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LITERATURE REVIEW ON SOLAR ENERGY AND BIOGAS UTILISATION FOR THE DEVELOPMENT OF SCALABLE CO-GENERATION POWER PLANTS

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Abstract: In this paper, we present the research results related to the project "Development and implementation of a scalable co-generation power plant solution integrating solar energy and biomass utilisation". Our objective is to develop an integrated solution in the field of local renewable and sustainable energy production, storage and use, where solar energy collected by PV/T collector, hydrogen and oxygen gas production by water decomposition, and biogas production by biomass utilisation are integrated into an innovative process, in different scales (scalable), to produce a compact device, which stores solar energy in the form of combustible gas in a container. Our research team members are working on different areas of tasks to achieve this goal. This article reviews the results of the first phase of this work, which involved a literature review and a groundwork.

Keywords: solar panel, solar collector, water purification, biogas components, gas mixture

1. Introduction

The use of renewable energies is an essential option for energy production [1], [2], [3]. Among these, the use of solar panels and solar collectors, which actively harness solar energy, is significant today. Solar panels generate electricity directly, while solar collectors generate heat water.

Storage of energy from renewables is also a cardinal issue. Practical solutions and their commercially successful forms have not yet led to any socio-economic breakthroughs, but it is one of the most researched areas. This area is critical if environmental and nature conservation aspects are considered, i.e. renewable and sustainable energy production [4], [5], [6].

The current implementation of some technologies for renewable and sustainable energy production is fragmented. Solar farms for electricity generation are built separately, solar collectors for domestic hot water are constructed separately, biogas plants are set up separately, and wind farms are installed individually. The project proposal provides a solution to the challenges where innovative integrated energy solutions are developed in a common field of local potential and high-tech solutions. This new solution will enable both local needs and global challenges to be met in a technically better and more economical way than has previously been possible.

The new solution to be developed:

- integrates the production of hydrogen by solar panels to improve biogas,
- provides a solution for the local use of oxygen,
- enables local renewable (solar) and sustainable (biogas) production,
- provides energy storage adapted to local variable energy demand,

- can be installed in several sizes.

This solution aims to achieve integration at the process level, i.e., one technology enhances the goodness and efficiency of the other process. This aim will be achieved using the advanced elements of the digitalisation and Industry 4.0 technology platform, particularly artificial intelligence-based algorithms and sensor systems as data sources. The R&D project aims to synthesise these two areas to create a marketable, complex physical energy production system that does not yet exist, creating a technology transfer (know-how) that can be sold on the global market.

The device is built up of the modules illustrated in Figure 1. The photovoltaic (PV) module, which is the starting element, uses solar energy to generate electricity, which is then used by the next element to produce hydrogen and oxygen from the decomposition of water.

The third key element of the system is the biogas module. This element uses thermal energy generated by a solar collector to increase the efficiency of the fermentation process. The composition and energy content of the resulting biogas can be increased by adding hydrogen gas obtained from the previous modules.

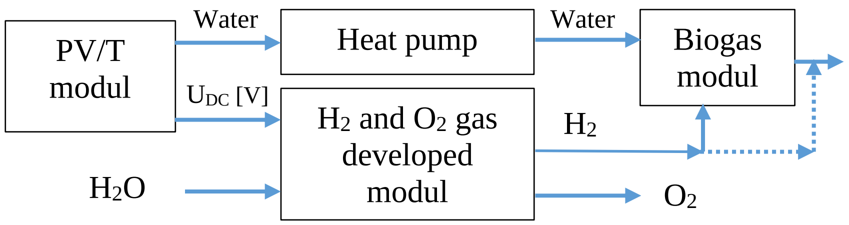

Figure 1. Modules of the designed scalable co-generation device

In this section of our research work, we reviewed the literature related to the design, functioning and use of the presented modules (solar panel, solar collector, water purification, fermentor), the composition of input/output materials, as well as the studies carried out in related fields. The following literature review will be presented on solar cells, solar collectors, water decomposition, biogas production, biogas composition, biogas utilisation, and gas mixtures.

2. Literature review

2.1. Solar photovoltaic cells

This chapter focuses on solar cells, which convert solar energy directly into electricity. In addition to the types of solar panels, the methods used to store the energy produced and the technical devices used for this purpose are also discussed.

The types of solar cells produced by different technologies were reviewed, ranging from traditional silicon-based solar cells to emerging technologies currently in the experimental stage [7].

To evaluate the different technologies, we need to consider the fulfilment of several criteria, the most important of which are [8]:

- high-efficiency opportunity
- availability of materials used
- reasonable cost of materials
- the possibility of low production cost technology
- product stability over time (decades)
- environmentally friendly product and production technology

Today, the market is dominated by silicon-based solar cells, crystalline silicon in cells made using slice technology and amorphous silicon made using thin film technology [9].

Most solar cells are made from crystalline silicon and are very similar in design to silicon-based devices such as rectifier diodes. The technology uses silicon plates and is therefore called slice technology. The advantage is that it is self-carrying; the disadvantage is that it requires a large quantity, expensive, semiconducting, high-quality material [10].

- Crystalline silicon solar cells
  - Monocrystalline silicon solar cells
  - Polycrystalline silicon solar cells
  - Silicon Ribbon Solar Cells
- Thin film solar cells
  - Amorphous silicon solar cells
  - Gallium Arsenide (GaAs) Solar cells
  - Cadmium telluride (CdTe) based solar cells
  - Copper Indium Diselenide (CIS and CIGS) solar cells
- Emerging solar technologies
  - Dye-sensitised solar cells
  - Organic solar cells
  - CZTS solar cells
  - Perovskite solar cells
  - Quantum dot solar cells
  - Multi-junction solar cells

The method of determining the amperage current-voltage (I-V) characteristic, an essential characteristic of solar cells, and through this, the determination of the maximum operating power point of a solar cell, including the influence of environmental factors (temperature, intensity) on this characteristic, has been developed [11], [12], [13].

Special attention will be given to grid-connected solar PV systems and the grid inverters needed to operate them, showing the main types used [14], [15], [16].

We have also reviewed the characteristics of off-grid solar PV systems, focusing on the characteristics of battery farms for storing the energy produced and the typical types of batteries used [17].

We have examined the problem of charge controllers for battery operation and the problem of island mode inverters [18], [19]. We have also looked at the possibility of combining other energy sources with solar PV systems in a hybrid system to achieve energy security [20], [21], [22], [23], [24].

2.2. Solar thermal collectors

The following will present the situation and potential of solar thermal energy. Accordingly, an overview of solar collector design, operation, development history, types, applications, and solutions to improve efficiency and effectiveness will be presented based on the available literature. Following these aspects, PV/T collectors will be reviewed, followed by heat exchangers and heat storage, based on available publications and their results. The chapter concludes with a literature review on heat pumps for thermal utilisation.

Since in an in-use building, in addition to the demand for electricity, there is also a need for heating (hot water production, space heating) [25] and cooling (space cooling), an obvious solution is to use waste heat by placing a collector behind the solar panels and at the same time improve the efficiency of the solar panel due to the lower operating temperature. However, the investment costs are higher for PV/T than for PV, as the system must be built for both utilisations. If a heat pump is planned in the system, PV/T is a more optimal solution than PV, as hot water and heating are also required.

However, there are also cases where the production of hot water (in swimming pools, and food processing plants) is solved by air-to-water heat pumps [26], [27], [28]. Another common form of heat pump is the ground source heat pump, which can also be used to produce hot water and thus heat buildings [29]. In this project, we are using a water-to-water heat pump.

The research results of the PV/T system, detailed below, form the basis of this technology and show the future trend of the PV/T system.

Ramos et al. conducted a theoretical and experimental thermographic analysis of the PV/T system investigated in their case study under different conditions [30]. Their results show that PV/T can produce significantly more energy at maximum solar energy values than PV.

In summer operation, Shao et al. analysed the efficiency of a PV/T system and compared it with the results obtained by operating only the PV part [31]. Their results show that the performance and efficiency of PV/T are always higher than those measured for PV.

Liang et al. conducted an empirical study to investigate the performance of a graphite-filled PV/T collector. Their research results showed that between 8:00 and 16:00 h, the average electrical efficiency of the PV/T collector and the classical PV module was 6.46% and 5.15%, respectively, i.e., PV/T in this form resulted in an additional electrical efficiency of 25.4% [32].

Duffie and Beckman also investigated the temperature distribution of the flat plate collector perpendicular to the direction of the fluid flow, showing that the temperature is higher between the tubes than around the tubes because there is not as much heat transport and dissipation [33]. However, due to the good thermal conductivity of the material connecting the tube to the absorber, the temperature inside the tube can be considered the same.

A delay in the change in the temperature of the solar fluid reflects the change in radiation. In the transient case, the response function is the solar fluid temperature curve plotted as a function of elapsed time. The time over which the temperature change in the collector due to the change in radiation decreases to one per *e* parts is called the collector time constant [34].

The time constants of collectors have been determined for various flat plate collectors by Pierson and Padet [35]. They investigated the effect of different collector parameters (absorber thickness, glass cover thickness, number of glass layers, heat capacity and mass flow of the working medium) on this value and found a numerical correlation between them.

The first theoretical context for the response function was given by Rogers [36]. The transient behaviour of collectors was described by Hill et al., De Ron and Kamminga [37], [38], [39]. A practical method for determining the response function characteristics was developed by Prapas et al., which gives the thermal characteristics of the collector step by step over short time intervals [40].

Physically based models become more complex and challenging to solve if they consider more influencing factors. In contrast to these models, new modelling methods can be applied, e.g. artificial intelligence-based models.

Cooling PV and increasing the efficiency of thermal utilisation with liquid is more effective than with air due to the higher specific heat and surface heat transfer coefficient. Thus, liquid PV/T is more efficient than air PV/T; however, when coupled to a heat pump system, the use of liquid heat pumps requires soil works, while the air solution is more favourable in terms of mobility [41], [42], [43].

The literature gives many examples of the benefits of combining PV and heat pumps if we also wish to produce heat with the energy system. With mobility in mind, air-source heat pumps are a more viable option. Once the energy needs have been estimated, sizing is necessary for optimal system operation. Connecting the heat pump to a solar panel makes the system greener, and even off-grid can be achieved. If a heat pump is combined with a PV/T collector, thermal and electrical efficiency is improved, but the system becomes more complex, which is a disadvantage during construction, and PV/T is less scalable due to the limited supply, which is also a disadvantage.

2.3. The importance of water electrolysis (Hydrogen production) in energy production, storage, and utilisation

Only water electrolysis technologies can achieve the required production volume among the green hydrogen production solutions. Electricity-based water decomposition is also the most important of the water separation technologies, and therefore, investigating the efficiency of these technologies and their potential for improvement is a current topic in energy research worldwide.

A considerable amount of research focuses on the time evolution of cell voltage, i.e., the change in electrical potential as a function of time, which significantly impacts the water electrolysis process. The electric current causes water molecules to split into hydrogen and oxygen gases, but the speed and efficiency of this process are highly dependent on the level and changes in the electric voltage.

Frequent fluctuations or continuous changes in the cell voltage also affect the efficiency of the cell, the performance of the cell and the amount of gas produced. The rate of change depends on the parameters of the voltage connected to the cell, i.e. its characteristics, amplitude, frequency and offset.

The literature on variable-current water splitting is mainly concerned with the effects of voltage pulses and intermittent direct current [44], [45], [46], [47], [48]. In the literature on the subject, we can find contradictory information, with some authors publishing results that are far from the reality: 96.8% energy savings with high-frequency pulses [47], or even unrealistically low efficiency with DC and intermittent DC (9-13%) [48]. Overall, based on the literature review and evaluation, the efficiency of a water-splitting cell operating at a given power is highest for DC, and deviation from DC will mainly cause an increase in cell power and gas flow rate against a decrease in efficiency.

Shimizu et al. conducted extensive studies to determine the characteristics of DC water splitting complemented with ultrashort voltage pulses [49]. In their study, the authors used pulses with a bandwidth of about 300 ns under a DC power supply to the cell. The frequency of the applied pulses ranged from 2 kHz to 25 kHz.

Further results on voltage pulse water splitting technology and alternating current behaviour of the cell [50]:

- Bockris and Potter first observed the discharge phenomenon of electric double-layer capacitance after voltage interruption [51].
- Tseung and Vassie recorded an increase in amperage of 2 to 6 times compared to the DC voltage test [52].
- Viswanathan, et al. published a numerical solution for the current flow in a variable electric potential space in a water-splitting cell [53]. It was shown that even if the amperage reaches a higher value than in the DC case, the intensity of hydrogen production cannot be higher.
- Ibl modelled the material flow and capacitive effects during pulsed electroplating [54].
- Brandon and Kelsall have shown that the bubbles produced leave the electrode surface immediately after the voltage or amperage is interrupted [55].
- Khosla, et al. have measured that the size of the bubbles can be well controlled by the bandwidth of the applied pulses [56].
- Vanags, et al. have outlined the mechanism of hydrogen formation during inductive voltage pulses, showing that their method of using wolfram electrodes is more efficient than platinum [57].
- Kaveh, et al. measured an increase in conductivity of up to 50% for *pulse-width modulation* excitation with a 50% fill factor compared to DC testing [58].
- Mazloomi and Sulaiman found that excitation with *pulse-width modulation* signals at different voltage levels and fill factors resulted in higher efficiency at lower voltages and lower fill factors [59].
- Martiningsih, et al. discovered a nonlinear relationship between the *pulse-width modulation* filling factor and the intensity of hydrogen production [60].

Dobos investigated the evolution of a water-splitting cell's hydrogen production and energetic characteristics using sinusoidally alternating voltage with different frequencies and offset values. He found the evolution of the volumetric flow rate of hydrogen gas produced and the power consumption of the cell as a function of the frequency, amplitude and offset of the applied alternating voltage. [61]

2.4. Biogas components

The main constituents of biogases are methane and carbon dioxide due to microbiological processes. There is no higher hydrocarbon content at all. The biggest technological problem in the biogas plants is the foaming of the digesters. This undesired process is in a strong connection to the gas formation too. [62]. This kind of technological problems can be solved mainly by adequate stirring [63], [64], and sometimes the more precise preparation of the input material (e.g. right size chopping) can help to avoid the inconveniences [65]. Anyway, the chips-size of the materials used for energetic purpose is very much determines the process and its efficiency [66].

In general, biogases are composed of 45-75 mol% CH_4 and 25-55 mol% inert components (CO_2, N_2), which due to their non-combustible nature, significantly reduce the combustion parameters such as lower heating value, upper heating value, lower and upper Wobbe coefficient [67], [68].

As a result of these properties, biogases are purified, which enriches the biogas in methane, reducing its inert content and removing unwanted components. The degree of purification depends on the intended use [69].

Main components of biogases:

The main components of biogases are also found in natural gas, which are:

- methane (CH_4)
- carbon dioxide (CO_2)

- oxygen (O_2)
- hydrogen (H_2)
- nitrogen (N_2)
- water vapour (H_2O)

Co-components of biogases:

- hydrogen sulphide (H_2S) and elemental sulphur (S)
  It can be present in significant amounts (10 000 mg/m^3) in the gases produced during fermentation processes. It causes corrosion in metals and SO_2 emissions when burnt. Hydrogen sulphide reacts with the water vapour content of the combustion products to form sulphuric acid (H_2SO_3), an effect further enhanced by organic sulphur compounds, as sulphur dioxide is also formed when sulphur is burnt. It must be separated from the biogas composition in each case.
- carbon monoxide (CO)
  All types of biogas can contain this flammable, highly toxic gas in quantities of 10 mg/m^3. As a potent reducing agent, it reduces oxides of metals to elemental metals.
- Ammonium (NH_3)
  It can be found in all biogas types in varying amounts, up to 100 mg/m^3. It worsens the ignition parameters and contributes to NO_x emissions. It may cause corrosion of metals. To avoid this process, the water vapour content of the gas should be kept low.
- nitrous oxide (N_2O)
  Landfill gases contain tiny amounts of this non-toxic gas. It feeds combustion, and under the influence of heat, it breaks down into nitrogen molecules and oxygen atoms, so it has no meaning.
- sulphur dioxide (SO_2)
  Typically found in landfill gas in quantities of some amounts 10 mg/m^3. Much higher amounts are produced during the combustion of the hydrogen sulphide content in biogases. SO_2 reacts with water to form sulphuric acid (H_2SO_3), and its effect should therefore be considered in combustion analyses.
- hydrogen cyanide (HCN)
  Highly toxic hydrogen cyanide is found only in landfill gases and can be almost completely removed from the gas composition by the aqueous washing process.

Some components are specific to biogases. These include nitrogen oxides (NO_x) or hydrogen chloride (HCl), typical landfill gases. All biogas compositions contain chlorine- and fluorine-containing compounds, highly salt-forming elements (Cl-, F-) and can be found in biogases in quantities of up to 100 mg/m^3. Their gases are toxic, combusting explosively with hydrogen and combining with metals to form halogenides. With the water vapour content of the combustion products, chlorine forms hypochlorous acid and fluorine forms hydrogen fluoride with hydrogen peroxide, which decomposes rapidly on heating [67].

The accompanying components of biogases:

In addition to the principal and co-components of biogases, nearly 200 additional accompanying components can be detected in each gas composition, which does not even represent 5 % of the total composition.

Siloxanes are mainly found in biogases from sewage treatment plants and landfills. They pose a hazard to movable components, as their combustion produces SiO_2, which can lead to abrasion of rotating elements, changes in pipeline direction and constrictions. Research has shown that specific biogas cleaning processes can reduce siloxane amounts to as little as 0.3 mg/m^3.

Halogenated hydrocarbons are mainly found in landfill gases. If burnt under inappropriate conditions, they can lead to dioxins and furans, which harm health.

The BTX compounds (benzene, toluene, xylene) are flammable, toxic substances, mostly in depot gases. They damage mainly the PE piping of the distribution system operating at lower pressures. Volatile organic compounds are present in minimal quantities in landfill biogases.

There is no European regulation that guides the presence of mercury in biogas. It occurs mainly in landfill gases in deficient concentrations, which can cause corrosion of aluminium components. Experience has shown that a good-quality active carbon process can remove it from biogas. The industrial practice has set the value of mercury below 1.0 μg/m^3, but the presence and concentration of mercury require further investigation.

More than 20 metals can be found in biogases, such as copper, cobalt, chromium, manganese, lead, arsenic or nickel, in amounts of several 10 mg/m^3.

After biogas purification, organic microorganisms may remain in the biomethane, but their impact is not yet fully understood and is currently under research. However, current in-feed practice has not shown any problems that could be attributed to this. Gases from unconventional sources may contain aromatic hydrocarbons, which can damage PE piping, rubber and synthetic elements and are carcinogenic and involved in soot formation [67].

Landfill gases contain the highest levels of undesirable components and are the most expensive to purify [70].

2.5. Properties of gas mixtures

The literature review has shown that biogas mixtures present unstable combustion in different burners due to their low calorific value. Researchers prefer to enrich biogas with different fuel additives to reduce these instabilities. Yılmaz et al. investigated the performance of oxygen enrichment of biogas flame in a model gas turbine burner [71]. They found that the biogas flame became more stable under acoustic perturbation at 24% O_2 compared to air combustion. Zouagri et al. investigated the characterisation of biogas/syngas mixtures [72]. The study results showed that increasing the amount of CO_2 in the mixture causes a decrease in maximum temperature and NO_x emissions. Skvorcinskiene et al. investigated the combustion of biogas from waste with low CH_4 content, enriched with syngas and oxygen in a vortex-assisted combustor [73]. Three vortex generators with different lamella angles (37◦, 45◦, 53◦) were used in the experiment. The results showed that the vortex generator with a 45◦ blade angle produced the lowest CO emissions. Striugas et al. investigated the combustion instability of a mixture of syngas and oxygenated biogas [74]. They showed that adding oxygen and syngas increased the OH*, CH* and C_2* chemiluminescence and flame stability.

Wang and colleagues investigated how adding propane and oxygen to biogas affects combustion instability [75]. The results showed that oxygen enrichment increased the explosion pressure of the flame. In cases where the oxygen content of the oxidiser was between 25% and 29%, the addition of propane significantly reduced the flame spread rate. Boussetla and co-workers investigated the development of NO emission under premixed Moderate and Intensive Low Dilution (MILD) combustion conditions in biogas/hydrogen mixtures [76]. It was shown that the addition of N_2 for MILD combustion resulted in reduced flame temperatures. In addition, it was observed that an increase in the H_2 content of the fuel mixture made the NNH mechanism dominant in NO formation.

It can be observed that some studies in the literature have also investigated the addition of pure hydrogen to fuels in gas turbine burners. Arenillas et al. investigated the effect of hydrogen addition on the flame area of biogas [77]. The results showed that adding hydrogen increased the flame's stability and temperature. Wei and co-workers investigated the specific heat flux and CO and NO emissions of biogas/hydrogen flames [78]. They added 10% H_2 to a 75% CH_4 - 25% CO_2 mixture and investigated different equivalence ratios. Arenillas et al. investigated the combustion of biogas/hydrogen mixtures [77]. As the biogas mixture was tested at three different methane ratios (70%, 60%, 50%), the H_2 ratio was varied between 5 and 25%. The results showed that stable combustion did not occur when the proportion of CO_2 in the biogas was above 40%. Yilmaz et al. investigated $H_2/CH_4/CO_2$ mixtures in their study [79]. The proportion of hydrogen in all mixtures was kept high and varied between 50% and 70%. The results showed that the thermal NO_x mechanism was not dominant. In addition, the fuel mixture containing 50% H_2 caused 30 times more NO emissions than the mixture containing 70% of H_2.

From the literature review, it becomes evident that investigating combustion instability and emission behaviour of biogas mixtures is an important topic. These studies have identified the positive effects of hydrogen addition and oxygen enrichment on reducing combustion instability. Considering these studies, it can be seen that the effects of simultaneous enrichment with hydrogen and oxygen, especially in premixed combustion, have not been investigated in the literature. In addition, while the literature has investigated the variation of temperature, emission, flame profile and laminar combustion velocity change data in studies to determine combustion instability, no research has been observed to investigate thermoacoustic instabilities with simultaneous enrichment with hydrogen and oxygen in biogas flame. Determination of dynamic instabilities is a method used in combustion studies due to the flame-distorting effect of external acoustic perturbations.

2.6. Effect of hydrogen mixing on the combustion characteristics of biogas

Biogas has an advantage over other renewable fuels, such as synthesis gas (produced from biomass and municipal solid waste gasification), in that it is produced directly from wet organic waste sources with minimal pre-processing [80]. However, the calorific value of biogas is low, e.g. at 1 bar pressure and 298 K, the calorific value of biogas (60% CH_4 - 40% CO_2) is around 30 MJ/kg, compared to natural gas (50 MJ/kg) and hydrogen (120.971 MJ/kg). The lower calorific value of biogas is due to the high percentage of carbon dioxide present in the mixture (20-60% (v/v)), depending on the source and the digestion process used to produce it [81], [82].

Although the presence of carbon dioxide in biogas reduces pollutant emissions, it has a negative impact on the overall combustion characteristics of biogas [83], [84].

Carbon dioxide in biogas leads to a narrow range of flammability marginal values, reduced laminar flame velocity and lower flame temperatures than other commonly used fuels [85], [86].

The other major problem that arises from the high CO_2 content in biogas is the lower reactivity, which leads to flame suppression in cases where biogas is used as fuel in industrial burners. Several researchers have sought to understand the flame stabilisation behaviour of biogas at different equivalence ratios [87]. These studies show that carbon dioxide's thermal and chemical properties lead to lower reactivity, which limits the practical use of biogas in burners. For this reason, using pure biogas as a fuel for compression engines or gas turbines is limited due to its low laminar combustion rate and its flame, which tends to extinguish and hinder stable operation [88], [89].

The use of pure biogas in internal combustion engines and gas turbines is severely limited due to the poor combustion properties mentioned above [90]. The combustion properties of biogas can be improved by adding fuels with higher reactivity, thus converting low calorific value raw/pure biogas into high-quality fuel.

Application of laboratory simulation methods can result moderated biogas reactor processes, and the number of the malfunctions of an existing system can be reduced. The specific gas production can be optimised. According to this the electric capacity value can grow by 10-15 % [62].

One proposed solution is to add a high-reactivity fuel (e.g. hydrogen) to the biogas to improve reactivity with minimal changes in pollutant emissions. The primary combustion characteristics of premixed flames are laminar flame velocity (Su), ignition delay and self-ignition in premixed combustion. Two other crucial criteria for fuel selection are the adiabatic flame temperature (Tad) and the combustibility limits. Adding hydrogen to hydrocarbons improves these combustion characteristics [91]. The reason for this is that the hydrogen has several favourable combustion properties (high reactivity and heat release rate, high extinction velocity and laminar flame velocity, low ignition delay and wide flammability limit), which are suitable for making combustion processes more uniform [92], [93].

Adding hydrogen also increases the concentration of H- and OH-radicals, thus improving the overall reactivity of the mixture. It is also known that using 100% hydrogen in internal combustion engines presents several storage and safety problems [94]. To take advantage and overcome clean hydrogen problems, several researchers have proposed replacing the fractions of hydrocarbon fuels such as methane Karim et al., and El-Ghafoure et al., liquefied petroleum gas, Kishore et al., n-butane, Tang et al., n-decan ($CH_3(CH_2)8CH_3$), Yu et al., etc. with hydrogen in the mixture [95], [96], [92], [97], [98]. Ali and Varunkumar presented the combustion process of different fuel mixtures with and without hydrogen for non-premixed flames, emphasising the flame formation process. [99]. An essential element in investigating these processes is examining the extinction transformation rate (ag). The extinction transformation rate (ag) is defined as the component of the velocity gradient perpendicular to the flame surface at the time of extinction. Like the laminar flame velocity (Su) of premixed flames, the extinction transformation rate (ag) is an essential characteristic of non-premixed flames. The results show that the extinction transformation rate (ag) increases by 2-2.5 times for CO_2 dilution and by 2.6-3.8 times for N_2 dilution, while the amount of CO increases by 10 vol% in fuel mixtures with H_2 increased by 5%. The higher CO % in the fuel results in higher flame temperatures, which increases the overall reactivity of the fuel, leading to an increase in ag values.

In the case of a premixed flame, laminar flame velocity, self-ignition and ignition delay are used to give the combustion characteristics of any given fuel-oxidiser combination. These characteristics provide essential information on the reactivity and exothermicity of a given fuel-oxidiser mixture. It also provides essential information on the diffusion and reactive properties of the mixture. Comparison of experimentally obtained laminar flame speed (Su), ignition delay and self-ignition values with calculated values provides helpful information on validation, reduction and optimisation mechanisms [98], [100].

3. Conclusion

Investigating the combustion characteristics of alternative renewable fuels and their use in existing combustion systems has recently received considerable attention worldwide. This is due to the increasing demand for energy used for electricity production, heating or powering households, fuelling vehicles and manufacturing processes. Among synthetically produced renewable fuels, biogas is one of the promising substitutes, as it has lower processing costs and a slightly higher density than natural gas.

Our research work in the field of local, renewable and sustainable energy production, storage and use is focused on the development of an integrated solution that enables the production of hydrogen gas (H_2) and oxygen gas (O_2) by water decomposition (H_2O) using photovoltaic (PV) solar cells and the production of biogas by biomass utilisation in an innovative process, thus achieving the production of compact devices of different sizes (scalable). The aim is to transform solar energy into combustible gas stored in a container.

The advantage of the system is that the biogas-hydrogen mixture it produces can be stored, and the intensity, period and interval of its use can be planned as required. It can be reused to generate electricity, heat or mechanical energy using a gas engine, gas engine-electric generator, gas boiler or gas burner.

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