an energy vector. Until this goal is achieved, hydrogen produced from fossil fuels will predominate. Still, capturing and storing the resulting CO_2 becomes a prerequisite for hydrogen to contribute to the overall reduction of CO_2 emissions in the transport sector. The predominance of fossil hydrogen is expected from about 2030, as reflected in the various hydrogen roadmaps, as is the subsequent role of renewables. The specific costs of producing hydrogen from renewables are not considered competitive with most other options in this period, except for biomass. The cost of hydrogen production depends mainly on the assumed prices of the feedstock. The typical price range up to 2030 is between 0.08 and 0.12 USD/kW·h (2.6–4 $/kg). In the long term, up to 2050, with the expected increase in raw material (fossil fuel) prices and CO_2 prices, hydrogen production costs will also increase [29].

Based on the above, biomass provides renewable and sustainable energy in other forms such as syngas, biogas and hydrogen. Hydrogen energy has great potential for decarbonizing various sectors due to its versatility. At the same time, hydrogen energy production is considered environmentally friendly. However, even though the main precursors to produce hydrogen gas are readily available in various countries, these resources are not yet used and, as a result, hydrogen gas is not included in the energy balance of states [23].

Thus, today, hydrogen is mainly produced from fossil fuels (Figure 2) [30]. Hydrogen production from biomass through gasification can become a favorable alternative for future decarbonization applications based on renewable and carbon dioxide-neutral hydrogen.

However, it should be noted that biomass accounts for about 14 % of global energy consumption, which is higher than coal (12 %) and comparable to gas (15 %) and electricity (14 %). Biomass is a significant energy source for many developing countries, but much of it is non-commercial [31, 32].

Figure 3 shows the future trend of hydrogen supplies for three developed countries/regions — the US, EU, and Japan. As can be seen, hydrogen supplies will largely depend on fossil sources – natural gas and coal. Carbon capture and sequestration technologies are planned to be important in achieving climate goals. However, the amount of hydrogen produced from renewable sources should also increase significantly. It becomes clear that hydrogen supplies depend on regional differences in resource endowments. While Japan includes renewable electricity only as a source of renewable hydrogen, the EU and the US plan to increase hydrogen production through biomass gasification [33].

Numerous papers review current possible principles of industrial hydrogen production based on biomass gasification. Generally, hydrogen from renewable sources can be produced electrochemically, biochemically, or thermochemically. All three methods allow hydrogen production without CO_2 emissions (Figure 4). H_2@Scale is a US Department of Energy (DOE) initiative that brings together stakeholders to advance affordable hydrogen and reve-

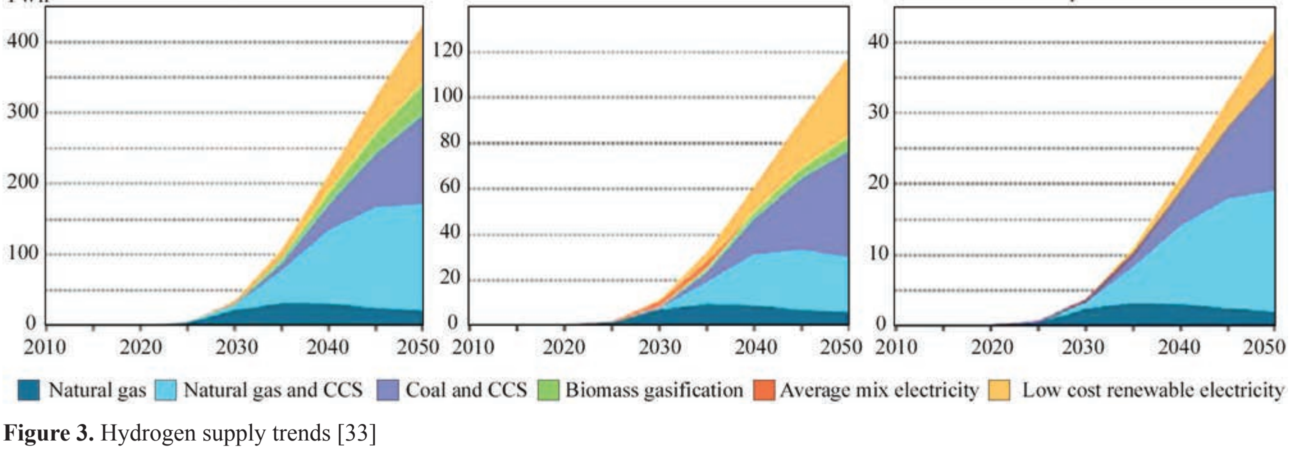

Figure 3. Hydrogen supply trends [33]

nue-generating opportunities in various energy sectors. It includes DOE-funded projects and activities jointly funded by national laboratories and industry to accelerate early-stage research and demonstration of hydrogen technologies.

This study focuses on the thermochemical approach through biomass gasification (wood chips, agricultural waste). Specifically, the potential industrial production of hydrogen is considered with an emphasis on plasma gasification technologies. Figure 5 shows the general scheme of the hydrogen production process by plasma gasification.

The scheme includes gas cleaning and enrichment, which are necessary to remove CO and CO_2, as well as trace components such as H_2S, HCl, and fly ash.

There are many differences in the characteristics of biomass. Solid biomass fuels commonly used in large-scale power plants include agricultural residues, short-rotation energy crops, and others. Their compositions vary significantly in the proportions of volatile matter and fixed carbon. Most lignocellulosic biomass (e.g., woody and herbaceous materials) has about 75–85 % volatile matter and about 15–17 % fixed carbon. Biomass varies significantly in physical characteristics, density, and thermal properties. Density ranges from 200–300 kg/m^3. Thermal conductivity for biomass particles is from 0.05 W/(m·K) for some herbaceous materials and from 0.1 to 0.15 W/(m·K) for woody materials [34]. A future industrial gasification system will likely use various available biomass resources. Therefore, the design will need to consider the variability of fuel combustion characteristics. To ensure optimum efficiency, it is necessary to control particle size, predict the behavior of inorganic components in the reactor, particularly the role of potassium, and control fouling and ash deposition effectively.

Plasma gasification involves a sequence of solid mass loss phases, including drying, pyrolysis — volatiles yield, and charcoal formation and gasification. This is followed by homogeneous partial oxidation of the volatiles approaching thermodynamic equilibrium and completion of the water shift reaction. Oxidation of both volatiles and charcoal occurs in the absence of O_2 at a rate proportional to the available O_2 and temperature.

The plasma torch is an independent source of concentrated heat, which allows the reactor temperature to

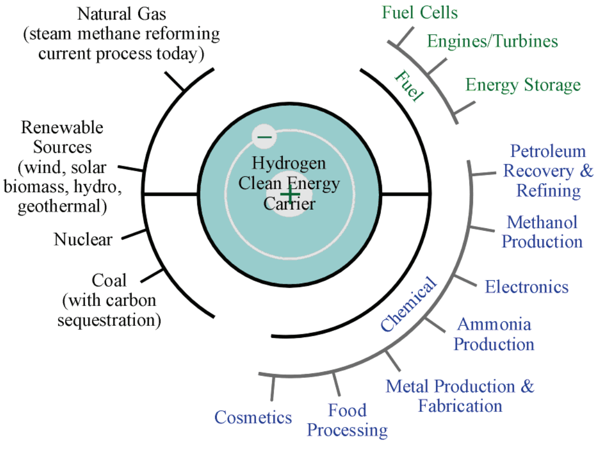

Figure 4. H_2@Scale vision for hydrogen production, including from renewable sources, and its use

be controlled independently of variations in feedstock quality and air/oxygen/steam supply required for its gasification. Optimum parameters can be established and easily maintained and are not affected by the state of the material being processed. This provides significant advantages in process variability compared to gasification without an external heat source. Plasma can be effectively used in each phase of the process, providing a considerable increase in efficiency within the framework of the strategy for converting feedstock into specified gasification products. However, its preferred place of use follows the process's logic.

A thermal analysis of weight loss was performed for five types of biomass pellet fuel. The heating rate of 20 °C/min is indicative for the assessments. TG and DTG curves were obtained (Figure 6, *a*, *b*) [35].

It can be seen from Figure 6 that the pyrolysis of five kinds of biomass pellet fuel mainly includes three stages: *1*, water evaporation stage; *2*, volatile matter release stage; *3*, fixed carbon oxidation stage. In the first drying stage, from room temperature to about 170 °C, the peak weight loss temperature is at 100 °C, and the weight loss at this stage is about 10 %. During heating, pellets absorb heat to evaporate water (free water, crystal water, absorbed water, etc.). This is the drying stage of the five kinds of biomass pellet fuel, and its composition has not changed significantly. The second stage is volatile matter release at about 190–450 °C. This is the stage of the main weight loss of the five kinds of biomass pellet fuel and the formation of the initial carbon layer. The main chemical components in the five types of biomass pellet fuel

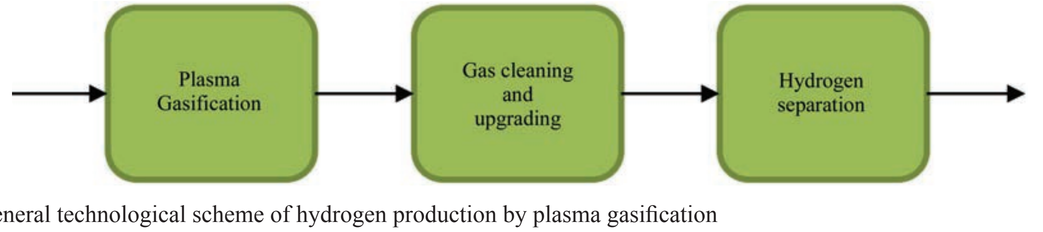

Figure 5. General technological scheme of hydrogen production by plasma gasification

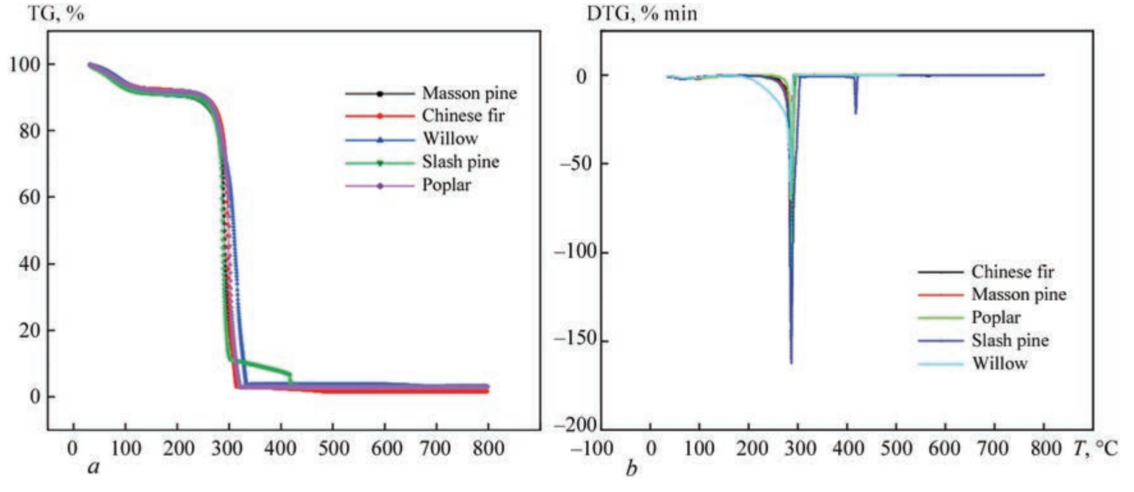

Figure 6. Thermal analysis of weight loss of biomass fuel (conducted for five types of biomass pellet fuel): *a* — TG curves; *b* — DTG curves [35]

are cellulose, hemicellulose, lignin, etc. The weight loss at this stage is about 75 %. The third stage is after 450 °C, where slow oxidation and decomposition of the carbon layer occur. The weight loss at this stage is about 10 %. The pyrolysis of organic matter in the five types of biomass pellet fuel is complete. Residual ash and other non-decomposable substances remain. The gasification results of the five types of biomass pellet fuel are approximately the same.

It is essential to characterize the fuel in measured durations of the various gasification stages to optimize the process for productivity and reaction completeness. Such valuable data for predicting the mass loss behavior of different particle sizes will inform operators about the need to adjust milling and temperature requirements [36] presents an experimental method for investigating the durations of the various combustion stages of individual particles for three types of wood biomass fuels. The volume of data obtained allows the evaluation of empirical expressions for the relationship between particle mass and the duration of volatile release and combustion of charcoal.

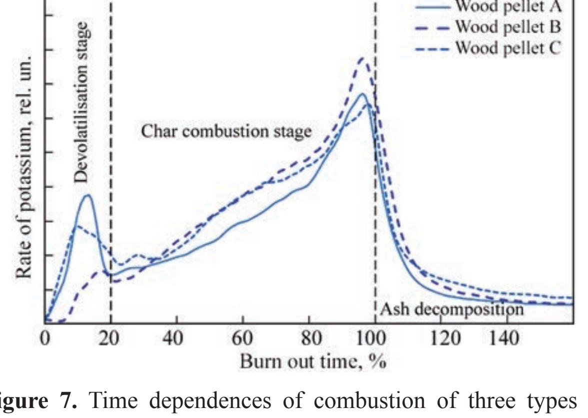

Figure 7. Time dependences of combustion of three types of wood pellets with the release of potassium and indication of the gasification stages [38]

The combustion temperature of biomass in large power plants reaches up to 1600 K. Such temperatures influence the separation of inorganic components through phase changes. In biomass fuels, particularly potassium, can be present in various forms and pass into the gas phase during combustion at elevated temperatures. Subsequently, the combustion products cool and condense on the surface of the furnace and heat exchangers. Potassium chloride and hydroxide lead to an increase in corrosion deposits and ash adhesion. Potassium in the gas phase can also lead to the formation of sulfate aerosols and recombine with other solid-phase components of ash, affecting the behavior of ash during melting and, consequently, affecting the formation of carbon and slag in the furnace [37]. The pattern of potassium release obtained in experiments on the combustion of various types of wood pellet fuels is shown in Figure 7 [38]. These data allow us to trace the physical mechanisms of the process and contribute to the development of models for the gasification of biomass particles.

As Figures 6 and 7 shows, the limiting stage of biomass gasification is the gasification of the carbon layer. Since the authors developed the theme of generating a plasma mixture of water vapor and atmospheric pressure oxygen using an electrodeless discharge to process biomass to obtain hydrogen [39], the main attention should be paid to the gasification of the carbon layer.

Oxygen and steam are the preferred gasifying agents for producing hydrogen-rich synthesis gas [40]. One of the key factors affecting the process performance is the steam-to-oxygen ratio at the reactor inlet. Both laboratory and industrial test data show that a higher steam-to-oxygen ratio also increases the water gas shift reaction rate. As a result of the influence of the steam-to-oxygen ratio on the thermodynamic and kinetic properties of the process, higher

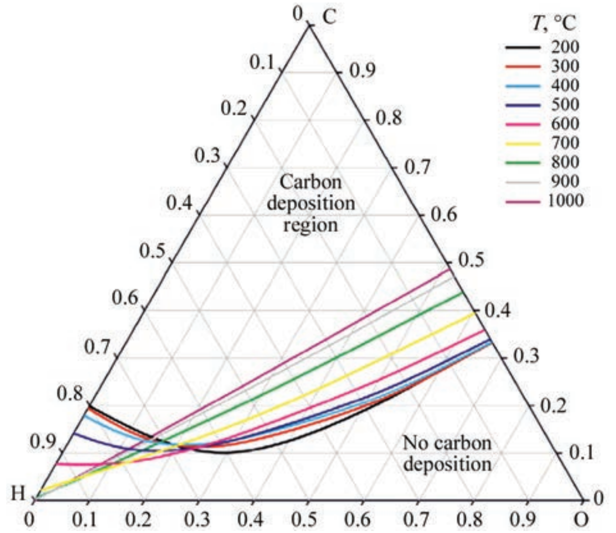

Figure 8. Ternary C–H–O diagram for the solid phase of all carbon allotropes at a pressure of 1 bar [41]

values result in higher CO conversion and lower CO content in the outlet gas. In addition to CO conversion, the steam-to-oxygen ratio can also affect the production of hydrocarbons (primarily methane) from the reaction:

$$2CO + 2H_2 \leftrightarrow CH_4 + CO_2 \ (\Delta H = -244 \text{ kJ/kmol}).$$

A minimum steam-to-oxygen ratio of ~0.4 at the reactor inlet should be ensured to minimize such undesirable reactions. In addition, a certain amount of steam prevents the risk of coking and carbon deposition on the surface. Depending on the feedstock fed to the reactor, typical steam to oxygen molar ratio ranges from 0.6 to 2.2, and the steam to carbon ratio varies between 2.8 and 4.2. Figure 8 [41] shows the ternary C–H–O diagram for a pressure of 1 bar, indicating a zone with thermodynamic preference for coking and carbon deposition.

To increase the yield of H_2 and reduce the CO content in the generated synthesis gas, the water shift reaction:

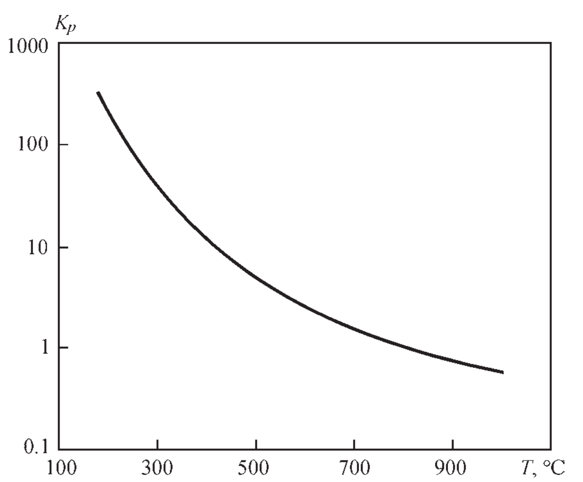

Figure 9. Change in the equilibrium constant (Kp) for the water gas shift reaction depending on temperature [42]

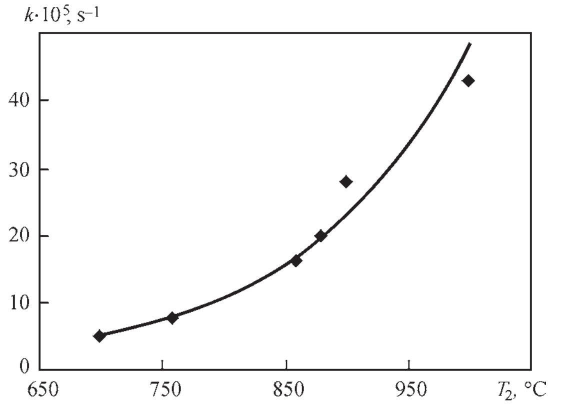

Figure 10. Effect of temperature in the feedstock layer on the carbon conversion rate [43]

$$CO + H_2O \leftrightarrow H_2 + CO_2 \ (\Delta H = -41.2 \text{ kJ/kmol}),$$

is a well-established technology in industrial large-scale hydrogen production plants, or to set the syngas' CO/H_2 ratio.

The water shift reaction converts carbon monoxide and steam into hydrogen and carbon dioxide. The equilibrium constant decreases with temperature, so high conversions are favored at low temperatures, as shown in Figure 9 [42].

When superheated water vapor is used as a heat carrier and reagent for carbon conversion, the conversion rate increases with increasing temperature (Figure 10) [43].

This is entirely consistent with the concepts of thermal activation of chemical processes — with an increase in temperature, their speed increases, and the increase in temperature is ensured by the rise in the temperature of water vapor, i.e. with an increase in the temperature of the vapor, the conversion rate and the depth of the reactions increase. Figure 11 [43] shows typical results of a study of the kinetics of gas evolution in the gasification process of carbonized coal.

The main process of carbon with water vapor interaction:

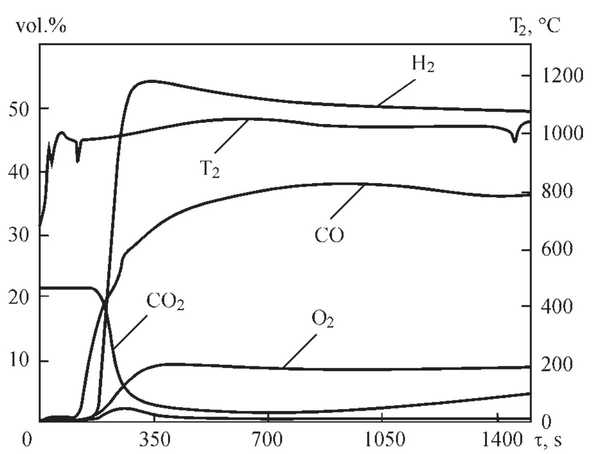

Figure 11. Dependence of the yield of gaseous products of coal gasification on time

$$C + H_2O \rightarrow CO + H_2.$$

The following dependencies on Figure 11 are noteworthy. During the gasification process, the hydrogen concentration decreases while the oxygen content in the mixture increases. At the same time, the ratio of CO and CO_2 concentrations remains virtually unchanged throughout the process. The amount of hydrogen in the reaction products decreases due to its oxidation by oxygen according to the reaction:

$$2H_2 + O_2 \rightarrow 2H_2O,$$

in this case, oxygen obtained by the reaction $CO_2 \rightarrow \rightarrow C + O_2$ is used. This reaction itself becomes possible, on the one hand, due to the oxidation of CO by superheated water vapor $CO + H_2CO \rightarrow CO_2 + H_2$, and on the other hand, due to the presence of mineral impurities in coal that have catalytic activity in the reaction $O_2 \rightarrow C + O_2$ [44].

Based on the above assessment of the state of the art in large-scale biomass gasification, the projection onto plasma technologies today is as follows. Plasma has been recognized as an effective method for destroying hazardous waste for decades. However, plasma generators consume a lot of electricity. As a result, the rising cost of electricity and pollution from coal-fired power plants have made plasma an expensive and environmentally questionable disposal method. Until 2000, most research into plasma use for waste recycling aimed at achieving complete pyrolytic decomposition as far as possible. Nevertheless, the more sophisticated the process, the higher the power consumption. Even with large volumes of waste destroyed, pyrolytic gasification requires much more energy than it produces. Only when the cost of eliminating the hazard posed by the waste is very high does plasma become an economically viable method of waste destruction [45]. Currently, the thermal processing industry is studying ways to analyze and optimize the efficiency of installations [46, 47]. A sensitivity analysis of the operating parameters of the plasma gasification process was performed to maximize the net energy produced and minimize the plant cost. Where available, correlations from the literature and market data were used to calculate the capital and operating costs of the process. For example, a case study of a plasma gasification plant processing 750 tons of municipal solid waste per day was conducted in Greece. This analysis showed that the cost of the plasma gasification process is comparable to the conventional incineration process. In addition, plasma gasification has produced better environmental and technical results [46]. This fact offers a new framework for reconsidering the historical cost and energy consumption issues that have previously limited the development of plasma processing. To compete with fossil fuel-based technologies, large-scale gasification plants still require significant technological development supported by economic subsidies and incentives, efficient operating strategies, and global policies pushing for carbon-neutral solutions. The work [48] shows that specific investments tend to decrease over the years, for gasification plants designed to produce electricity, cogeneration energy and liquid biofuels (Figure 12).

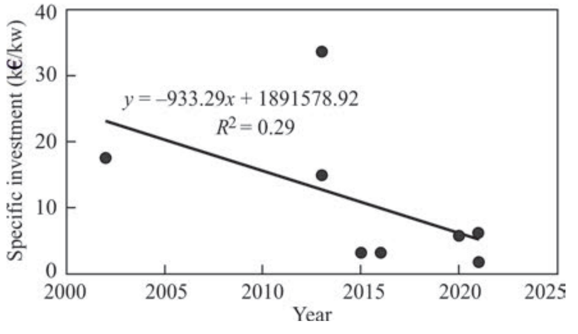

Figure 12. The relationship between investment and year, as well as the corresponding linear regression equation for electricity, cogeneration plants and biofuel gasification plants [48]

While plasma gasification has many advantages, some disadvantages need to be considered before investing in this technology. One of the main disadvantages of plasma gasification is its high cost. The process requires expensive equipment and trained personnel, making it prohibitively expensive for many individuals and organizations. Additionally, the high cost of plasma gasification can make it difficult to justify the price, especially when cheaper methods are available. Another disadvantage of plasma gasification is that it requires specialized training. Individuals wishing to perform the procedure must undergo extensive training to operate specialized equipment safely and effectively. Overall, plasma gasification offers a promising solution to reducing reliance on traditional waste management methods while helping to become more environmentally friendly. Like any other technology or process, this method has advantages and disadvantages that need to be considered. The challenge for those considering using plasma in waste processing is to achieve low energy consumption, high energy value of the gas, low capital and operating costs, and long equipment uptime.

To meet the requirement for long operating times, microwave [49] and induction plasma [50] are currently being considered. The emergence of new plasma technologies in thermochemical conversion methods may open up new avenues for the economical production of H_2 and value-added products. Plasma gasification has been developed commercially, typically using direct current plasma discharge technolo-

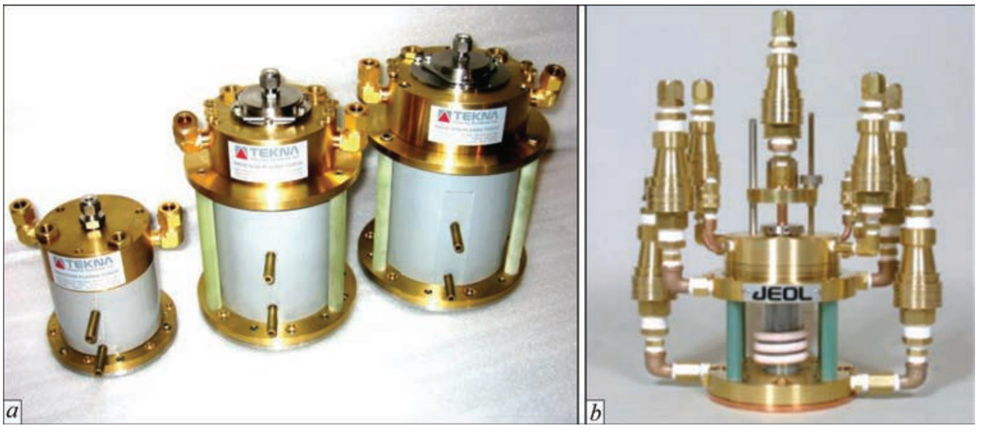

Figure 13. High-frequency induction plasma torches: *a* — Tekna (from 40–200 kW); *b* — JEOL

gy [51]. However, direct current torches suffer from short electrode life in the presence of oxidizing gases, leading to inconvenience and high operating costs associated with their replacement. An alternative is the use of electrodeless plasma torches.

For small and industrial scale waste recycling, three types of advanced thermal plasma technologies are considered: DC atmospheric plasma torches, radio frequency plasma torches and microwave plasma torches. The authors of [52] conducted a comparative study of all three plasma torches for energy and waste recycling applications. The simulation modelling and experimental results were presented with an indirect DC plasma torch and a high-frequency induction plasma torch. The results show that DC plasma torches and high-frequency induction plasma torches are economical and beneficial for large-scale waste recycling and energy production. Meanwhile, a microwave plasma torch can be used for small-scale waste recycling. Overall, minimizing the environmental impact and cost-effectiveness of the process are the most critical parameters to improve the feasibility and sustainability of plasma-based waste recycling plants. High-frequency induction plasma torches with plasma power from 15 to 200 kW are designed for more than 10,000 hours of non-stop operation [53]. They have found application in the chemical and metallurgical industries due to their high reliability and long service life without parts replacement (within 2–3 months).

Modern high-frequency induction plasma torches from TEKNA [54] and JEOL [55] (Figure 13) have reached a prominent level of perfection and meet the requirements for a plasma gasification system.

For adequate control of gasification processes and developing and optimizing plasma reactors, reliable information about the RF discharge and plasma torch parameters is necessary. The task is simplified in biomass gasification since the jet induction plasma torch operates for a long time in one mode. The extended laminar torch of the optimized induction plasma torch has well-filled temperature and velocity profiles (Figure 14, *a–c*) [56]. It should be noted that many studies have been conducted on the temperature and velocity of the jet of induction plasma torches by direct measurements, using probes and optical emission spectra. For clarity, the calculated picture of the temperature and velocity fields in the torch of the plasma torch induction is given here; it agrees with the experiment.

The torch was modeled in ANSYS Fluent; the geometry was meshed to discretize the space. The mesh independence study was performed by refining the cell size, which is expressed as the number of cells per millimeter of axial distance.

The industry uses high-frequency induction (HFI) plasma torches for various applications. To get more benefit, many attempts have been made to improve the HFI plasma torch, which included optimizing its operating conditions, size and shape. However, the optimization efforts [57–59] did not produce long-term results, leaving the original design proposed by Reed [60] in the 1960s, which remains virtually unchanged. However, recent efforts [61] have been revived and developed in [56]. A significant improvement is achieved by using conical geometry (Figure 13, *b*). This geometry significantly reduced gas and power consumption and improved performance. Special HFI plasma torches shown in Figure 13 are available to operate with every class of HF power sources. They feature highly efficient designs to maximize plasma thermal processing effects, excellent ruggedness and stability. Adopts dual-pipe water cooling system: the inner tube is made of ceramic with higher strength than quartz tube, which ensures stable operation for a long time under atmospheric pressure, under ultra-high temperature and strong oxidizing environment such as HCl, HF, or HBr.

In the first years of studying the HFI plasma, experimenters used available power sources (tube generators) and the first results were obtained in a wide frequency range from 0.5 to 60 MHz. Later,

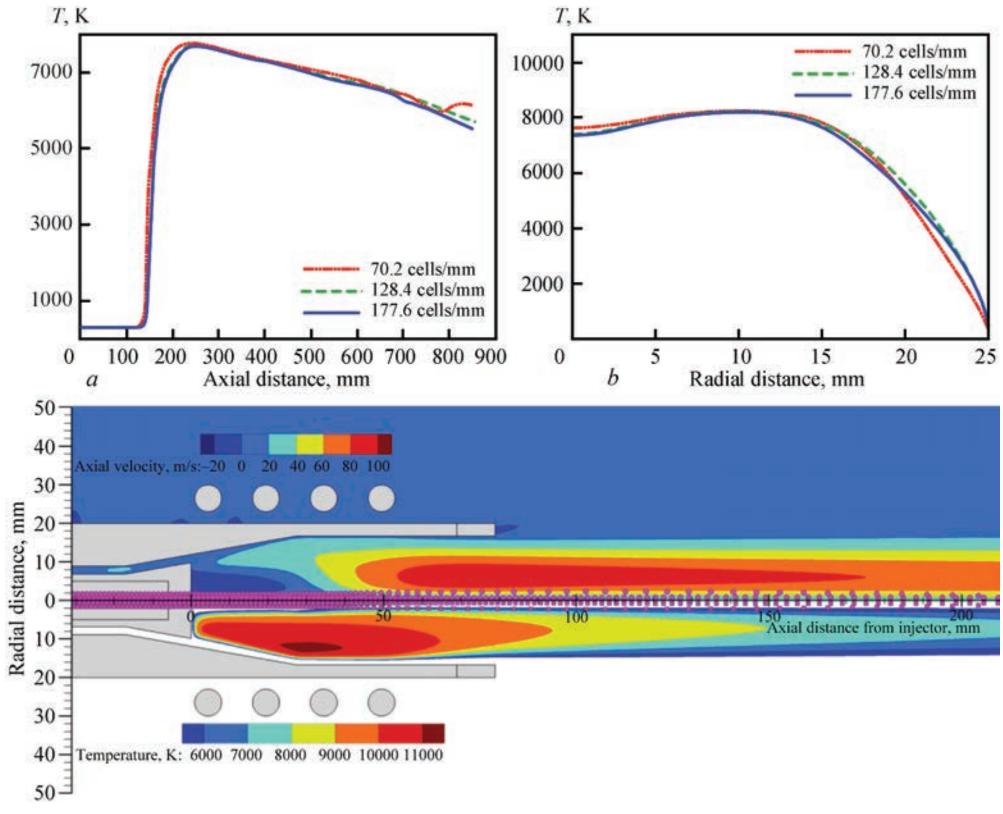

Figure 14. Parameters distribution in the torch of a conventional high-frequency induction plasma torch: *a* — temperature along the central axis for different cell sizes; *b* — radial distribution of temperature at the plasma torch outlet for cells of various sizes; *c* — contours of axial velocity and temperature

a standard series of frequencies of 0.44, 1.76, and 5.28 MHz and oscillatory powers of 60, 160, and 1000 kW tube generators were established [62]. The most important consumer of energy is the generator tube. Energy losses at the anode of the generator tube are 25–33 % of the total electricity consumed; this circumstance determines the entire energy of HFI plasma installations. A good frequency for HFI plasma torches is 5.28 MHz and higher; losses in a metal plasma torch are 1.3 % of the consumed power. A frequency of 1.76 MHz from the point of view of using a metal plasma torch is considered the limiting one, below which one should not go — losses are already 4–6 %. At a frequency of 0.44 MHz, the losses in the plasma torch, inductor, and circuits become equal to those in the generator lamp. The overall efficiency of the HFI plasma installation on the generator lamp at a frequency of 1.76–5.28 MHz is 60–64 %.

High-frequency induction plasma torches, which can currently become the main link in the technological process, with a plasma power of 15 to 200 kW, are designed for more than 10,000 hours of continuous operation. The strategy is to combine gasification and maximum gas purification in a single reactor to obtain high-quality and heat of combustion synthesis gas. Energy recovery and combining primary purification with gasification make the system more compact, reduce heat losses and take up less space in the plant. Increasing the purity of the gas leaving the biomass gasification system, eliminating tar contaminants, maximizing the reduction of alkali metals, solid particles, nitrogen (N_2), sulfur (S), and chlorine (Cl_2) simplifies filtration and purification with the minimization of catalysts and sorbents.

The new concept of organizing the technological process and constructing a reactor using plasma induction ensures a uniform gas-dynamic regime throughout the volume of the gasification zone and an effective and uniform thermal effect on the entire volume of the solid carbon-containing material and the gas phase in the gasification zone, and, consequently, a uniform distribution of temperature and concentrations in the gasification zone. This contributes to the creation of uniform conditions for chemical reactions both in the solid carbon-containing material and in the gas phase, as well as a stable composition and high energy indicators for obtaining synthesis gas with the maximum approximation to thermodynamic equilibrium [50]. Super-equilibrium surface heating from the jet of high-enthalpy dissociated gas mixture of the induction plasma torch is expected [63]. The effect of super-equilibrium heating is observed when a dissociated chemically nonequilibrium gas flow generated by the induction plasma torch flows around a surface with non-uniform catalytic properties. When passing from a non-catalytic to a catalytic surface region, there is a jump in the heat flux and temperature to levels significantly exceeding the values obtained on a fully catalytic surface or in the case of an equilibrium boundary layer. The effect is due to the fact that, under identical external flow conditions, the concentration of dissociated gas atoms in the boundary layer on a non-catalytic surface is higher than in the case of a catalytic surface, and their recombination further downstream on the catalytic surface leads to its additional heating. In experiments with a sample, sections of which were coated with chromium-nickel spinel, the temperature behind the transition line from the low- to the highly catalytic surface region exceeded the temperature measured in the same area during flow around a fully highly catalytic surface by 140 °C [64]. In subsonic jets of dissociated air on a flat, highly catalytic surface, heat fluxes with a density of 150 to 3750 kW/m^2 were realized. This phenomenon is fundamental at the gasification stage of solid carbon mixed with ash residue.

The key issue in scaling up plasma gasification of biomass is the specific energy consumption of electricity per kilogram of waste. Let us present several illustrative processes. Calculations of plasma gasification processes of waste in a shaft reactor made it possible to estimate energy costs and outline ways to reduce them [65]. Figure 15 shows the dependence of the productivity of the gasification process on the average statistical composition of waste on the power of an external energy source. The heat of combustion was within 7–10 MJ/kg with a mass fraction of carbon and hydrogen in the feedstock of 20–30 %. For comparison, the heat of combustion of sunflower husk biomass is 19.4 MJ/kg with a mass fraction of carbon and hydrogen of 54 %. In the shaft plasma furnace, for which the dependencies were obtained (Figure 15), moisture is used as an oxidizer, determining the initial moisture content of the raw material, and plasma torches can operate with the supply of superheated steam or air, the oxygen of which acts only as an additional oxidizer in the gasification process. For the adopted furnace scheme, with an increase in the temperature in the reactor, there is an increase in electrical energy consumption, but the potential energy of the synthesis gas increases by the same amount. With an increase in temperature from 1100 to 1300 °C, the hydrogen content in dry synthesis gas decreases from 57.5 to 57 %, and the CO content increases from 34 to 36.5 %. Here, the required mass flow rate of the oxidizer does not exceed 5–7 % of the mass flow rate of the resulting synthesis gas. Electrical energy consumption from 0.68 kW·h/kg (humidity close to zero) to 1.5 kW·h/kg (humidity 0.15 g/kg). The main conclusion is that new technologies for processing

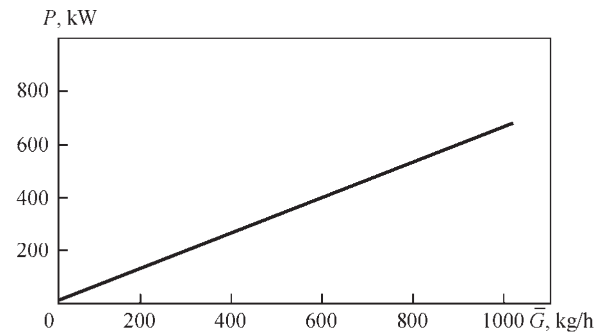

Figure 15. Dependence of the productivity of the waste gasification process on the power of an external energy source [65]

carbon-containing waste accepted for implementation should be based on using oxygen and superheated water vapor to temperatures >1000 °C as an oxidizer.

New technologies should be implemented in weakly oxidizing and reducing atmospheres and have two spatially separated zones: a medium-temperature zone (T < 1000 °C) for drying, pyrolysis and gasification, and a high-temperature zone (T > 1300 °C) for completing the gasification processes, removing the inorganic part of the waste and heating the gaseous product (gas synthesis) to the optimum temperature.

In [66], the use of plasma technology for processing biomass (BM) in the form of mixed manure of cattle, horses, sheep, goats and pigs (moisture content 30 %) is analyzed. The characteristic composition of the biomass (manure) is as follows in mass %: H_2O — 30; C — 29.07; H — 4.06; O — 32.08; S — 0.26; N — 1.22; P_2O_5 — 0.61; K_2O — 1.47; CaO — 0.86; and MgO — 0.37. Most of the organic matter consists of cellulose ($(C_6H_{10}O_5)_n$) and some organic sulfur (S). BM consists of 95.21 % organic matter; the mineral content is 4.79 %. The biomass has a calorific value of 16 MJ/kg. The following mixtures by weight were used for plasma gasification and pyrolysis: 100 % BM + 25 % air and 100 % BM + 25 % nitrogen, respectively. Experimental studies of plasma-chemical gasification and pyrolysis of BM were conducted on a setup whose main elements were a direct-current plasma torch (nominal power 70 kW) and a plasma-chemical reactor with a BM capacity of about 50 kg/h. The degree of gasification and specific energy consumption of the plasma are shown in Figure 16.

It is evident from Figure 16 that the degree of gasification increased with increasing temperature in both cases, but it was slightly faster for gasification than for pyrolysis. However, at a temperature of 950 K, the degree of gasification reached 100 % for both processes. When comparing the parameters of the plasma treatment of biomass, the calculated and experimental data showed satisfactory agreement, with a discrepancy of no more than 16 %. The plasma-treated biomass products were free of harmful impurities in calcula-

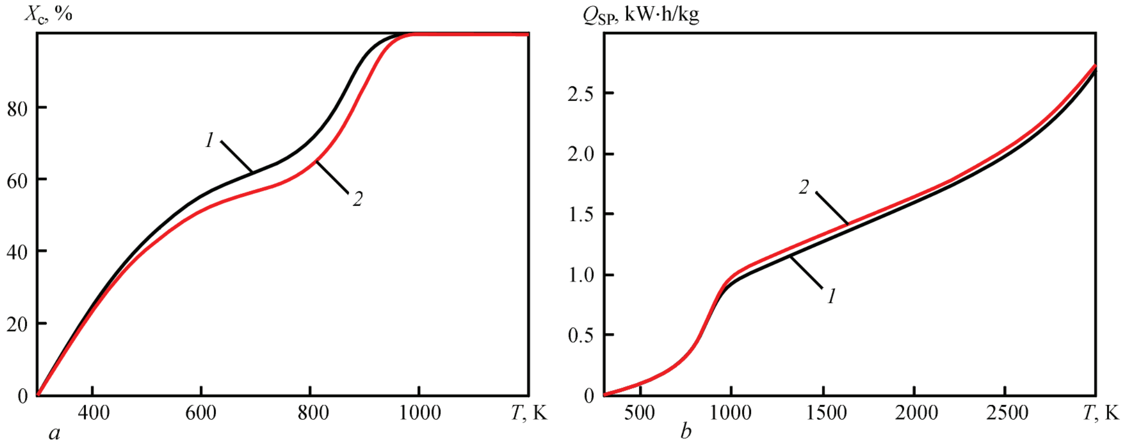

Figure 16. Dependence of the degree of gasification (*a*) and energy consumption of plasma (*b*) during gasification of biomass-manure on temperature: *1* — plasma gasification; *2* — plasma pyrolysis [66]

tions and experiments, confirming the environmental benefits of plasma treatment. Using the exergy coefficients of the heat of combustion of biomass, it was concluded that plasma gasification of biomass is 25 % more efficient than traditional combustion.

The possibility of gasification of wood pellets to synthesis gas in a thermal air plasma environment was determined [67]. The influence of the plasma torch power, plasma-forming gas consumption, and equivalence coefficient on biomass gasification was analyzed. The synthesis gas yield varied from 59.95 to 62.51 %, and the H_2/CO ratio ranged from 0.68 to 0.8. The highest concentrations of H_2 and CO in the resulting gas were 26.6 and 33.35 %, respectively, which gave an H_2/CO ratio of 0.8. The net calorific value of the resulting synthesis gas varied from 7.62 to 8.82 MJ/Nm^3. The carbon and energy conversion coefficients were 85.3–97.2 and 29.23–30.57 %, respectively. Specific energy consumption varied in the range of 165.47–195.61 kJ/mol of synthesis gas. At the same time, the particular energy consumption for wood waste gasification and gasification efficiency were 2.49 kW·h/kg and 82 %, respectively. In addition, the energy and mass balance assessment showed that when gasifying 20.73 kg/h of wood pellets, the resulting synthesis gas can produce 15–18 kW·h and 111–114 kW·h of electrical and thermal energy, respectively.

Of the three biomasses studied [68] (sugar cake, rice husks and sawdust), sawdust is the most suitable for the process of obtaining hydrogen-rich synthesis gas, since it can produce more hydrogen (~97 g/kg biomass). However, plasma torches require higher electricity consumption (2.23 kW·h/kg biomass). In this sense, rice husk shows the worst results with a maximum specific hydrogen production of 54 g/kg biomass at 27.5 kW·h/kg of produced hydrogen. As a conclusion, this study confirmed that plasma gasification with an air-steam mixture as a gasifying agent can be used to produce hydrogen-rich gas with specific production in the range of 1.79–2.80, 1.68–2.37, and 2.09–2.81 Nm^3/kg from sugar cake, rice husk, and sawdust, respectively. And with lower electricity consumption per kilogram of hydrogen than aqueous hydrolysis.

Atmospheric pressure plasma jets are the main tool for gasification. It is estimated that the plasma torch consumes only 2–5 % of the total energy input into the gasification system, and up to 80 % of the total energy input into the feedstock can be recovered in the produced synthesis gas. In 2010, Scientific Certification Systems (SCS) reported that the plasma gasification process resulted in the lowest greenhouse gas emissions for the same amount of energy, with approximately 31 mln tons less CO_2 equivalent/MWh compared to landfill with energy recovery and approximately 50,000 tons less CO_2 equivalent/MWh compared to natural gas combustion [69]. However, based on the above results and the goals of sustainable energy development, integrating highly efficient biomass gasifiers of any type into advanced production systems will occur on a comparative basis in the future global energy market. In recent years, manufacturers have made numerous efforts to reduce the cost of implementing biomass gasifiers. The main inhibitory factor is the higher cost of purchasing plasma equipment in the proposed cycle compared to traditional processes and the use of complex equipment. This study assesses the place of an improved plasma cycle for producing high-power and efficient energy sources. The reduction in equipment cost is directly related to the reduction in electricity consumption by plasma burners (kW·h/kg biomass) while maintaining efficiency. Reduction in overall energy consumption of the system can be achieved by optimizing energy flows in the gasification reactor — minimizing the Gibbs free energy [70] and using plasma not only as an additional heat source, but also for local stimulation of chemical reactions in the superequilibrium heating zone. The following should be considered. 1. The temperature of the exhaust synthesis gas is high, 1000 °C and above, and there are many opportunities for waste heat utilization in addition to the input of plasma energy and partial combustion of the waste material. The authors performed energy optimization of the biomass gasification system using high-temperature effluent synthesis gas for preheating the incoming water vapor. 2. Using high-volume HFI plasma (Figure 14) increases the effective area available for interaction with surfaces. 3. Using HFI plasma for local super-equilibrium heating and stimulation of chemical reactions. The reactor scheme adopted for modeling is shown in Figure 17.

Fulfilment of these conditions creates preconditions for reducing the plasma equipment's installed capacity with corresponding weight, dimensions and cost reduction. As a rule, RFI plasma equipment includes a power source (radio frequency generator and matching network), plasma torch and reactor. Most processes based on HFI plasma use equilibrium plasma in the temperature range of 8000–12000 K. Regarding commercial application of RFI plasma up to now it is mainly powder processing and space research, as well as some environmental applications: dissociation of hydrogen chloride, treatment of medical waste [71], decomposition of polyvinyl chloride (PVC) [72]. HFI plasma at low pressures is not considered here; only thermal plasma with high enthalpy is considered. The HFI method is essential for obtaining thermal plasma with high gas temperature at high pressures for biomass and waste processing gasification. Several problems require further study and development, such as the excitation of the HFI plasma discharge at atmospheric pressure and the efficiency of the HFI power supplies. They are based on the oscillator tube in the electrical circuit of the power electronics (Figure 18) [59, 61, 73]. Common problems in plasma generation are: size — HFI generators are usually large, heavy units; reliability — generators use tubes with a limited life; efficiency — generators with a power tube have always been inefficient. The reasons are: power losses — most of the power is dissipated in the tube; low reliability — in generators using power tubes, they are replaced approximately every two years, depending on the use; high voltage of the order of 10 kV is present in the generator, which increases the likelihood of failure; maintenance problems — generators are complex elements that require labor-intensive procedures for repair if a malfunction occurs. Most modern plasma HFI generators are beginning to use solid-state electronic components. This significantly reduces the size of contemporary plasma generators and is much more suitable for operation. HFI generators with an efficiency of 90 % and higher are currently successfully used at low-pressure and low-power plasma torches. Solid-state HFI generators (like Figure 19) of high power (>25 kW) are under development.

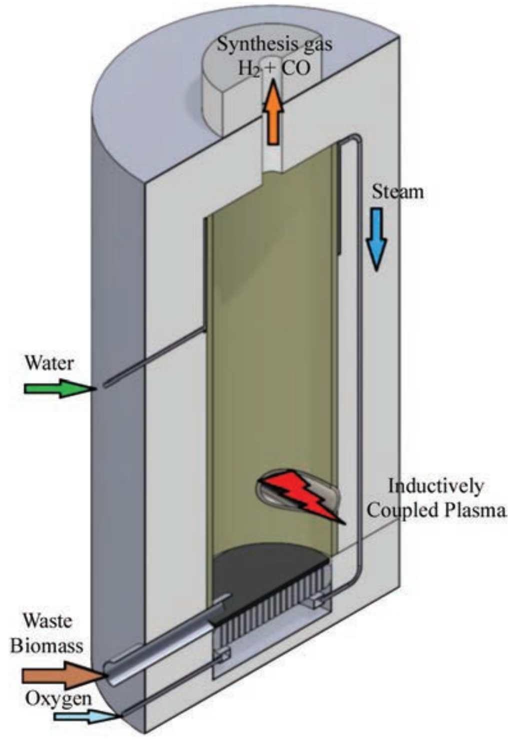

Figure 17. Scheme of the reactor adopted for modeling

Figure 19 shows the electrical circuit of the solid-state power supply for the HFI plasma torch [74].

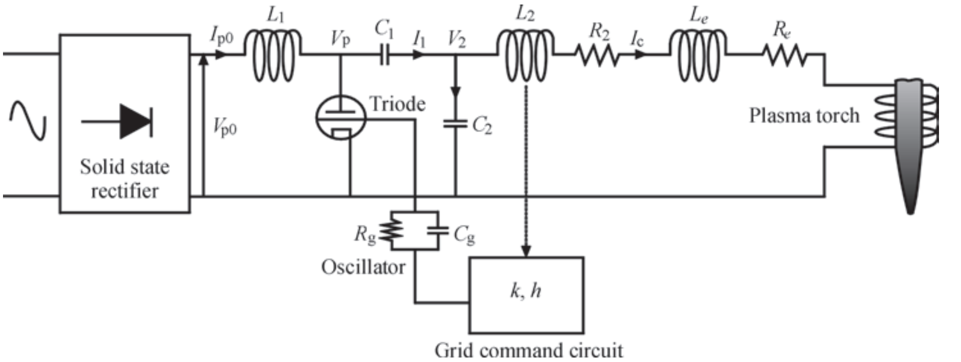

Figure 18. Typical structural electrical diagram of the power source of the HFI plasma torch with a generator lamp [59, 73]

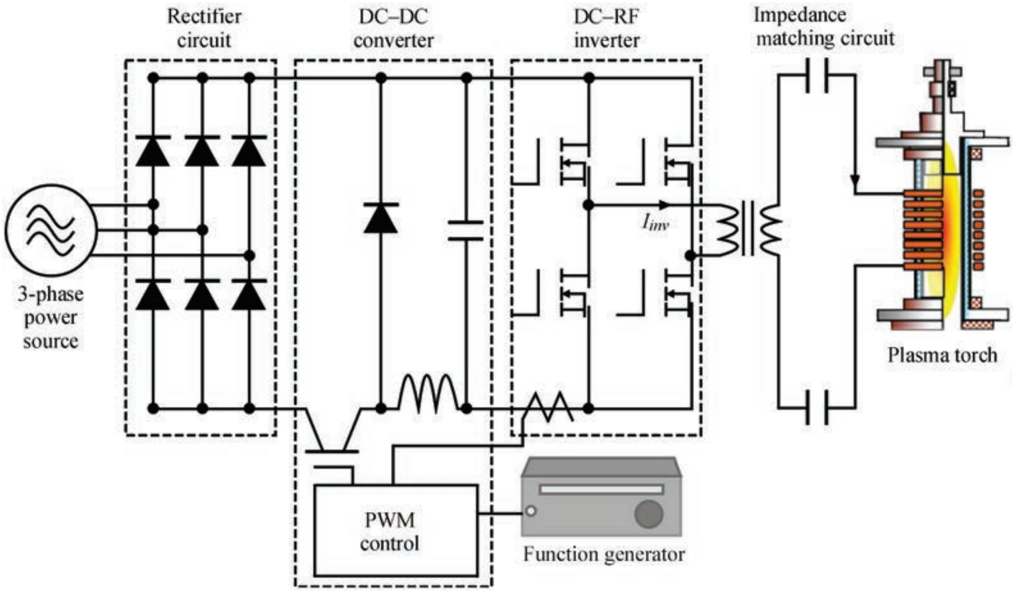

Figure 19. Scheme of a solid-state HFI generator for powering a plasmatron [74]

The power supply consists of four main parts: A rectifier circuit, an insulated gate, an IGBT bipolar transistor, a DC–DC chopper circuit, a full-bridge MOSFET inverter circuit, and an impedance matching circuit with a matching transformer and an LC series circuit. The MOSFET inverter frequency is adjusted within 350~450 kHz by phase-locked loop control to match the load impedance. This frequency of 350~450 kHz is much lower than that used in HFI plasma torches. In this case, the lower frequency electromagnetic field realizes a larger plasma skin depth, which helps maintain a large plasma volume. In addition, adopting this lower frequency allows the use of MOSFET energy at a low cost. It has been confirmed in experiments that this power supply's overall energy conversion efficiency is higher than 95 % for all cases. This higher energy conversion efficiency is an advantage of using semiconductors to support the high-power HFI plasma. The DC input power was recorded at 10 kW.

Modern powerful 13.56 MHz or 27.12 MHz, 120 kW, 50 Ω RF quartz-driven GENERATOR [75] on a generator tube still has low energy efficiency, significant dimensions, and cost. Therefore, transistor amplifiers are considered as a power supply for the next generation of HFI sources. Advantages compared to vacuum tube oscillators: higher efficiency (90 % and higher), lower cost, circuit simplifications with lower cooling requirements, and, due to proven reliability, plus excellent characteristics, make solid-state amplifiers a desirable option for the next generation of power supplies [76]. Although these are weighty arguments, a solid-state oscillator must be experimentally confirmed by practical experience in working with plasma devices. Solid-state oscillators have replaced vacuum tube oscillators in radio broadcasting for many years. The advantages of using such well-designed serial products for the power supply of plasma sources are potentially higher reliability and lower costs than vacuum tubes.

The increase in power is achieved by combining. The tested solid-state generator consists of 50 modules, each with a maximum power of 1.5 kW. Four transistors switch each module. The resulting square waves are arranged in parallel on a "summator" ferrite core and then converted into a sine wave by an output filter. Even if one or more modules fail, the generator will still be operational, albeit at a lower maximum output power. The module can be replaced quickly, which increases the reliability and maintainability of the system compared to self-excited vacuum tube generators. Unlike vacuum tube generators, there is no high voltage inside the solid-state generator, and therefore, no stored energy must be removed during a quick shutdown. The modular concept and the absence of high voltage are other reasons to expect high reliability.

To scale up plasma gasification, generators must have a maximum output power of up to 200 kW to provide sufficient power reserve. For inductively coupled plasma, most modern solid-state systems provide an efficiency of about 70–75 %, i.e., 70–75 % of the consumed power goes into the plasma.

An increase in power based on solid-state generators can also be achieved based on a newly developed tandem-type induction thermoplasma system using two HFI power sources and two inductor coils for one plasma torch (Figure 20) [77].

A 40 kW, 1 MHz solid-state RF ICP power supply has been developed and tested at the ITER-India Institute for Plasma Research [78]. The 40 kW supply was

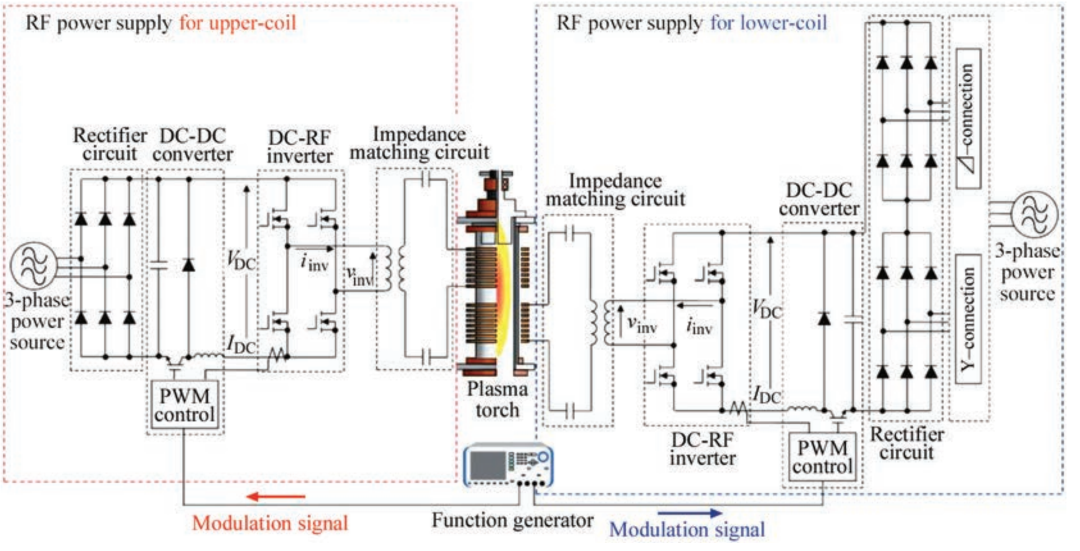

Figure 20. Tandem-type induction thermoplasma system

created by configuring multiple bridge inverter modules using latest generation switching semiconductors, magnetic combiners and LC network tuning to provide a 1 MHz sinusoidal output into a typical 50 Ω load (Figure 21). The experience with 40 kW HVHF provides significant insight into real-world scenarios in combination with RF-based plasma sources. This should form the basis for the next step, developing a 200 kW supply.

The problem of increasing the energy efficiency of induction plasma generators is quite solvable through energy-efficient conversion technology, the basis of which is the electronic component base of power electronics based on wide-bandgap semiconductors. The main semiconductor materials for power electronics are Si, GaAs, SiC, and GaN. All modern advances in high-power and ultra-high-power electronics are associated with silicon IGBTs. Is it possible to create IGBT devices based on GaAs, SiC, and GaN? [79]. When developing power electronic converters for plasma generators, they strive to achieve high efficiency and, at the same time, high power density. Increasing the switching frequency poses new challenges, since switching losses are proportional to the switching frequency, which limits the system's efficiency at high frequencies. At the same time, many standards put forward more stringent requirements for system efficiency. As for the operating frequency, most silicon-based designs today operate at 60–300 kHz. If the switching frequency is 500 kHz or higher, this can only be achieved with GaN. SiC is usually designed for 650–1200 V and higher operating voltages. Figure 22 shows a diagram of the dependence of power on frequency of various devices using them [80].

Silicon carbide is expected to grow in power electronics over the next five years to become the largest

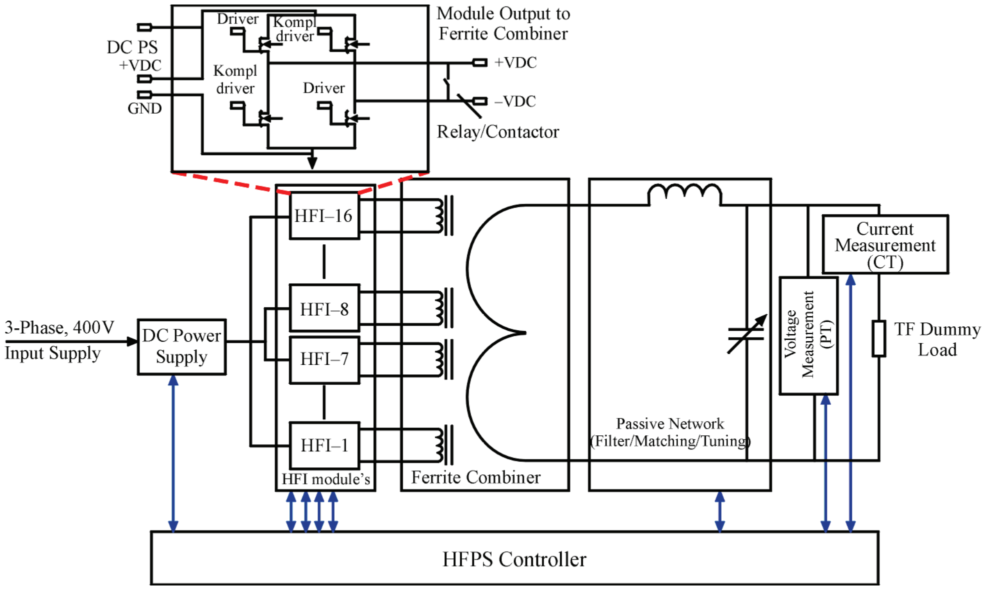

Figure 21. Schematic diagram of a 40 kW solid-state power supply for an induction plasma torch

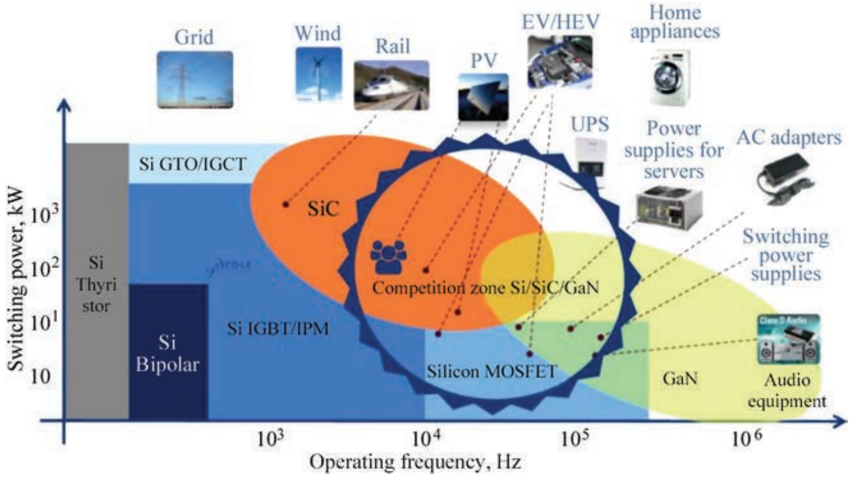

Figure 22. Diagram of the dependence of power on frequency and the area of application of power devices [80, 81]

broadband power market, followed by gallium nitride (in terms of power and FI demand). SiC enables higher voltage and power handling, while GaN enables higher frequency, which expands power applications to include HFI plasma generators.

The task is to transfer the latest research results to complex production quickly. Until now, the demand for power electronics for plasma engineering has mainly been associated with vacuum technology of thin films and etching. HRF plasma sources began to be studied in the late 1990s and eventually began to be widely used in the production of semiconductors [82, 83]. Solid-state devices of the Vacuum Power Plasma Supply (RF) 6 kW, 13.56 MHz are produced in serial production [84]. Further development of powerful RF plasma generators is possible in various directions, particularly as a space engine technology. Experimental results are presented for a powerful (up to 180 kW) inductive plasma generator with a high thermal efficiency of up to 84 % when exciting plasma in molecular gases [85].

Currently, solid-state power electronics technologies are rapidly evolving. New models represent innovative devices that utilize the good properties of wide band gap materials such as silicon carbide and gallium arsenide. Industrial and academic research interests are focused on developing proven and new power devices aimed at achieving good performance and increased energy savings, with an emphasis on the critical aspects and challenges that need to be addressed, in the authors' opinion, to fully realize the paradigm of better recycling of waste into useful products.

CONCLUSIONS

This paper presents positive arguments in favor of plasma gasification of biomass as a promising, viable and cost-effective technology. It is shown that the process is not limited to any specific feedstock and specific product, but is flexible in terms of processing biomass waste, which may be toxic or contaminated, into valuable products.

The effects of various plasma gasification parameters on the properties and yield of the syngas are analyzed to facilitate optimization of future research and the overall process. Plasma gasification can be an effective way to convert toxic and wet biomass into hydrogen-rich syngas, making the gasification process cleaner and operating at higher efficiency. Gasification, in general, has a number of negative social and environmental impacts, which can be minimized by appropriate plasma technology implementation.

As a result of many years of operation, plasma has been recognized as an effective method for destroying hazardous waste. However, plasma installations are expensive and use a lot of electricity. The article shows new technological solutions to these problems by optimizing energy flows in the gasification reactor, rational use of plasma as a concentrated energy flow, reducing electricity consumption by plasma burners, reducing the power and cost of plasma installations, and radically solving the problem of their reliability.

As can be seen from the study, plasma gasification of biomass has advantages over traditional options in obtaining hydrogen-enriched synthesis gas. As for the economic outlook, lower capital and operating costs are expected in the new approach to constructing large-scale production.

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ORCID
S.V. Petrov: 0000-0003-0373-8003,
O.I. Som: 0009-0009-4152-4832,
S.G. Bondarenko: 0000-0003-2305-6691,
O.V. Sanginova: 0000-0001-6378-7718,
M. Ganczarski: 0009-0009-0355-0677,
E. Rój: 0000-0002-8691-3315

CONFLICT OF INTEREST
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CORRESPONDING AUTHOR
S.V. Petrov
The Gas Institute of the NASU
39 Degtyarivska Str., 03113, Kyiv, Ukraine
E-mail: vizana.sp@gmail.com

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