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ADVANTAGES AND ECONOMIC FEASIBILITY OF STIRLING ENGINES AS A DISTRIBUTED GENERATION SOURCE AND COGENERATION TECHNOLOGY – A BRIEF REVIEW

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Abstract. *The present paper aims at analyzing the potentiality and economic feasibility of the Stirling engine, highlighting its use as a distributed generation source and cogeneration technology. With this intention, a research was performed followed by a selection of papers and other sources that dealt with the most relevant aspects of the topic. Another objective was the determination of hindrances to be overcome by the Stirling technology in order to become feasible. Furthermore, a table containing some examples of products regarding the referred applications of the Stirling engine is presented. Ultimately, it is concluded that the Stirling technology, despite its advantages and suitability regarding the proposed applications, is not yet commercially feasible, having currently only a minor presence in the market. This scenario can be attributed to the need for futher research and technical development as well as cost reduction.*

Keywords: *Stirling Engines, Distributed Generation, Cogeneration, Brief Review.*

1. INTRODUCTION

Electrical power is an indispensable resource to modern society, especially regarding economic activities, human comfort and life quality as well. However, energy consumption tends to increase substantially in the next decades, more precisely in about 48% from 2012 until 2040 (Fig 1a), together with the usage of all fossil fuel types, which should be responsible for 78% of all generated power by the end of this same period (Fig 1b) (International Energy Outlook, 2016).

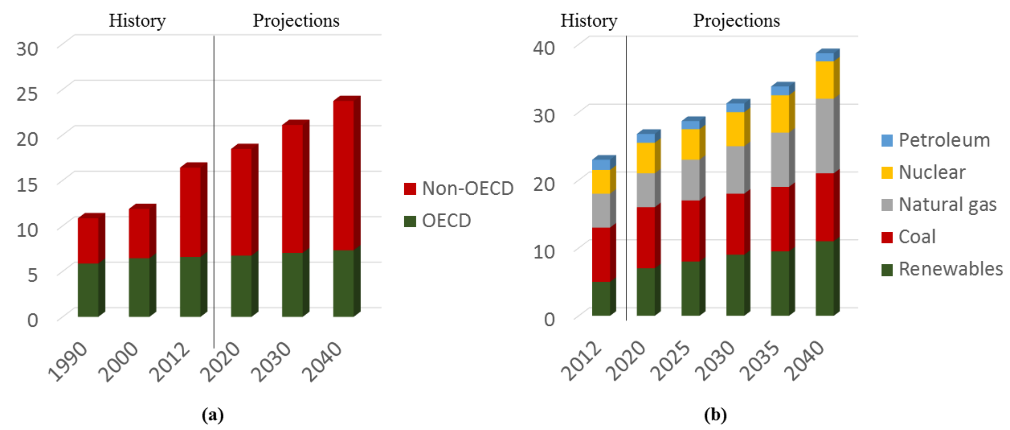

Figure 1. a) Projections for the global primary energy consumption in trillions of kilowatt-hour for members and not members of the Organization for Economic Cooperation and Development (OECD) and b) World net electricity generation by energy source in trillions of kilowatt-hour (International Energy Outlook, 2016) (Adapted)

The increasing fossil fuel usage contributes to the aggravation of environmental problems like acid rain and eutrophication (Caetano *et al*., 2017). In this context, the raise in energy demand is inconsistent with concerns regarding climate changes (Warner and Jones, 2017) and it may, given the reduced energy availability, prevent tendencies of economic growth experienced in the past (Murphy and Hall, 2011). At the same time, more than one billion people still do not have access to electrical energy, even with all electricity generation increment (IEA and WB, 2015).

This situation calls for the adoption of more efficient and clean ways of energy production, like cogeneration of heat and power (CHP) and trigeneration of cooling, heating and power (CCHP).

In case of isolated areas, distant from consumption centers, the most appropriate and economical way of meeting the electricity demand is with Distributed Generation (DG) since, as pointed by Pepermans *et al*., 2005, it cuts down distribution and transmission costs, being more versatile, reliable and prone to the incorporation of renewable energy sources. To illustrate this, about 5% of all energy produced is made unavailable in the United States (US) due to transmission and distribution losses, while the associated costs of these two operations add up to 70% of energy generation costs (Fig 2) (EIA, 2017). Besides that, according to ANEEL (National Agency of Electrical Energy; 2017), GD is able to reduce grid loading and environmental impacts, contributing to the diversification of the energetic matrix as well.

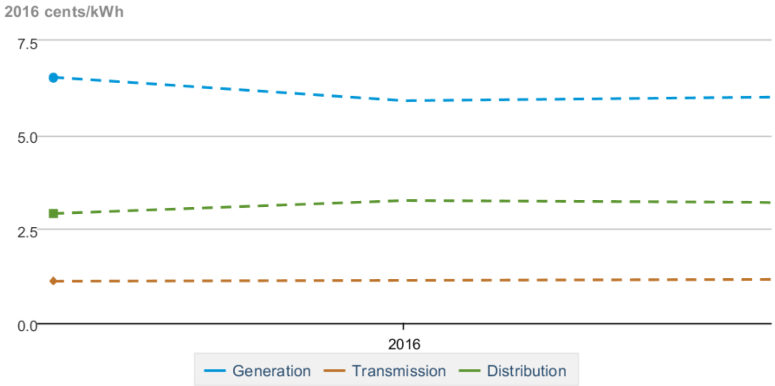

Figure 2. Generation, transmission and distribution costs in the United States from 2015 to 2017 in US cents per kWh (EIA, 2017)

The Stirling technology in this context poses as a promising DG technology, having many conveniences. Among them it is possible to point out a high theoretical efficiency, equivalent to the Carnot one, and the capability of using any source of energy as fuel, which can be of low cost or even cost free. Apart from that, there is also the aptitude of being less pollutant than conventional engines. (Timoumi *et al*., 2008).

In fact, the new development of the Stirling technology was mainly motivated by the recent interest in DG, being one of its most researched applications, with another substantial motivator being its possibility to be used in cogeneration systems, proportioning better energy usage and power saving.

The objective of this work was therefore to provide a brief review of the advantages, limitations and potentialities of the Stirling Engine (SE) regarding its use both as distributed generation and cogeneration technology, and also to report the main hindrances to its economic feasibility.

Ultimately, it should be noted that due to some imprecision regarding the definition of DG (El-Khattam and Salama, 2004) it is important to explicit the one adopted in this paper. Thus, the definition used here is of a small scale, close to the final costumer generation, that has no connection to the main electrical grid. This definition is similar to the proposed by Dondi *et al*., 2002.

2. OPERATING PRINCIPLE OF THE STIRLING ENGINE

Before proceeding with this review, a brief explanation of what would be a SE and how it works is considered.

Stirling engines are external combustion engines which operate according to an equally named cycle, where the working fluid stays permanently confined to the system. In order to make the study of its thermodynamic cycle simpler, given its complexity, the real Stirling cycle is approximated to an idealized one, as exposed by Fig 3a. According to this approach, the cycle would be composed respectively by an isothermal expansion (1-2), an isochoric cooling (2-3), an isothermal compression (3-4) and an isochoric heating (4-1). It is worth mentioning that both isothermal processes involve heat gain or loss by the working fluid with the hot and cold reservoirs (Q_{IN} e Q_{OUT}), while the isovolumetric processes deal with heat exchange between the working fluid and the regenerator ($Q_{R,IN}$ e $Q_{R,OUT}$).

The operating process of a SE can be better visualized for a hypothetical Stirling model, as depicted by Fig 3b. As shown, at state 1, the working fluid is completely contained at one of the two chambers, the left one in this case, being at both high pressure and temperature (T_H). Then it receives heat from an external hot source and expands isothermally, producing work as it makes the piston in its chamber move. At state 2, the cycle reaches its maximum volume and both pistons start moving to the left at the same ratio, keeping the system's volume constant. During this stage (2-3), the working fluid is forced through the regenerator, being cooled to the temperature T_L. When pressure finally drops to its minimum at state 3, the left piston interrupts its movement and the right one starts to compress isothermally the gas, which exchanges heat with the cold reservoir but remains at the same temperature T_L (3-4). Finally, in order to complete the cycle, both pistons move to the left at the same ratio, keeping the volume of the system constant and forcing the working fluid through the regenerator again (4-1). Then, the gas receives thermal energy until regaining the temperature T_H and the cycle is restarted.

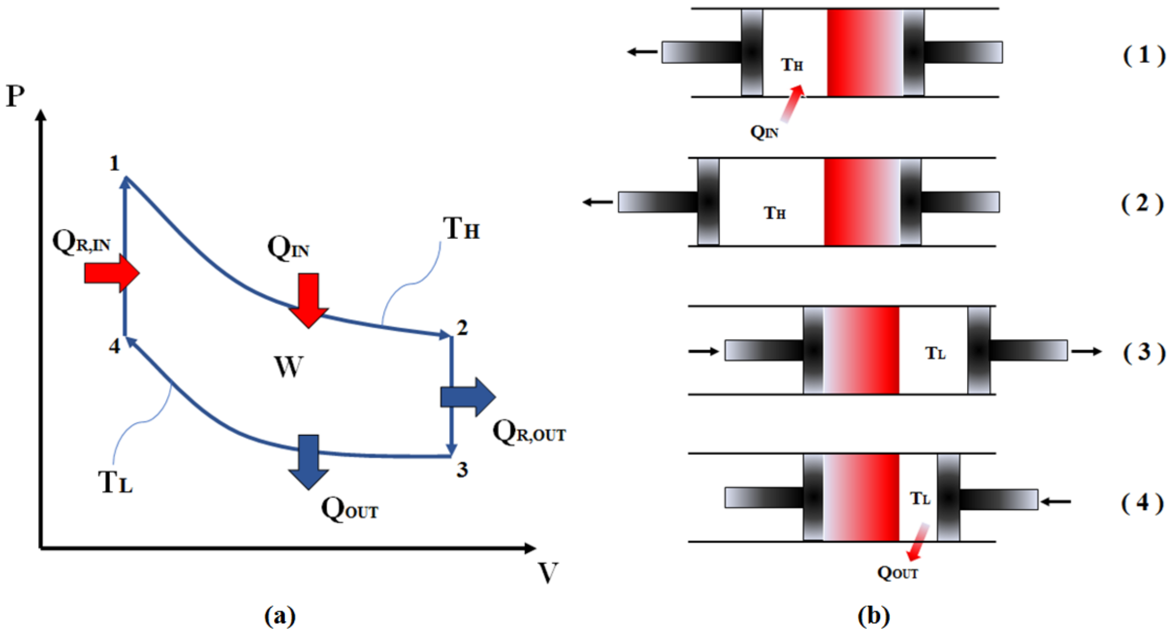

Figure 3. (a) Ideal Stirling thermodynamic cycle and (b) Main states of Stirling cycle

3. RESEARCH METHODOLOGY

The research was oriented towards answering the three following questions: What are the advantages of the Stirling Engine as a distributed generation source and cogeneration technology? Is it economically feasible? Which would be the reasons preventing its feasibility?

Having these questions as a starting point, publications were found through the Metasearch of CAPES (Brazil's Higher Education Coordination of Personnel Perfecting) using as key-words the combination of the word "Stirling" with the following terms: "engine", "technology", "distributed generation" and "cogeneration". The articles whose titles contained some of these key-words were then selected and had their abstracts read, with the ones that had no relationship with the scope of this research being excluded. Lastly, the remaining publications were read and had their relevant information extracted. It is worth to point out that besides scientific and academic publications some other sources like technical studies were incorporated, given its relevance to the addressed topic and credibility.

Filters regarding the research period were not used, being included publications until 2017's middle in order to incorporate the most recent information to this review. Moreover, the research was conducted on a global level in the attempt to offer a more general and better view about the topic, since, as proposed by Webster and Watson (2002), a complete review should not be restricted only to a specific geographic region.

4. ADVANTAGES OF STIRLING ENGINES AS A DG AND COGENERATION SOURCE

The SE has several advantages when compared to other DG sources. One of them lies in the fact that the engine operates on a closed cycle, what allows the selection of a working fluid, rather than air, with much desirable properties to maximize engine performance, as chemical inertia and high thermal conductivity. Nevertheless, one of the main advantages of a SE resides in its external combustion, since it occurs in a separate system, and thus creates the possibility of utilizing a great variety of fuels to power the engine. (Thombare and Verma, 2008; Çengel and Boles, 2013).

This flexibility is not only restricted to the fuel type but also to its quality, with the possibility of using so called "dirty" combustibles like biomass, firewood and landfill gas without the need of pretreatment or cleaning (Stirling

Engine Assessment, 2002). That allows the usage of locally available fuels as, for instance, agricultural waste, what consists in a desirable feature regarding distributed generation.

In fact, virtually any heat source can be employed to run a Stirling motor (Goswami and Kreith, 2007). Thus, it is capable of making use of the low grade thermal energy that is widely available in many industrial applications and in nature as well, making it suitable to be used with renewable sources like solar or geothermic energy (Wang *et al.*, 2016).

In this sense, a solar dish Stirling system has a higher efficiency than any other large scale solar generation technology, being able to achieve a solar concentration of about 3,000 suns at reported annual efficiencies of 23% (Stine and Diver, 1994).

Furthermore, Stirling engines are considered simple in construction, safe, and low noise devices (Alfarawi *et al.*, 2017). These aspects added to the fact that they have a thermal to electrical ratio similar to the one demanded by a domestic load make them ideal for residential application (Valenti *et al*., 2014).

Ultimately, it is important to stress that SEs have high efficiency, meaning they are suitable for cogeneration (Maraver *et al*., 2013), and, given that the combustion process occurs in a continuous way, and thus tends to be more complete, they produce less emissions compared to conventional engines. (Kong *et al.*, 2004; Moran *et al*., 2011).

This fact was demonstrated by both computational simulations and experiments. For instance, Kaldehi *et al*., 2017, reports reductions of at least 40%, 50% and 40% for CO_2, CO and NO_x, respectively, as a result of a simulation with an alfa type Stirling. In turn, Öberg *et al*., 2004 concludes that the emission levels measured after testing a commercial Stirling model neither presented any health hazards, nor had any negative environmental impacts.

5. HINDRANCES AND LIMITATIONS

Despite all presented advantages and possibilities, Stirling engines have also a couple of limitations and face some hindrances to their feasibility. Figure 4, illustrates how small the diffusion level of the Stirling technology in the market is, being practically inexistent, or less than 3 % to be more specific.

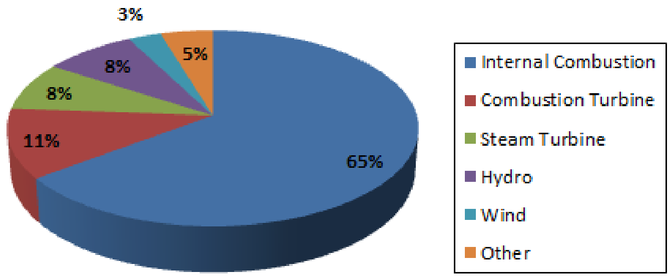

Figure 4. Percent of distributed generation by technology type. (Carley, 2009) (Adapted)

One of the main problems, according to several authors (Corria *et al.*, 2006, Alfarawi *et al*., 2017, Ferreira *et al.*, 2016b) would be the high investment cost of the SE. This can be attributed to the special materials and alloys required to endure the system's operating conditions, which are usually of elevated temperature and pressure (Ferreira *et al.*, 2016b). At the same time, there is low market demand for this technology, which is unfamiliar to the general public, and thus cannot benefit from cost reductions proportioned by mass production (Öberg *et al.*, 2004).

Concerning technical aspects, the major issue has been the system durability and reliability in the long run. Some parts subjected to excessive wear, like the shaft seal assembly and piston rings, are expected to have a lifespan of only 5,000 to 10,000 hours, while there is still a need to reduce material stress and corrosion in the high pressure and/or high temperature heater heads. Beyond this, the wear of piston rings generates particles that obstruct the fine meshed heat matrices used in the regenerators, impairing their performance. (Stirling Engine Assessment, 2002).

Corroborating with the former ideas, Mancini *et al*., 2003, also asserts the need for subsequent technological development, particularly regarding the creation of low cost components which are able to provide reliability to the system. Furthermore, since combustion occurs at atmospheric pressure, Stirling engines have a low power density when compared with Diesel ones (Flannery *et al.*, 2017) and other internal combustion engines in general.

Another relevant technical hurdle is that, although different working fluids may be used to increase considerably the engine performance in relation to the one proportionated by air, like helium (Cheng and Chen, 2017; Abuelyamen *et al.*, 2017), there are problems involving their long-term containment (Minassians and Sanders, 2011). One of the challenges is to design a piston rod seal which is able to keep the working fluid inside the cylinder and prevent lubrication oil from entering it, being, even after several tested solutions, a delicate component of the system (Obernberger *et al.*, 2003). This need for sealing enhancement is also observed by Thombare and Verma (2008), who point out the complexity of projecting a system taking into account thermal, mechanical and fluidic factors.

In relation to solar dish SEs, there are limitations both with low temperature and high temperature ones. The former has low efficiency and specific power in comparison to the latter which, in turn, requires a more complex design and expensive alloys, having thus a higher cost (Sripakagorn and Srikam, 2011).

Moreover, regarding the possibility of using so called dirty fuels to power the SE, like biomass or flue gas, it is important to highlight that ash from these fuels might melt when burned and may cause fouling or slagging issues (Maraver *et al*., 2013). As a result, the heat transfer in the combustion systems is impaired. Corroborating with this idea, Podesser (1999), considers the dust content of the flue gas as the main problem with his biomass powered SE.

Lastly, it is worth mentioning that although being invented in the 19th century, many fundamental design questions still lack a definitive answer, like the way to produce power, whether linear alternator or crankshaft, and system operating temperature and speed, whether high or low. (Stirling Engine Assessment, 2002).

6. PROPOSED SOLUTIONS

If by one side the potentiality of the Stirling technology makes it a subject of interest, by another some of its current hurdles difficult its commercial implementation. Therefore, the SE remains as an object of research and development in both companies and universities in many countries, having as main enhancement goals efficiency increase, reduction of dead volume and decrease of manufacturing and maintenance costs (Erol *et al*., 2017).

Smirnov and Golkar (2015), by instance, in face of the actual indetermination of many fundamental design questions, proposed a tradespace exploration framework to assist the project an analysis of an SE. This tool allows the determination of parameters of the thermodynamic cycle and engine performance as well, being also able to estimate its capital cost. It still has a tradespace model based in five fundamental design parameters, respectively: engine type, cold and hot source temperature, engine stroke and engine bore. In this way, it is possible to identify the most adequate engine architectures and design parameters to meet a particular application. An interesting result is the indication that alfa type engines would be more suitable for waste heat recovery, while the beta type would be more adequate for domestic CHP. (Smirnov and Golkar, 2015).

Aiming to reduce problems in relation to working fluid leakage, Alberti and Crema (2014), in turn, suggest a double-acting engine configuration, in which the cylinders are opposed as in a boxer engine. With the same objective, Kaldehi *et al*. (2017) proposes a considerable reduction of operating pressure, being able to achieve in a computational simulation with an alfa SE, at 35 bar, the same power of a real engine at 110 bar, the SOLO V161.

Regarding the selection of the operating temperature of a solar dish Stirling system, Sripakagorn and Srikam (2011) proposes the adoption of a moderated working temperature, which would be capable of balancing both cost and efficiency. As a result of their experimental study, it was observed that an increase from 350 to 500 °C in operating temperature could provide a considerable increment in speed and an increase of about 50% torque. Therefore, the operation at moderate temperature could be competitive in relation to the one at high temperature.

7. REPORTED COSTS

Despite several authors reporting the high cost of the SE, this is not an absolute consensus, with some authors like Kong *et al*., 2004 and Kongtragool and Wongwises, 2003 stating the opposite. This could be attributed to the great versatility of the Stirling technology, which may incorporate different sizes and configurations, each one with its own associated costs (Öberg *et al.*, 2004). Another worth mentioning fact is that each author utilizes a specific method when performing a cost analysis.

In fact, few cost analysis were found in the researched sources. This may be attributed to the fact that, as pointed out by Ferreira *et al.*, 2017a, much of the academic research is mainly focused on the technical aspects of the subject. Therefore, other relevant aspects, like the economic ones, may be cast aside. An example of this is the proposition by Chmielewski *et al.*, 2016 to use a diamond-tungsten material in high temperature heat exchangers, what in spite of improving the system efficiency, ignores the fact that it may increase considerably the cost of the engine and thereby harm its feasibility.

Nevertheless, it was possible to acquire some information of estimated costs, primarily regarding solar dish Stirling systems. Ferreira *et al.*, 2017a, while performing a thermal-economic optimization study of a low scale solar powered CHP Stirling system, reports a value of 18,059 € as the total capital cost of the plant. The components said to have contributed the most for this amount were the engine bulk, corresponding to 29% of the total, and the 7.86 m diameter solar dish, contributing with 27%. The proposed plant is to have an annual investment of 1,705 €/year, being able to produce, at its optimal condition, 3,61 kW of electricity and 9,35 kW of thermal power with a 74,1% thermal efficiency.

Still regarding a solar dish Stirling, Minassians and Sanders (2011), estimates the cost per watt of a 2 to 3 kW engine to be of 0.30 USD/W. This value was obtained using basically the mass of the materials employed in the construction of some prototypes and considering economies of scale. However, Mancini *et al.*, 2003 utilizes a more elaborated approach when assessing the cost of this type of system, taking into account other cost related aspects as inflation, taxes, insurance and operating and maintenance costs in order to determine the Levelized Energy Cost (LEC), that is, the ratio between the total annual cost and the total amount of annually produced energy. Thereby, Mancini *et al.*

(2003) estimates, for the actual market scenario, an initial investment ranging from 8,000 to 10,000 USD and a cost per kilowatt of 1 USD/kW. Furthermore, the aforementioned mentioned source point out that these expenses may be reduced through an increase in system reliability, what would lower operating and maintenance costs, and also by a raise in the quantity of manufactured units, which is capable of decreasing its initial costs.

In case of biomass powered Stirling systems, Corria *et al.* (2006) reports a generation cost of 1,125 to 1,500 USD/kW. Among the expenses which had most influence on these values, it is possible to indicate the cost of the system itself and the ones related to its operation and maintenance. The fuel price, biomass in this case, although not contributing as much as the mentioned variables, is considered as a decisive factor for the system feasibility (Corria *et al.*, 2006).

On the other hand, Kong *et al*. (2004) when performing an economic feasibility analysis of a CCHP Stirling cogeneration system, highlights that it is related to the avoided cost, annual savings and payback period. The assessed system cost is about 70,000 USD, with the SE being responsible alone for 42,000 USD from this total. Despite the apparent high cost, the authors determine a period of two to about three years for the investment to be paid back, considering their local economic scenario. Besides that, the plant is reported to provide a 33% primary energy saving in comparison with a conventional independent system.

8. GENERAL ECONOMIC ASPECTS

Beyond technical aspects of the Stirling technology itself, there are economic factors which assume a prominent role in the determination of the Stirling technology feasibility (Ferreira *et al.*, 2017a). These aspects vary from region to region and may include electrical grid availability, energy price, competitiveness level with other technologies and governmental policies, among others.

By instance, Öberg *et al.* (2004) stress the importance that deregulation of the energy market has regarding the feasibility not only of the Stirling technology but also in respect to all DG technologies. In their study, the above authors conclude that the analyzed gas powered cogeneration Stirling system is not competitive in the Swedish market in face of conditions as the low electricity price, the high encompassment level of the domestic electrical grid and limitations in the gas distribution one. In contrast, a biomass powered Stirling generator in Brazil is said to be capable of providing energy at a lower cost than the electricity purchased from the grid, what makes it widely competitive (Corria *et al*., 2006).

An also very important factor is the regulation framework which, as showed by González-Pino *et al*. (2015) may play a decisive role in relation to the competitiveness of micro-CHP and particularly the Stirling technology. In their study, it was observed that the high level of feed-in tariffs and support policies in countries like Germany and United Kingdom, could provide very attractive payback periods and improvements twice as higher than those in the case of Spain. Therefore, they conclude that the Spanish regulation still has much to improve in order to make micro-CHP, and especially the Stirling technology, competitive.

Moreover, it is worth mentioning that not only macroeconomic aspects may influence the implantation of the Stirling technology. Corroborating with this idea, Balcombe *et al.*, 2015 shows that even the variation on demanded energy from one residence to another may constitute a decisive factor in promoting the feasibility of their hybrid photovoltaic CHP Stirling system, concluding that it would be financially beneficial just for domestic consumptions higher than 4,300 kWh/year.

Ultimately, it is important to stress that economic factors do not simply say if a DG technology, is viable or not, but may also establish the optimum way of adjusting it to a given application. As an example of this, Bartela *et al*., 2017 points out that, since there is a limited heat demand on the polish domestic market, their biomass integrated gasification combined heat and power system (BIGCHP) with a SE is best suited for this market than a conventional cogeneration one, of internal combustion, due its capability of sacrificing efficiency in heat production to increase the efficiency in electricity generation.

9. COMMERCIAL STIRLING ENGINES

Even with the presented hindrances, many companies have conducted extensive research focused in the Stirling technology. Among them it is possible to mention: General Motors Company (USA), DAF (Netherlands), United Stirling (U.S.A), MAN-MWM Group (Germany), Ford Motors Company (U.S.A.), Siemens (Germany), Cummins (U.S.A.), Perkins (U.K.), and NASA (U.S.A.) (Erol *et al.*, 2017). The intended applications range from the more traditional cogeneration and solar thermal energy conversion to underwater propulsion and space exploration (Sala *et al*., 2015).

The Swedish company Kockmus, by instance, has manufactured Stirling engines of 75 kW to be employed as an air-independent propulsion unit (AIP) at submarines. The unit is able to extend in several weeks the submarine operation period when submersed, in comparison with traditional diesel-electric engines. The North-American company STM Power Inc., in turn, has produced Stirling based cogeneration systems, claiming of being able of generation 44 kW of heat and 25 kW of electricity. Another example of commercial Stirling technology as a cogeneration system is the

SOLO V161, built by SOLO Kleinmotoren GmbH, which may also be used to generate power from a solar dish configuration (Öberg *et al.*, 2004).

Table 1 presents a set of DG and cogeneration Stirling technology developed by some companies.

Table 1. Set of DG and cogeneration Stirling technology, by company, contry, model, application and maximum output.

Company	Country	Model	Application	Maximum output
Kockums [(1)]	Sweden	Kockmus Stirling AIP	Submarine propulsion unit	75 kW
STM Power Inc.	USA	STM 4-120	Cogeneration	Heat: 45 kW Power: 25 kW
Stirling Energy Systems [(2)]	USA	SES Dish-Stirling Systems	Power production using solar energy	24.9 kW
Sunpower Inc.	USA	BIOWATTT	Cogeneration	10 kW
Tessera Solar	USA	Maricopa Solar Plant	Power production using solar energy	1.5 MW
Stirling Technology Inc.	USA	ST 5	Water pumping	3.7 kW
SAIC/STM	USA and China	SunDish	Power production using solar energy	22.9 kW
United Stirling, Inc.	USA and Sweden	V160 D	Power production using solar energy	27 kW
Cleanergy	Sweden	SunBox	Power production using solar energy	13 kW
SOLO Kleinmotoren GmbH	Germany	SOLO V161	Cogeneration	Heat: 26 kW Power: 9.5 kW
VE-Ingenieure	Germany	ST05G	Demonstration	0.5 kW
Schlaich Bergermann und Partner (SBP)	Germany, Spain and others	EuroDish	Power production using solar energy	10 kW
Stirling DK	Denmark	SDK	Power production	35 kW
Whisper Tech Limited.	New Zealand	WhisperGen	Cogeneration	Heat: 6 kW Power: 800 W
Sigma Elektroteknisk A.S [(3)]	Norway	PCP 1-130	Cogeneration	Heat: 9 kW Power: 1.5 kW
Inspirit Energy Holdings Plc	United Kingdom	Inspirit Charge	Cogeneration	Heat: 15 kW Power: 3 kW
Suction Gas Engine Mfg. Co., Ltd	Japan	Low temperature differential engine	Power production	1 kW

[(1)] Acquired by SAAB
[(2)] Closed in 2011
[(3)] Current denomination: Merck

10. CONCLUSION

It is concluded that the Stirling engine is very suitable to be employed both as distributed generation and cogeneration technology, since it is versatile, being able to be employed with practically any energy sources available, efficient and in accordance with current environmental concerns. Moreover, SEs are safe and low noise devices adequate for domestic applications. Faced with all these advantages, it is possible to observe a considerable business interest in relation to the Stirling technology, with several companies attempting to develop products from it. Despite of that, there are some hindrances preventing its massive market entrance. One of them is the high cost of the SE, due to its low production level and the usually expensive materials used in its construction. Other major problems include the lack of reliability and durability of its components, which poses as big hurdle, especially regarding DG applications, and also technical issues as working fluid leakage. Therefore, as a result, the Stirling technology still remains mainly as an object of research and development by companies and the academic community, being not yet feasible for most markets. Lastly, it is important to highlight that besides technical aspects, economic factors and governmental policies may greatly influence the feasibility of the Stirling distributed generation and cogeneration technology, and that these factors must be properly assessed and if one intends to make this technology competitive at a given market.

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