Potential of fueling spark-ignition engines with syngas or syngas blends for power generation in rural electrification: A short review and S.W.O.T. analysis

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Dolly Armel Sylvain ANDRIATOAVINA[a,b], Damien Ali Hamada FAKRA[c,*], Ny Aina Manitra Nany RAZAFINDRALAMBO[b], Jean Philippe PRAENE[c], José Marie Michel ANDRIAMAMPIANINA[a,b]

[a] *Laboratoire de Dynamique de l'Atmosphère, du Climat et des Océans (DyACO) – University of Antananarivo, BP 566, Antananarivo 101, Madagascar*

[b] *Institut Supérieur de Technologie d'Antananarivo (IST-T), Dr Rasoamiaramanana Iadiambola Street, Ampasampito RN 2, Antananarivo 101, Madagascar*

[c] *Physics and Mathematical Engineering Laboratory for Energy and Environment - University of La Réunion, 117 General Ailleret Street - 97430 Le Tampon - La Réunion, France*

Abstract

Biomass gasification represents one of the most attractive solutions in rural electrification projects. It enables energy recovery from agricultural waste or forest resources in rural areas isolated from the grid. The use of the syngas produced by gasification in spark-ignition engines offers the local population a simple, available, and low-cost technology to meet their electrical energy needs. However, the loss of engine performance when fueled with syngas, compared to gasoline operation, has prompted researchers to study the mixing of syngas with other types of fuel to overcome its low heating value. This article, therefore, presents a review of the use of syngas in spark-ignition engines, either fully, or in a mixture as the pilot fuel or as an additive. A S.W.O.T. analysis is then conducted based on the results of the review with a focus on applications in rural electrification. The study highlights the contribution of syngas enrichment to the improvement of the quantity and quality of electrical energy produced. When syngas is used as an additive, its impact is not directly energetic but rather on the engine's lifetime, which is extended thanks to more stable operation and faster combustion. The review also shows that the use of syngas blends affects the quantity of pollutants in the engine's exhaust gas: CO, NOx and HC are reduced when syngas is enriched. However, CO and CO_2 emissions may increase when syngas is used as an additive due to the presence of these gases in the input. In the context of rural electrification, the use of syngas blends may improve the sustainability of the project through a better quality of service and a longer lifetime of the facility. However, a higher level of competence is required for people in charge of the site to control the production processes and the fuel-mixing. Finally, this study indicates the need for more research to explore the use of other fuels such as alcohol in the blend or the use of syngas blends in compression ignition engines.

Keywords: Syngas, Blends, Spark-ignition engine, Rural electrification, S.W.O.T analysis

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* Corresponding author
Email address: fakra@univ-reunion.fr (Damien Ali Hamada FAKRA)

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1. Introduction

Energy autonomy is one of the major factors in the development of a country [1]. The possession of an important oil resource can be a source of international conflict or even war [2] and has always been a major factor in a country's ranking on the scale of economic wealth. However, with the global awareness of the risks linked to the exploitation of fossil resources, the energy sector has now entered a transition phase to gradually reduce the use of petroleum products in favor of renewable energy [3].

Renewable energy defined as a source of energy whose natural renewal is much faster than consumption and which is considered inexhaustible on a human scale [3], it represents the hope of a future free of energy problems where everyone will be able to have the amount of energy they need without having to endanger the future of the planet [4]. Renewable energy is therefore a guarantee of sustainable development because it allows economic growth to be harmonized with the preservation of the environment [5]. At least, this is one of the objectives pursued by researchers in the field.

One sector that particularly favors renewable energy is rural electrification [6]. Often located in isolated areas not connected to the grid, rural electrification projects must turn to locally available resources to meet the energy needs of the community [7]. Depending on the area in question, these local resources may be solar, wind, hydro, geothermal, or biomass energy.

Biomass represents the amount of energy stored in animal or plant materials that can be recovered through biochemical or thermochemical decomposition processes [8]. While the biochemical process favors wet biomass, thermochemical transformation is most suitable for dry biomass such as certain agricultural wastes and wood residues [9]. The main thermochemical biomass transformation pathways applied in rural electrification are combustion, pyrolysis, and gasification [7]. Combustion consists of burning biomass and recovering the heat generated for direct use (cooking) or steam production (boiler) [10]. Pyrolysis consists of decomposing biomass in the presence of heat but in the absence of oxygen or insufficient quantities to prevent combustion. It can produce solid fuel (biochar), liquid fuel (bio-oil), and gaseous fuel (syngas) [11].

Gasification is a process situated between combustion and pyrolysis: the biomass undergoes a partial oxidation process that transforms it into a gas-rich in CO, H_2 and CH_4 called syngas. The syngas also contains other non-combustible gases such as CO_2, N_2, O_2, or H_2O. Gasification produces other undesirable products such as tar or ashes that can still be valorized in other pathways [12].

Syngas is a combustible gas that can be used to power a gas turbine or an internal combustion engine, but the latter benefits from greater flexibility for fuels with a variable composition such as syngas [13, 14]. In internal combustion engines, syngas can be mixed with diesel fuel (dual-fuel mode) in the case of compression-ignition engines, or used 100% in the case of spark-ignition engines [15]. Spark-ignition engines, therefore, benefit from the possibility of pure renewable supply. That is why this revised article focuses on the use of syngas in spark-ignition engines.

However, due to the low heating value of the syngas, engines suffer from power derating compared to gasoline operation [16]. Thus, in recent years, research has been carried out on the use of syngas mixtures in spark-ignition engines. In some studies, syngas takes the role of the pilot fuel, but in other cases, syngas is used as an additive. The objectives sought by the researchers may include increasing engine performance but also reducing pollutant emissions or improving combustion.

1.1. Statement of significance

Previous studies has investigated the use of syngas in internal combustion engines [13, 14, 16, 15]. This work discusses the need for technical modifications to the engines to adapt them to the syngas fuelling. Some difficulties are hightlighted such as tar deposits in the engine or power derating due to the nature of syngas. Other studies such as those of Martinez et al. [12] and Asadullah [17] include the production of gas in downdraft gasifiers and deal with the logistics of supplying and processing biomass and syngas.

But a missing part in all these already published work is the study of the mixing of syngas with other types of fuels (apart from the diesel-syngas mixture in dual-fuel IC[1] engines). These mixtures of syngas with other fuels play an important role in the development of syngas valorization systems. They represent a step forward in the efforts to improve the durability and energy efficiency of systems for converting the chemical energy of the syngas into the mechanical energy available at the engine shaft. While the use of syngas in SI engines dates back to the 1920s, the papers that study its blending with other fuels have all been published in the last decade. It can therefore be said that it is a recent technology innovation in the discipline of bioenergy that deserves to be treated in more detail.

This paper, therefore, aims to fill this gap by presenting a review of all studies conducted on the use of syngas or syngas mixture in spark-ignition engines. The objective of the review is to synthesize the main results found by the researchers guide future works. A S.W.O.T. analysis is then performed, based on the results of the review, to identify the positive and negative points of each type of mixture concerning the internal and external environment. The S.W.O.T analysis is oriented towards the evaluation of each syngas mixture for applications in rural electrification. This analysis aims to assess the potential benefits and barriers of each mixture in the context of power generation in rural areas.

1.2. Methodology

The review was conducted by selecting all of the papers published investigating the use of syngas and syngas blends in spark ignited engines. One of the main observations made when

[1]Internal Combustion

performing this study is the lack of research papers published about the use of syngas blends in spark-ignited engines. So far, 17 papers published from 2010 to 2019 are collected. So, all of these papers are included in the review. Thus, this review represents the work done in this area. For the use of 100% syngas in SI engine, the results reported in research papers published from 2010 to 2019 are considered. These 23 articles have been identified from the Google Scholar database and we have considered those published in journals housed by editors, such as Elsevier, who are well recognised by the scientific community. The results presented in these papers are grouped and compared according to each topic covered: fuel characteristics, engine operation, engine performance, and pollutant emissions. The tendencies observed are highlighted and used to draw conclusions concerning the aspect considered.

2. Syngas Production

2.1. Gasification Process

Gasification is the process of converting carbon-rich biomass into a gaseous fuel called syngas. The transformation is done by partial oxidation of the biomass in the presence of a reactive gas that can be air, oxygen, water vapor, or a mixture of these. Gasification differs from combustion by the lack of oxidizing agent which prevents the complete conversion of carbon and hydrogen from the biomass to CO_2 and H_2O. Thus, with an amount of air always below stoichiometry, the gas formed contains combustible gases which are H_2, CO, and CH_4. The syngas can also contain other non-combustible gases such as CO_2, N_2, O_2, or H_2O [12].

The gasification process can be described by four simultaneous phases: the drying phase during which the moisture contained in the biomass is evaporated, pyrolysis during which the dried biomass is transformed into a mixture of gas, tar and coal, combustion during which the volatile matter and part of the coal from the pyrolysis are oxidized in the presence of oxygen from the air, and gasification during which the carbon in the coal is oxidized at high temperature by water vapor and carbon dioxide to give syngas.

The parameters influencing the gasification process are the amount of air or steam supplied to the reactor, the temperature, and the pressure in the reactor [18]. Depending on the size of the reactor, the intended use of the gas produced and the type of reactor, gasification can take place at temperatures of 500°C to 1400°C and pressures of 1 to 33 bar [19].

The amount of energy contained in the products of the thermochemical conversion of biomass depends on the amount of oxygen consumed in the reaction, represented by the equivalent ratio ϕ. For very low values of ϕ, the reaction that takes place is pyrolysis. For values of ϕ greater than or equal to 1, combustion occurs. Gasification is situated between pyrolysis and combustion with an equivalent ratio of about 0.25, it is with this value of ϕ that we can convert the maximum biomass energy to gas [20].

The heating value of syngas depends on the biomass from which it is produced and also on the gasifying agent or reactive gas used. When the gasifying agent is oxygen or water vapor, the gas obtained has an average heating value between 10 and 28 MJ/Nm^3. This gas is free of nitrogen. When the gasifying agent is air, the gas obtained has a low heating value between 4 and 7 MJ/Nm^3. This gas can contain up to 50% nitrogen [14].

2.2. The Different Types of Gasification Reactors

There are three major types of gasification reactors: fixed bed gasifiers, fluidized bed gasifiers, and entrained flow gasifiers. Fixed bed gasifiers can be of the downdraft or updraft type, fluidized bed gasifiers can be of the bubbling or circulating type [21].

Fixed bed gasifiers are the simplest and most economical of the gasification reactor types. They are therefore the most suitable for small-scale gasification projects. Depending on the direction of gas flow through the reactor, a distinction can be made between downdraft and updraft fixed-bed gasifiers. In downdraft or co-current gasifiers, the biomass is introduced from the top of the reactor while the gasifying agent is injected from the side. The syngas and biomass flow in the same direction, hence the term co-current. In updraft or counter-current gasifiers, the biomass is introduced from the top but the gasifying agent is injected from the bottom of the reactor. The generated syngas, therefore, flows in the opposite direction of the biomass and exits from the top of the reactor [20].

Differences in the performance of downdraft and updraft gasifiers result from the effects of the direction of the gas flow in the reactor. The counter-current flow of syngas and biomass allows heat recovery from the gas to heat and dry the biomass, resulting in improved thermal efficiency. However, the passage of the gas through the cold zone does not allow good gasification of the tar it contains. So, the syngas produced from an updraft reactor may contain 5% to 20% tar and is not suitable for use in internal combustion engines [20]. Compared to the updraft gasifiers, the gas that is formed in the downdraft type passes through a high-temperature zone that favors the cracking of tar. The resulting syngas therefore generally contains less than 1% tar and is more suitable for use in internal combustion engines [20]. The disadvantage of this reactor is, however, the faster passage time of the gas through the reactor, which reduces the carbon conversion efficiency. The moisture content of the biomass must also be less than 30% to be gasified. Finally, downdraft gasifiers require biomass sizes between 40 and 100 mm to avoid blocking or channeling phenomena that increase tar formation [22].

To improve mixing and heat transfer, fluidization phenomena can be created by adding a bed of materials in gasification gasifiers. This technology is known as fluidized bed gasifiers. The bed of materials is used to store the heat generated by the exothermic reaction (combustion) and then to fuel the endothermic reactions (pyrolysis, gasification). It can be made of inert materials such as silica sand or natural rocks such as olivine or dolomites [22].

There are two types of fluidized bed gasifiers. In bubbling fluidized bed gasifiers, the gasifying agent is used as the fluidizing gas. The fluidization velocity is between 1 and 3 m/s. It has the advantage of being able to gasify several types of biomass but suffers from low efficiency because gasification takes place in the fluidization phase. In circulating fluidized bed gasifiers, fluidization takes place in a turbulent state with a speed 3 to 5 times higher than that of the bubbling type. The mixing of the biomass and the gasifying agent is then more efficient resulting in a better heat transfer and a better carbon conversion rate with less tar formation. The disadvantages of these gasifiers are complex design and high capital and operating costs [22].

Entrained flow gasifiers are reserved for the gasification of fine coal particles, with sizes between 75 and 100 μm. A very high temperature of 1400 to 1800°C and high pressure of 20 to 70 bar allows the generation of a tar-free syngas. The carbon conversion rate is almost 100% even though the reaction time is low, from 1 to 5 s. The main drawbacks of entrained flow gasifiers are also a very high investment and operating costs [22].

3. Bibliography overview

Blending syngas with other types of fuels is quite a recent innovation in the use of syngas in spark-ignition engines. Although syngas has been used to fuel spark-ignition engines since the 1920s, articles concerning their mixtures have been published in the last ten years. This review presents the results of recent studies on the use of 100% syngas in spark-ignition engines, followed by cases of syngas enrichment with methane or biogas, and then presents the use of syngas as an additive to enrich methane, a methane-rich fuel or gasoline.

A summary of the reviewed articles, with the aspects covered by each of the authors, is shown in Table 1. It can be seen that the authors are more interested in the energy aspects of the system (Fuel LHV, engine power/torque) when syngas is used alone or as the main fuel compared to cases where syngas is used as an additive. In this second case, the aspects dealt with by the authors are mainly thermal efficiency, combustion, and pollutant emissions. This is due to the low heating value of syngas compared to the other types of fuel in the mixture. Thus, the benefits brought by its addition as an additive are more significant on the improvement of the combustion phenomenon (stability, speed, more completeness, etc.) than on the quantity of energy generated.

The behaviors of pollutant emissions in each article reviewed are summarized in Table 2. The main factor determining the quantity of CO in the exhaust is its presence in the input syngas [23, 24, 25]. More CO is transferred to the exhaust for lower combustion efficiency which is affected by the air-fuel ratio and engine speed [24]. So, when combustion time is shortened, as when syngas is added to gasoline [26], the oxidation is less complete and more CO is found in the exhaust gas. CH_4 and H_2 in syngas also promote CO formation [27]. CO concentration is found lowered by methane enrichment of syngas [28, 29, 30], or by the addition of syngas in landfill gas [31, 32]. NOx formation is mainly influenced by the combustion temperature which is promoted by the presence of H_2 and CO in syngas [24, 27, 33]. But CO is found more influential than H_2 [34]. Ignition timing also affects the formation of NOx and has even more influence than H_2 [35]. Another factor is the quantity of N_2 in the intake air [24] which is transformed to NOx primarily through the thermal route. But NNH and N_2O routes become more important for leaner fuel mixture [36]. For low strain rate combustion NO_2 is the main pathway [37]. The quantity of NOx in the exhaust gas in lowered when syngas is mixed with methane [28, 29, 30], landfill gas [31, 32], biogas [35], and gasoline [38]. HC formation is influenced by the engine speed [24]. It is increased in lean fuel mixture [33] but reduced when syngas is mixed with methane [28, 29, 30], and landfill gas [31, 32]. When syngas is added to gasoline, HC emissions decrease as well due to a faster and more complete combustion.

The following chapters (Chapters 4, 5, 6) give more details about the results found by each of the authors in the use of syngas or syngas blends in spark-ignited engines.

Table 1: Summary of the articles reviewed and the issues addressed

Authors	**Start-up procedure**	**Engine modifications**	**Fuel LHV**	**Power - Torque**	**Fuel consumption**	**Efficiency**	**Air-fuel ratio**	**Combustion**	**Main results**
100% syngas									
Shah et al. [39]	X		X	X	X	X			- The lower LHV of syngas compared to gasoline causes a decrease of the engine power and an increase of fuel consumption.
Gitano-Briggs and Kean [40]	X	X	X	X	X				- The engine can be started directly with syngas due to some modifications: advance by 13 ° of the ignition timing, the addition of a 12 μF capacitor, control of air, gas, and fuel mixture flows by an electronic control system - Engine's power is lower compared to gasoline operation.
Shivapuji and Dasappa [41]		X	X			X		X	- H_2 in syngas increases the engine thermal efficiency at full load but decreases it at partial load - H_2 also improves the combustion (increases heat generation and flame laminar velocity, decreases combustion duration)
Ran et al. [25]						X	X		- Syngas can be burned with the leanest mixture compared to gasoline, ethanol, compressed natural gas which allows having the best engine efficiency.
Indrawan et al. [42]				X		X	X		- Syngas operation has lower speed, torque, engine power and electricity production efficiency compared to natural gas.
Enrichment with methane or biogas									

Table 1 continued from previous page

Authors	Start-up procedure	Engine modifications	Fuel LHV	Power - Torque	Fuel consumption	Efficiency	Air-fuel ratio	Combustion	Main results
Hagos et al. [43, 29, 44]				X	X	X	X		- Methane enrichment of syngas increases the engine torque and improves the thermal efficiency while reducing fuel consumption.
Szwaja et al. [45]			X	X				X	- Methane enrichment of syngas increases the engine power and improves the work cycle stability but the effects are minor beyond 40% of methane.
Nadaleti and Przybyla [46]			X						- The addition of biogas in syngas increases the heating value of the mixture the effect is not linear and beyond 50% increase in heating value is no longer significant.
Blending with methane or methane-rich biofuel									
Kohn et al. [31] and Jechan Lee and Marco J. Castaldi [32]						X			- Syngas addition in landfill gas improves the engine's efficiency.
Hyoseok Cha et al. [34]		X		X		X		X	- Syngas addition in natural gas improves the fuel conversion efficiency and increases the maximum pressure inside the cylinder - The effects do not vary linearly with the enrichment.
He et al. [23]				X		X		X	- H_2 and CO addition in natural gas improve the thermal efficiency and the combustion (increased pressure and heat release, faster combustion, more stable work cycle) - H_2 has a greater influence on engine performance than CO

Table 1 continued from previous page

Authors	Start-up procedure	Engine modifications	Fuel LHV	Power - Torque	Fuel consumption	Efficiency	Air-fuel ratio	Combustion	Main results
Fischer and Jiang [27]								X	- CH_4 content in bio-syngas delays the ignition, CO slightly accelerates ignition, H_2 accelerates ignition and raises combustion temperature
Kan et al. [35]						X		X	- Addition of syngas in biogas slightly improves the indicated thermal efficiency, and lowers the knock tendency.
Watson et al. [36]									- Biogas-syngas mixture has a lower NOx emissions compared to methane operation.
Mameri et al. [37]									- NO_2 is the main pathway of NOx formation in biogas-syngas combustions low strain rate but prompt route becomes more important as the strain rate increases
Blending with gasoline									
Dai et al. [33]						X		X	- Addition of syngas in gasoline improves thermal efficiency and enhances maximum cylinder pressure.
Ji et al. [26]						X		X	- Addition of syngas in gasoline increases thermal efficiency, combustion speed, and in-cylinder pressure but beyond 0.92% of syngas, the in-cylinder pressure drops.
Ji et al. [38]						X		X	- Addition of syngas in gasoline increases thermal efficiency, shortens the combustion duration.

Table 1 continued from previous page

Authors	Start-up procedure	Engine modifications	Fuel LHV	Power - Torque	Fuel consumption	Efficiency	Air-fuel ratio	Combustion	Main results
Jain et al. [47]								X	- Addition of H_2 or syngas in gasoline has minor effects below 50% vol. Above 50%, the addition of H_2 increases the ignition delay for temperatures below 900 K but promotes ignition for temperatures above 1000°K - Above 80%, the ignition is more influenced by H_2 than by C8H18 - Addition of CO has a negligible effect on the ignition.

Table 2: Pollutants behavior reported in the articles reviewed

Authors	**CO emissions**	**NOx emissions**	**CO_2 emissions**	**HC emissions**	**Pollutant behavior**
100% syngas					
Shah et al. [39]	X	X	X		- CO and NOx emissions are reduced compared to gasoline operation but CO_2 emissions increase.
Meng et al. [24]	X	X		X	- CO, NOx, and HC emissions increase with the engine's speed - The presence of CO in the engine exhaust gas depends mainly on the CO content of the syngas, and the combustion efficiency which is affected by the air-fuel ratio and engine speed - NOx emissions increase with engine speed and are promoted by the presence of H_2 and CO in syngas, which increases the combustion temperature and N_2 contained in the intake air.
Ran et al. [25]	X	X		X	- CO content of syngas increases CO emissions compared to gasoline, ethanol, or compressed natural gas operation.
Indrawan et al. [42]	X	X	X	X	- CO, NOx, HC, and SO_2 emissions decrease compared to natural gas operation but CO_2 emissions increase.
Enrichment with methane or biogas					
Hagos et al. [43, 29, 44]	X	X		X	- CO, NOx and HC emissions are slightly reduced with methane enrichment of syngas.
Szwaja et al. [45]	X	X	X	X	- CO, NOx, HC emissions are similar to those obtained with pure methane but CO_2 emissions increase.
Blending with methane or methane-rich biofuel					
Kohn et al. [31] and Jechan Lee and Marco J. Castaldi [32]	X	X		X	- Syngas addition in landfill gas reduces CO, NOx and HC emissions.

Table 2 continued from previous page

Authors	CO emissions	NOx emissions	CO_2 emissions	HC emissions	Pollutant behavior
Hyoseok Cha et al. [34]		X			- NOx emissions do not vary linearly with the amount of syngas added to methane - CO is more influential in the formation of NOx than H_2
He et al. [23]	X			X	- The most determining component of CO emissions is the CO contained in syngas which can end up in the exhaust if the combustion is not complete.
Fischer and Jiang [27]	X	X			- CH_4 and H_2 promoted CO emissions, H_2 increases NOx emissions - CO emissions depend partly on the H_2 and CH_4 contained in syngas - NOx emissions are favored by the presence of H_2 which increases the combustion temperature
Kan et al. [35]		X			- The ignition timing has even more influence than H_2 on the formation of NOx during biogas-syngas combustion - NOx emissions decrease with the addition of syngas in biogas.
Watson et al. [36]		X			- Biogas-syngas mixture has lower NOx emissions compared to methane operation - The most preponderant route for NO formation during the combustion of syngas is the thermal route, NNH and N_2O routes become more significant when the fuel mixture is leaner.
Mameri et al. [37]		X			- NO_2 is the main pathway of NOx formation in biogas-syngas combustions low strain rate but prompt route becomes more important as the strain rate increases
Blending with gasoline					

Table 2 continued from previous page

Authors	**CO emissions**	**NOx emissions**	**CO_2 emissions**	**HC emissions**	**Pollutant behavior**
Dai et al. [33]	X	X		X	- The addition of syngas in gasoline increases slightly CO emissions because of the presence of this gas at the intake - The addition of syngas increases the combustion temperature and thus promotes NOx formation - HC emissions decrease with the addition of syngas to gasoline due to faster and more complete combustion - HC emissions increase with lean fuel mixture.
Ji et al. [26]	X	X		X	- CO emissions are promoted by the reduced combustion time brought about by the addition of syngas in gasoline, which makes oxidation less complete - The addition of syngas to gasoline reduces the combustion temperature and lowers NOx and HC emissions.
Ji et al. [38]		X		X	- Addition of syngas in gasoline shortens the combustion duration and lowers NOx and HC emissions.

4. 100% Syngas in Spark-Ignition Engines

4.1. Brief History

The use of syngas in spark-ignition engines began in the 1920s with the invention by the French engineer George Imbert of gasifiers installed on vehicles [13, 14]. World War II, which led to a major shortage of gasoline, marked the boom in these gas vehicles with production reaching 7 million units [48]. However, towards the end of the war, the return to normal of fossil fuel supply caused the end of the use of syngas to power vehicles. The use of syngas has since been dedicated to power generation systems. The interest in syngas utilization has been heightened by the oil crisis of the 1970s [13, 14] and the global awareness of the depletion of fossil resources [49]. Currently, much research is being conducted to improve gasification-based power generation plants.

4.2. Syngas Storage

An advantage of using syngas compared to the use of fossil is the possibility to produce it directly on the end-use site, so avoiding the issues related to transportation. The gasifier unit, converting biomass to syngas, can be linked directly to the generator set which consumes the gas produced. So, the remaining purpose of a storage unit is to ensure that the pressure of the gas entering the engine is constant. For example, Shah et al. [39] used a commercial 0.1 m^3 stainless steel LPG tanks to store syngas at 1500 kN/m^2 before using it to fuel a 5500 W portable generator. To prevent environment from being contaminated with CO, the excess syngas is burnt in a flare.

4.3. Fuel Heating Value

One of the greatest advantages of fueling spark-ignition engines with syngas is the ability to produce its fuel without relying on the traditional gasoline supply chain. However, compared to gasoline, syngas has a low heating value. This heating value varies according to the amount of combustible gas contained in the syngas [41] but it is generally between 4 and 6 MJ/Nm^3 for gasification in a downdraft gasifier with air as a gasifying agent. Shah et al. [39], for example, produced syngas with a heating value of 5.179 MJ/kg (compared to 44.4 MJ/kg for gasoline) from wood chips. Gitano-Briggs and Kean [40] obtained from wood pellets syngas having a heating value of 4.5 MJ/kg. Shivapuji and Dasappa [41] have used four samples of syngas with LHV ranging from 3.14 to 7.55 MJ/kg, and Ran et al. [25] fueled an SI engine with syngas of 20.5 MJ/kg.

4.4. Engine Modifications

This large difference between the energy density of gasoline and syngas may require modifications of the engine to make it run. To fuel with syngas a 650 W Yamaha 950 generator set, which was designed to run on gasoline, Gitano-Briggs and Kean [40] made improvements to the ignition timing, self-induction capacitors, lubrication system, and most importantly the air and fuel flow control. The syngas they used is derived from the gasification of wood pellets in a 5 kW downdraft gasifier and has a lower heating value of 4.5 MJ/kg. Gitano-Briggs and Kean [40] advanced the ignition timing of the engine by 13°. This adjustment of the ignition timing advance is explained by Shivapuji and Dasappa [41] as being due to the high laminar velocity of the syngas flame. A 20 μF capacitor was also added by Gitano-Briggs and Kean [40] to the 15 μF capacitor connected in parallel with the alternator output terminals. They designed and installed an electronic control system commanded by pulse-width modulations to regulate the air and gas flow separately, i.e., the air-fuel ratio, and the throttle, i.e., the engine speed. Since the generator set has a two-stroke engine, they added an oil tank and an electric solenoid pump to provide the lubrication intended to be mixed with the gasoline. Through these various modifications, Gitano-Briggs and Kean were able to operate the generator set directly with syngas without using gasoline during the starting phase as in the case of Shah et al. [39]. They stated that this performance is mainly due to the control of the ignition timing and the air and fuel flow. An adjustment of the air-fuel ratio is, moreover, necessary throughout the operation because the quality of the syngas varies according to the consumption of the biomass in the gasifier. The unit consumes approximately 3.2 Nm^3 of syngas per hour to produce 360 W of electrical power.

4.5. Tar removal

Another aspect to be treated with care when using syngas in spark-ignition engines is the presence of tar, which can lead to disturbances in the gas circuit and engine failures. When measuring the gas flow, Gitano-Briggs and Kean [40], for example, found that the rotameter they used was obstructed after 30 minutes of operation, resulting in restricted gas flow and under-fueling of the engine. So they removed the rotameter once the flow measurement had been completed. Nevertheless, after 7 hours of operation, they inspected the interior of the engine and observed no significant tar deposits. They then recommended maintenance of the piston and combustion chamber after 1 week of operation.

According to Shah et al. [39], to avoid the risk of deterioration due to the deposit, the syngas feeding an internal combustion engine must have less than 50 mg/Nm^3 of tar. The first step to limit tar formation in the syngas is the use of downdraft gasifiers during the gasification phase [50]. In downdraft gasifiers, the gas formed passes through a high-temperature zone, which favors the cracking of the tar [20]. The second barrier that prevents engine contamination is the use of a series of filters to clean the gas and retain the tar. These can be physical methods such as cleaning with water (wet scrubbers, water spray towers), passing the gas through a cyclone [51], the use of biomass-based filters (wood chips, sawdust) [52]; or chemical methods such as catalytic cracking [53].

4.6. Engine Power

One of the direct consequences of the low heating value of the syngas is the decrease of the power delivered by the engine. In their experiment, Gitano-Briggs and Kean [40], for example, measured a 45% decrease compared to gasoline operation for a power output of 360 W. In the case of Shah et al. [39], the syngas-fuelled engine produced 1932 W compared to 2451 W with gasoline. However, it should be noted that the power of the engine with syngas is only 1.76 times less than with gasoline, while the density of the syngas is 423 times less than that of gasoline. This difference in density has to be compensated by a more consequent flow of the syngas, so, if the engine consumes 80 Nl/min of gas to produce 1932 W, it only needs 1,42 l/h of gasoline to generate 2451 W [39]. Indrawan et al. [42] also measured a 28% decrease in engine power when fuelled with syngas compared to natural gas.

4.7. Air-Fuel Ratio

The amount of syngas to be mixed with air must also be increased to ensure its ignition in the engine. If with gasoline the stoichiometric air-fuel ratio is 14.7, Indrawan et al. [42] determined optimal syngas combustion with a stoichiometric ratio of 1.6. However, Ran et al. [25] observed that compared to gasoline, ethanol, and compressed natural gas, syngas is the one that can ignite with the leanest fuel mixture (fuel-air equivalent ratio: $0.3 < \phi < 0.7$).

4.8. Engine Efficiency

One of the advantages of lean-burn combustion is the increase in engine efficiency. Therefore, Ran et al. [25] achieved maximum efficiency with syngas compared to gasoline, ethanol, and compressed natural gas. This advantage comes from the high specific heat ratio (γ) of the fuel mixture when combustion is lean [25]. The absence of hydrocarbons in the syngas also allows it to have a high combustion efficiency. Nevertheless, when the combustion of the syngas is close to the stoichiometry, Shah et al. [39] obtained efficiency almost similar to gasoline operation (19.1% against 19.3% with gasoline). Indrawan et al. [42] even measured a lower efficiency compared to compressed natural gas (21.3% compared to 22.7% with compressed natural gas).

Shivapuji and Dasappa [41] studied the influence of the amount of H_2 contained in the syngas on engine efficiency. They found that when the engine is running at full load (wide-open throttle), the presence of H_2 in the syngas increases thermal efficiency. However, when the engine runs at a partial load, the trend is reversed, and thermal efficiency decreases with the H_2 content. Furthermore, H_2 in the syngas increases the combustion temperature and promotes convective losses. It also increases the pressure inside the cylinders, which represents more mechanical energy produced but also more friction and therefore more losses [41].

4.9. Combustion

According to Shivapuji and Dasappa [41], the H_2 content in syngas reduces the energy required for ignition, improves heat generation during combustion, increases the laminar flame velocity and the maximum heat generated, reduces the duration of combustion but prolongs its terminal phase.

4.10. Pollutant Emissions

While the use of syngas in spark-ignition engines is generally at a disadvantage compared to other fuels in terms of engine power (stoichiometric combustion) [40, 39, 42], it has a clear advantage regarding pollutant emissions. Indeed, compared to the use of gasoline, Shah et al. [39] measured a significant reduction in CO and NOx emissions (between -30 and -90% for CO and between -54 and -84% for NOx). Indrawan et al. [42] also found a decrease in CO, NOx, HC, and SO_2 emissions compared to natural gas use. It is only in CO_2 emissions that syngas shows an increase compared to gasoline (between 33 and 167%) and natural gas [39, 42].

The presence of CO in the engine exhaust gas depends mainly on the CO content of the syngas [24]. It also varies with the air-fuel ratio, which affects combustion efficiency [24]. Finally, according to experiments conducted by Meng et al. [24] on a 1.6 L Jetta vehicle engine, CO emissions increase significantly when the engine speed exceeds 3200 rpm.

According to Meng et al. [24], NOx emissions increase with engine speed. They are also promoted by the presence of H2 and CO in the syngas, which increases the combustion temperature, favoring the formation of NOx [24]. Thus, when the syngas burns in a lean fuel mixture, NOx emissions are reduced because of the lower combustion temperature [25]. The N_2 contained in the intake air also contributes to the formation of NOx in the engine exhaust [24].

As with CO and NOx, Meng et al. [24] observed that HC emissions increase with engine speed. They also relate the presence of HC in the exhaust gas to the incomplete combustion of CH_4 and C_2H_4 because of H_2 and CO which react more with oxygen and burn faster [24].

5. Syngas Enrichment in Spark-Ignition Engines

5.1. Fuel Heating Value

The first effect of adding methane or biogas to syngas is to improve the heating value of the mixture. For example, by gasifying municipal sewage sludge, Szwaja et al. [45] obtained syngas composed of 13% H_2, 16% CO, 3% CH_4, 15% CO_2 and 53% N_2 which has a lower heating value of 4.46 MJ/Nm^3. But by adding 40% methane, they increased the heating value of the mixture by 37%.

Nadaleti and Przybyla [46] have, for their part, composed two examples of syngas: one called Syngas1 containing 18.3% H_2, 25.4% CO, 2.4% CH_4, 13.6% CO_2 and 40.3% N_2 and having a lower heating value of 6.04 MJ/Nm^3; the other called Syngas2 containing 13.5% H_2, 14.8% CO, 2.4% CH_4, 12.8% CO_2 and 56.5% N_2 with a lower heating value of 4.19 MJ/Nm^3. These compositions represent the characteristics of syngas obtained by the gasification of rice husks in Brazil. The authors then composed biogas consisting of 70% CH_4 and 30% CO_2 called Bio70. This biogas represents the composition of the product of the anaerobic treatment of rice parboiling effluents in Brazil. Nadaleti and Przybyla [46] found that a 10% addition of Bio70 in Syngas1 increases the heating value of the fuel mixture by 5.4% for a stoichiometric air-fuel ratio. The improvement is

13.2% with Syngas2. However, the authors noted the non-linearity of the enrichment because the increase in heating value is no longer very significant above 50% of Bio70.

5.2. Engine Power

The increased heating value of the fuel allows the engine power to deliver more power. Hagos et al. [28, 29, 30] powered a single-cylinder direct-injection spark-ignition engine with three types of fuel: compressed natural gas (CNG), consisting of methane; syngas, consisting of 50% H_2 and 50% CO; and methane-enriched syngas (MES), consisting of 40% H_2, 40% CO and 20% CH_4 [28]. The torque developed by the engine is the lowest with the syngas. But when methane is added, the torque increases and even exceeds that of compressed natural gas. This result is in agreement with that found by Szwaja et al. [45] who obtained a power output similar to that of pure methane when their engine is fuelled by a mixture of 60% syngas and 40% methane. In accordance with Nadaleti and Przybyla's [46] remark on the non-linearity of the enrichment effects, Szwaja et al. [45] also observed that the methane contribution is no longer very significant beyond this 40%.

5.3. Engine efficiency, Specific Fuel Consumption, Air-Fuel Ratio

In addition to the gain in engine power, Hagos et al. [28] also achieved with methane enrichment a 30.2% improvement in engine thermal efficiency and a 21.3% reduction in specific fuel consumption. Besides, the addition of methane makes it possible to extend the flammability range of the gas and to operate the engine with a leaner fuel mixture.

5.4. Indicated Mean Effective Pressure Variation

Another problem that can be solved by enrichment is the instability encountered when the heating value of the syngas is too low to run the engine properly. When Szwaja et al. [45] fed a 2.68 L 4-cylinder engine with syngas having a lower heating value of 4.46 MJ/Nm_3, they measured instability in the working cycle marked by a coefficient of variance of indicated mean effective pressure (COVIMEP) greater than 5%. These instabilities are inadequate, especially for an application in power generation. After the addition of 40% methane to the syngas, the cycle became more stable with a reduced COVIMEP value of 3.2%.

5.5. Pollutant Emissions

Concerning pollutant emissions, methane enrichment of syngas slightly reduces CO, NOx, and HC emissions [28]. In the experiments conducted by Szwaja et al. [45], these emissions (CO, NOx, HC) are similar to those obtained with pure methane. The only increase recorded is for CO_2 emissions, which rose from 820 to 950 g/kWh when methane is added at 40% [45].

6. Syngas as an Additive in Spark-Ignition Engines

Another possible use of syngas in spark-ignition engines is as an additive to enrich or improve the performance of another fuel. Syngas-enriched fuels found in the literature can be classified into two groups: methane or a methane-rich biofuel (natural gas or landfill gas); and gasoline. Since syngas has a lower heating value than these two fuels, the improvement obtained by adding it is not really in the engine power but rather in the efficiency, combustion, and pollutant emissions.

6.1. Engine Efficiency

Kohn et al. [31] as well as Jechan Lee and Marco J. Castaldi [32] worked on a Honda GC160E spark-ignition engine fuelled by landfill gas. They composed a gas consisting of 50% CH_4 and 50% CO_2 which represents the standard composition of landfill gas [31]. Then, they composed a syngas by mixing H_2 and CH_4 with a volume ratio of $H_2/CO = 2$. By adding 5% of the syngas to the landfill gas, the authors found a 10% improvement in engine efficiency. However, by increasing the volume of syngas added to 10 and 15%, the efficiency decreases slightly, and consumption increases.

Cha et al. [34] also studied the feeding of a 4-cylinder spark ignition engine with a mixture of natural gas and syngas. The engine had a compression ratio of 13:1 because it was a compression-ignition engine but the injectors were replaced by spark plugs. To have stable experimental conditions and to avoid mechanical damage, the authors limited the engine power to 50% of its maximum capacity and its rotation speed to 1800 rpm. The composition of the syngas is defined by the volume ratio $H_2/CO = 1$ while natural gas is represented by methane, its main constituent. Three mixtures are used and compared to methane: $CH_4 + CO$, $CH_4 + H_2$, and $CH_4 + H_2 + CO$. The quantity of syngas added to natural gas is varied at 5, 10 then 15% of the heating value of the mixture. With the addition of 5% syngas, the authors obtained an improvement of 4.8% in fuel conversion efficiency for the $CH_4 + H_2$ mixture, 2.9% for the $CH_4 + H_2 + CO$ mixture, and 1.5% for the $CH_4 + CO$ mixture. Although efficiency increases slightly with 10 and 15% syngas, Cha et al. [34] noted that the improvement is not proportional to the volume added. From these results, the authors deduced that the H_2 in the syngas contributes more to the improvement of engine performance than CO.

The results of Cha et al. [34] are in agreement with those found by He et al. [23]. The latter studied the effects of enriching natural gas, composed of 96% methane, with H_2, CO, or a mixture of the two. The mixture is used to fuel a 4-cylinder spark-ignition gas engine. He et al. [23] have found that the addition of CO and/or H_2 improves the thermal efficiency of the engine and that maximum efficiency is obtained when the mixture contains the maximum amount of H_2. The influence of H_2 on efficiency is, therefore, shown to be more important than that of CO.

Kan et al. [35] analyzed the effects of the amount of H_2 in fuel and spark advance on the performance of a spark-ignition engine. They performed computational fluid dynamics (CFD) simulations based on KIVA4 software integrated with CHEMKIN. The fuels studied are biogas, composed of 65% CH_4 and 35% CO_2; and syngas composed of 15% CO, 17% H_2, 4% CH_4, 15% CO_2, 0.14% O_2 and 48.86% N_2. These gases are produced from horticultural waste. The syngas is mixed with biogas in a proportion ranging from 10 to 90%. Simulations carried out by Kan et al. [35] indicate that the thermal efficiency of the engine increases with the amount of H_2 when the ignition advance is small but decreases when the ignition advance becomes too large. The authors also found that thermal efficiency is slightly improved from 37% to 39% with the biogas-syngas mixture compared to the use of a single fuel.

The influence of the addition of syngas on the thermal efficiency of spark-ignition engines fuelled with gasoline has also been proved by Dai et al. [33] and Ji et al. [26, 38]. Dai et al. [33] recovered the exhaust temperature of a 4-cylinder 1.6L gasoline engine by using it to produce syngas by ethanol vaporeforming. The composition of the syngas varies according to the air-fuel ratio of the mixture, which varies the exhaust gas temperature. For an excess air rate of 1.36, it contains 62.93% H_2 and 22.57% CO_2. The syngas produced is injected at the intake and occupies 2.5% of the mixture for an ethanol flow rate of 40 ml/min. By adding this amount of syngas to gasoline, Dai et al. [33] found an increase in engine thermal efficiency of 38.6 to 40%. These results are confirmed by Ji et al. [26, 38] who also worked on the same system. By varying the amount of syngas in the mixture from 0 to 2.43%, the thermal efficiency of the engine increased from 34.52 to 39.01% [26]. Then, in another work by the same authors [38], the thermal efficiency increased from 35.88 to 39.54% for an addition of 0 to 1.84% of syngas.

6.2. Cylinder Pressure

Although syngas has a relatively low heating value, its addition to methane or gasoline increases the pressure released during combustion. Thus, by adding 5% syngas ($H_2/CO=1$) to natural gas (represented by methane), Cha et al. [34] measured a 7% increase in maximum cylinder pressure for the CH_4+ H_2 mixture, 4.9% for the CH_4+ H_2+ CO mixture and 2.2% for the CH_4+ CO mixture. This trend was also observed by He et al. [23].

Concerning gasoline enrichment, Dai et al. [33] stated that, due to the high flame and diffusion velocity of the mixture of H_2 and CO, favoring their rapid and complete combustion, as well as their low ignition energy, the maximum pressure released by combustion is increased when syngas is added to gasoline. Ji et al. [26] observed an increase in pressure for a volume of syngas ranging from 0 to 0.92%, but beyond this amount, the pressure decreases due to the low energy density of the syngas compared to gasoline.

6.3. Combustion

Another benefit of adding syngas to methane, to a methane-rich biofuel or gasoline is improved combustion. He et al. [23] found that adding H_2 and CO to natural gas increases the heat released from combustion while advancing its phase. Advancing the heat release phase reduces the flame development time and the duration of combustion [23]. He et al. [23] also discovered that H_2 has a greater influence than CO on improving combustion.

Fischer and Jiang [27] analyzed the effects of the main combustible gases of syngas, H_2, CO, and CH_4, on its ignition. They modeled the chemical kinetics of the combustion of a biogas-syngas mixture through three reaction mechanisms: the Gas Research Institute GRI 3.0 mechanism, its skeletal version DRM22, and the Heghes C1-C4 mechanism. They varied the methane content of the mixture from 8 to 11%, that of CO from 28 to 36%, and that of H_2 from 22 to 32%. Fischer and Jiang [27] found that the presence of H_2 in the mixture promotes ignition and increases the combustion temperature. CO also slightly accelerates ignition but allows better combustion with a lean fuel mixture rather than a stoichiometric or rich mixture. The authors, therefore, argue that the biogas-syngas mixture burns better when it contains less CO. Finally, among the three combustible gases, Fischer and Jiang [27] found that CH_4 delays the onset of ignition.

In addition to the effects of syngas on flame onset and development, He et al. [23] also found that the addition of H_2 and CO in natural gas improves the stability of the work cycle by reducing the coefficient of variance of indicated mean effective pressure (COVIMEP). Kan et al. [35] found that the addition of syngas to biogas reduces the risk of knocking.

Concerning gasoline, Ji et al. [26, 38] observed that combustion becomes faster with the addition of syngas. The flame development phase, characterized by CA0-10, is reduced by 6.2% with an addition of 2.43% syngas [26] and 8.4% with an addition of 1.84% syngas [38]. The flame propagation phase, characterized by CA10-90, is reduced by 4.5% with an addition of 2.43% syngas [26] and by 6.8% with an addition of 1.84% syngas [38].

Jain et al. [38] studied the effect of H_2 or syngas addition on isooctane ignition. A reduced mechanism consisting of 38 species and 74 reactions was developed by the authors to allow the simulation on the CHEMKIN software of the inflammation of the isooctane/H_2 mixture or the isooctane/syngas mixture. According to their studies, the effect of enrichment on inflammation is minor below 50%. Above 50%, the addition of H_2 delays inflammation for temperatures below 900°K but favors it for temperatures above 1000°K. Above 80%, inflammation is more influenced by H_2 than by C_8H_18. The authors also found that the addition of CO has a negligible effect on the ignition of the mixture, the most determining components being H_2 and C_8H_18.

6.4. Pollutant Emissions

Generally, the addition of syngas to methane, or a methane-rich biofuel, reduces the emission of pollutants in the exhaust gas. By adding 5% syngas to landfill gas, Kohn et al. [31] reduced CO emissions from 802 to 214 ppm. These emissions increase when the amount of syngas is varied between 10 and 15%, but they are still lower than those obtained without addition. The CO emissions depend partly on the H_2 and CH_4 contained in syngas [27] but the most determining component remains the CO which can end up in the exhaust if the combustion is not complete [23].

In the case of gasoline enrichment, the addition of syngas slightly increases CO emissions because of the presence of this gas at the intake [33]. This is further enhanced by the reduced combustion time brought about by the addition of syngas, which makes oxidation less complete [26].

In the work of Kohn et al. [31], the addition of 5% syngas in the landfill gas decreased NOx emissions by 100 to 62 ppm. As with CO, NOx emissions increase with 10 and 15% syngas but remain lower than landfill gas operation [31]. According to Fischer and Jiang [27], NOx emissions are favored by the presence of H_2 which increases the combustion temperature. When Watson et al. [36] compared the routes for NO formation during the combustion of syngas, biogas, or a mixture of both, they found that the most preponderant route for the case of syngas is the thermal route. However, the NNH and N_2O routes become more significant when the fuel mixture is leaner. Watson et al. [36] also found that NOx emissions are lower with the biogas-syngas mixture than with pure methane. Mameri et al. [37] also studied the NO formation routes in the combustion of a biogas-syngas mixture, focusing on the significance of the strain rate. They found that at a low strain rate, the NO_2 rout is predominant, but as the strain rate increases, the prompt route becomes more significant [37].

However, according to Kan et al. [35], the ignition timing has even more influence than H_2 on the formation of NOx during biogas-syngas combustion. These authors too found that NOx emissions decrease with the addition of syngas in biogas. Finally, Cha et al. [34] state that NOx emissions do not vary linearly with the amount of syngas added to methane and that CO is more influential in the formation of NOx than H_2.

Concerning gasoline enrichment, the NOx concentration in the exhaust gas depends on the temperature variation caused by the addition of syngas. In studies by Dai et al. [33], the addition of syngas increases the combustion temperature and thus promotes NOx formation. However, in the experiments conducted by Ji et al. [26], the addition of 2.43% syngas to gasoline reduced the combustion temperature and lowered NOx emissions by 15.47%. In another study by Ji et al. [38], the addition of 1.84% syngas also decreased NOx concentration from 2047 to 1499 ppm.

Concerning HC emissions, Kohn et al. [31] measured a reduction from 113 to 12 ppm with the addition of 5% syngas in the landfill gas. These emissions increase with 10% and 15% of syngas but remain lower than pure methane operation. These results are supported by He et al. [23] who recorded a decrease in HC emissions after adding H_2 and CO in natural gas.

In the case of gasoline, Ji et al. [26] obtained a 15.47% decrease in HC emissions with the addition of 2.43% syngas and a reduction from 3165 to 2436 ppm with 1.84% syngas. This is explained by Dai et al. [33] as being due to faster and more complete combustion. However, when the fuel mixture becomes leaner, with an excess air rate greater than 1.21, HC emissions increase [33].

7. S.W.O.T. Analysis of the Use of Syngas and Syngas Blends in Spark-Ignition Engines for rural electrification

Based on the information collected on the review of the use of syngas or syngas blends in spark-ignition engines, a S.W.O.T. analysis is performed to determine the positive and negative aspects of each case. The positive points listed concerning the internal environment of the system are identified as Strengths and the negative ones as Weaknesses. Opportunities represent the positive points concerning the external environment and Weaknesses represent the negative ones [54]. In the implementation of this S.W.O.T. analysis, the internal environmental aspects (Strengths and Weaknesses) are taken from the results published in the reviewed articles while the external environmental aspects (Opportunities and Threats) are deduced from their implications in rural electrification projects. The tables containing the detailed results of the S.W.O.T. analysis are presented in the appendixes found at the end of this article.

Table 3 shows the results of the S.W.O.T. analysis for the use of 100% syngas in spark-ignition engines. The main advantages listed are the possibility to run the engine on syngas in wider areas: 100% renewable use, higher compression ratio, leaner fuel mixture; and reduced emissions of pollutants, especially CO, NOx, and HC compared to gasoline or natural gas. These advantages promote the application of this technology in rural electrification projects as they allow the use of simple, available, and more affordable facilities compared to other syngas valorization technologies. As gasification can process different kinds of biomass, it allows a greater degree of autonomy regarding the variation in the availability of the feedstock. These factors thus contribute to the sustainability of rural electrification projects based on gasification.

The main disadvantages cited on the use of syngas in spark-ignition engines are the decrease in engine power, lower efficiency, and higher fuel consumption due to the low heating value of syngas. Modifications of the engine may be required to make it run on syngas and instability problems may occur as the quantity and quality of the syngas fluctuates. Compared to gasoline or natural gas, the combustion of syngas also emits more CO_2. The possible consequences of these drawbacks on rural electrification projects are the decrease in the quantity and quality of the electricity produced; the risk of deterioration of the equipment if the instability problems are not solved; and the environmental issues caused by greenhouse gas emissions.

Table 4 presents the results of the S.W.O.T. analysis on syngas enrichment in spark-ignition engines. Compared to the use of 100% syngas, the main advantages of methane or biogas enrichment are the increase in power output while reducing specific fuel consumption due to better thermal efficiency and a higher heating value of the fuel. Working cycle instabilities are reduced and CO, NOx, and HC emissions are lower than with 100% syngas. These improvements contribute to a more stable electrical power generation and ensure customers' satisfaction even following an increase in electricity demand. Solving instability problems increases the equipment durability and lower pollutant emissions can be an ecological argument in the fundraising process. However, the mixing of two types of fuel requires the control of two biomass transformation processes (gasification and methanation) and the control of the mixing device. The qualification of the site's technical staff is then more demanding, which makes it more difficult to operate in rural areas.

Tables 5 and 6 present the results of the S.W.O.T. analysis on the use of syngas as an additive in spark-ignition engines. The main benefits of syngas enrichment are related to efficiency, combustion, and pollutant emissions. The thermal efficiency of the engine increases, combustion becomes faster and generates more pressure, NOx, and HC emissions are reduced. In the case of methane-rich fuel enrichment, the working cycle becomes more stable and the risk of fuel self-ignition is lower. These improvements improve the durability of the engine and thus increase the sustainability of the electrification project. The main disadvantage identified during fuel blending remains the difficulty encountered in controlling the volumes of each fuel. This difficulty can be a hindrance in rural applications if a competent person is not always available on site. In the case of gasoline enrichment, the increase in CO emissions also increases the risk of intoxication of the people working on the site.

Concerning this use of syngas blends in rural electrification project, Andriatoavina et al. [55] have, very recently, conducted some studies assessing the potential of mixing syngas with HHO gas produced from solar electrolysis of water. It was found that adding HHO gas in syngas can improve the autonomy of the system up to 6 hours when producing 5 kW electrical power with a start reserve of 60 Nm^3. This study demonstrates the improvements brought by the enrichment of syngas with HHO gas in rural electrification projects.

8. Conclusion

This article studied the potential of the use of syngas and syngas blends in spark-ignition engines for power generation. A review was first conducted on the recent progress made in fuelling spark-ignition engines with 100% syngas, syngas enriched with methane or biogas, or syngas as an additive. A S.W.O.T. analysis was then carried out to identify the potential benefits or obstacles encountered when applying the mixture of syngas in rural electrification projects. The literature review and S.W.O.T. analysis highlight the following points:

- The use of 100% syngas allows the production of electricity from 100% renewable resources. This particularly facilitates application in rural electrification projects where the population does not have easy access to fossil fuel supplies. However, variations in the quantity and quality of the syngas can impact electricity production and present risks of unmet consumers' needs and reduced equipment lifetime.

- Enriching syngas with methane or methane-rich biofuels improves engine power, specific fuel consumption, work cycle stability, and pollutant emissions. These improvements are not proportional to the volume added and become less significant above 50% additive. Enrichment thus increases the quality of service provided by power generation facilities in rural areas. However, additional competence is required of the people in charge of the site to be able to control the production processes of each gas and to control each flow in the mixture.

- The use of syngas to enrich methane, a methane-rich biofuels, or gasoline brings benefits, not in terms of power, but in terms of thermal efficiency, speed of combustion, the stability of the work cycle and pollutant emissions. In order not to dilute the pilot fuel too much, the volume of the syngas must be kept below 5% in methane-rich biofuel, and below 2.5% in gasoline. This enrichment can extend the engine's lifetime and thus improve the sustainability of the electrification project. However, controlling the volume of each fuel in the mixture adds a degree of system complications that can affect its performance or durability if not controlled. But, in regards of the benefits brought by the use of syngas as an additive, the challenge of controlling the mixing process is worth being addressed.

The main contribution of this study is the identification of the benefits of mixing syngas with other fuels in rural electrification projects. The review is performed form papers studying the use of syngas blends in laboratory scale set-ups, focusing on engine performance and pollutant emissions. From this review, the authors deduced the benefit obtain in the application of rural electrification. So, it was found that syngas enrichment can improve the quality of service provided by the power generation facility in terms of stability and reliability. Otherwise, the use of syngas as additive can lengthen the lifetime of the facility through a better engine work cycle.

However, it is noted that the number of published articles dealing with the subject is still very low. Moreover, the type of fuel tested in mixtures with syngas is not much varied. It is either methane, a methane-rich biofuel such as biogas or natural gas, or gasoline. Some of these studies have also used syngas composed in a laboratory, which may have different compositions from those obtained in gasification reactors. All these remarks indicate that there is still a need to further investigate the subject by conducting experiments, preferably using syngas produced from gasifiers, and exploring the possibility of blending syngas with other types of biofuels such as ethanol, butanol or methanol. It is also interesting to pursue these studies by studying the use of syngas blending in compression-ignition engines.

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Appendix A

Table 3: S.W.O.T. analysis of the use of 100% syngas in spark-ignition engines

Strengths	Weaknesses	Opportunities	Threats
- Possibility of operating the engine with only syngas (compared to CI engine which required diesel to ignite the mixture) [15] - Possible use with higher compression ratio (thanks to the anti-knock characteristic of CO, CH_4, N_2, and CO_2) resulting in higher thermal efficiency [15] - Possible use with a leaner mixture compared to gasoline, ethanol, and compressed natural gas [25] - Highest combustion efficiency due to the absence of hydrocarbons in the chemical composition [25] - Reduction of CO and NOx emissions compared to gasoline operation [39]	- Decrease in fuel LHV compared to gasoline [39] - Increase of fuel consumption compared to gasoline operation [39] - Adjustment of the ignition timing necessary due to the high laminar velocity of the flame [41] - Modifications of the engine block, cylinder heads, or pistons may be required to increase the compression ratio - Engine durability can be affected by tar deposition [17] - Power derating compared to gasoline operation [39, 40]	- Increase of energy independence from fossil fuels [56] - More availability of engines and easier use compared to gas turbines [13] - Possible use in remote areas not supplied with fossil fuel to produce electricity - Low capital cost, reliability, good part-load performance, high operating efficiency, modularity, safer use compared to other types of combustion technologies [13] - Promotes sustainable development [56]	- Need for more fuel quantity to sustain production - Risk of forest overexploitation - Dependence of electricity production on the availability of the biomass - Expertise needed to implement engine modifications may affect the engine durability in rural areas - Instability of power supply compared to gasoline-fueled generator set

Table 3 continued from previous page

Strengths	Weaknesses	Opportunities	Threats
- Reduction of NOx emissions with a lean mixture which produces a low combustion temperature [25] - No emissions of hydrocarbons because syngas does not contain any in its composition [25] - Lower CO, NOX, HC, SO_2 emissions compared to natural gas operation [42]	- Decrease in the speed, torque, and power compared to natural gas operation [42] - Lower electricity production efficiency compared to natural gas [42] - Lower engine torque compared to compressed natural gas operation [28, 29, 30] - Work cycle instability: COVIMEP greater than 5% [45] - Increase of CO_2 emissions compared to gasoline operation [39] - Higher CO_2 emissions compared to natural gas operation especially at lower load [42]	- Electricity generation from local resources - Better use of agricultural waste - Resolution of agricultural waste disposal issues - Possible use of several types of biomass (producing different qualities of syngas) thanks to a wider range of operation - Fewer health issues related to facility operation - Facilitated funding thanks to lower pollutants emissions	- Higher risk of material breakdown due to combustion instability - Lower quality of the electricity generated due to combustion instability - Environmental concerns due to greenhouse gas emission (CO_2)

Appendix B

Table 4: S.W.O.T. analysis of syngas enrichment in spark-ignition Engines

Strengths	**Weaknesses**	**Opportunities**	**Threats**
- Increase of the mixture heating value [45, 46] - Reduced fuel consumption because of an improvement of the thermal efficiency [28, 29, 30] - Increase of engine torque, exceeding even natural gas operation [28, 29, 30] - Improvement of thermal efficiency [28, 29, 30] - Increase of power output equaling pure methane operation [45] - More stability (reduction of COV-IMEP) [45] - Reduction of CO, NOx, and HC emissions [28, 29, 30]	- Increase of CO_2 emissions [45] - Energy improvement limited to 50% addition [45, 46]	- Improvement of the autonomy of the facility - Decrease in the use of forest resource - Use of 100% biofuel - Increase of the electricity produced - Better satisfaction of electricity demand - Promotion of rural areas development - Improvement of the facility durability - Improvement of generated electricity quality - Fewer health issues related to facility operation - Facilitated funding thanks to lower pollutants emissions	- Higher risk of breakdown if the mixing of the fuels is not mastered - Need to control two processes (gasification and methanization) - Environmental concerns due to greenhouse gas emission (CO_2)

Appendix C

Table 5: S.W.O.T. analysis of the use of syngas as methane or methane-rich biofuel additive in spark-ignition engines

Strengths	Weaknesses	Opportunities	Threats
- Increase of the maximum pressure [34, 23] - Improvement of the thermal efficiency [23, 35] - Improvement of fuel conversion efficiency [34] - Increase in the rate of heat release [45] - Decrease in the flame development time and the combustion duration [45] - Lower knock tendency [35] - Reduction of COVIMEP [45] - Reduction of HC emissions [45] - Reduction of NOx emissions [35, 36]	- No increase in engine power	- Use of 100% biofuel - Increase of the electricity produced - Better satisfaction of electricity demand - Promotion of rural areas development - Enhancement of the quality of electricity produced - Improvement of the engine durability - Improvement of the project sustainability - Fewer health issues related to facility operation - Facilitated funding thanks to lower pollutants emissions	- Higher risk of breakdown if the mixing of the fuels is not mastered - Need to control two processes (gasification and methanization)

Appendix D

Table 6: S.W.O.T. analysis of the use of syngas as a gasoline additive in spark-ignition engines

Strengths	**Weaknesses**	**Opportunities**	**Threats**
- Improvement of thermal efficiency and maximum cylinder pressure [33, 26, 38] - Faster combustion [26, 38] - Reduction of HC emissions [33, 26, 38] - Reduction of NOx emissions [26, 38]	- Decrease in the pressure beyond 0.92% syngas [26, 38] - Increase of CO emissions [33, 26, 38]	- Improvement of the engine durability - Improvement of the project sustainability - Fewer health issues related to facility operation - Facilitated funding thanks to lower pollutant emissions	- Higher risk of breakdown if the mixing of the fuels is not mastered - Issues related to the use of fossil fuel (climate change, geopolitical concerns, oil price volatility, etc.) - Health issues related to CO emissions

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