SES Gasification Technology (SGT)

Technical Summary and Global Gasification Technologies Analysis

The Future of Gasification

June 2016

This SES Gasification Technology (SGT) technical summary and global gasification technologies analysis has been prepared to provide information and context required to understand the commercial capabilities of SGT, and its importance in the future of global gasification projects.

SES believes gasification can deliver a large share of energy projects needed for future growth in developing economies, with first emphasis in Asia. Additionally, traditional gasification markets, including chemicals and fertilizer, will also be implemented. The energy market in these regions, however, is most noteworthy as it is expected to grow rapidly over the next 20 years. SES believes that *today* is the correct time to positon for this growth.

Large populations in newly industrializing and developing countries, such as China, India, Indonesia, Africa, Afghanistan and Brazil, will emerge from poverty. Simultaneously, in these same regions, approximately two billion people will be born during the next two decades. This extreme confluence of events, unlike any in recent history, will drive a massive need for basic human requirements of food, water and energy.

These developing economies have unique characteristics, challenges and needs in order to grow. These include:

- Lack of domestic oil and natural gas supplies;
- Lack of infrastructure to transport liquefied natural gas (LNG);
- Increased expense and volatility of LNG and oil supplies;
- Locally sourced coal, especially low quality coal, is generally available and inexpensive;
- Strong desire for energy independence, utilization of domestic energy resources;
- Environmental need for cleaner, more efficient projects with lower emissions and water usage, and
- Huge growing demand for cleaner and small- to medium-scale power.

These market requirements will make the gasification of coal, biomass, municipal solid waste (MSW), and other low to negative value feeds very attractive. However, the premier gasification technologies of the past have limitations and SES believes will find little market share in this new and changing marketplace. Multi-tiered solutions that are able to tackle the triple challenges of energy demand, economics and environmental pollution, such as the ability to gasify waste products to create value-added necessities in an ecologically responsible manner, will prevail.

The new requirements of gasification technology are:

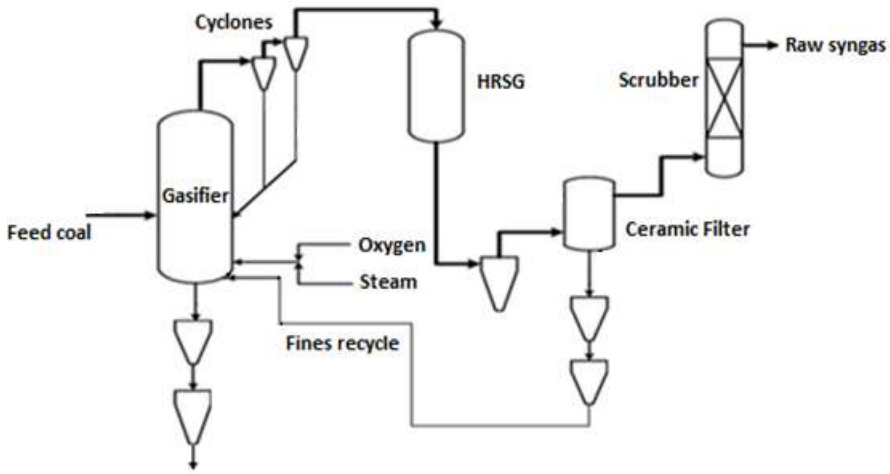
- Wide feedstock flexibility including the ability to handle multiple feed types, such as the lowest quality coals and coal wastes, biomass and MSW;
- Ability to change and manage feedstocks during operation;
- Ability to produce energy from synthesis gas (syngas) significantly cheaper than locally available oil and LNG;
- Lower capital costs than previous generations of gasification;
- Efficient extraction of energy from the feedstock (indicative of higher cold gas efficiency);
- Lowest possible water usage and minimal environmental impact, and
- Ability to modularize equipment, allowing for the quick deployment of distributed scale solutions, to reduce infrastructure requirements and feed/product transportations costs.

SGT is able to convert an industry-leading wide range of solid feedstocks, including the full range of types and qualities of coal and coal waste, biomass and MSW into syngas, which is then used to create end products such as power, industrial fuel gas, substitute natural gas (SNG), chemicals, ammonia for fertilizer, liquid fuels, and Direct Reduced Iron (DRI) for steel production. Many of these products may be co- or poly-generated from the same syngas source leading to optimized project economics.

Global gasification technologies are selected for projects primarily by comparison of the cost to generate syngas. Other selection criteria include capital cost, environmental impact, performance and availability risk, operability, and feedstock flexibility. This report evaluates SGT against other technologies with respect to these criteria. This evaluation considers:

1) **SGT** – enhanced fluidized bed technology;
2) **High Temperature Slurry Feed**, entrained flow – e.g. GE, E-Gas;
3) **High Temperature Dry Feed,** entrained flow – e.g. Siemens or Shell;
4) **Simple Fluidized Bed** – e.g. Ende/High Temperature Winkler;
5) **Moving Bed** – e.g. Lurgi and its derivatives, and
6) Much older generation Fixed Bed technologies which are very similar to Moving Bed types, but typically lower in pressure.

Typical SGT Process Arrangement



Syngas Production Cost

The cost of syngas from gasification is differentiated among technologies by the cost of feedstock, capital cost recovery, and power consumption. Staffing costs are similar among all technologies.

Feedstock Cost

As with any natural resource, the price of coal is highly dependent on its quality, measured by heating value per ton and ash/sulfur content. Coal reserves in India, for example, typically exhibit high ash and low heating values. As with any commodity, the price is also tied to the supply and demand. Historic and current coal utilization has been heavily weighted towards the higher and medium quality coals, leading to lower availability of these coals, compared to the vast availability of lower rank coals. This is increasing the price differential beyond the quality impact. In addition, there are significant coal resources that are not currently classified as reserves because there were no prior technologies (gasification or coal combustion) that could process these coals economically. SGT can open up these previously untapped coal resources.

Carbon conversion alone, while still important, does not provide a complete picture of feedstock utilization. The critical measure for economics is the cold gas efficiency (CGE), which is the amount of the coal energy that is converted to useful syngas (H_2+CO+CH_4) versus CO_2 and byproducts. High Temperature technologies inherently have a CGE penalty because they require more heat than the others to maintain the high gasification reaction temperatures. High Temperature Slurry Feed technology has an additional CGE penalty due to the significant energy used to evaporate the water in the slurry. Low CGEs drive low capital and operating costs. As the coal quality becomes lower, with higher ash and moisture content, the CGE penalties for these technologies, as compared to SGT, become prohibitively large. SGT has demonstrated the highest cold gas efficiencies in the industry, with CGEs up to 85% on high quality coals and minimal CGE penalty for lower quality coals, thus allowing SGT to offer superior economics for projects that desire to gasify lower cost, lower quality coals.

Carbon conversion is also very important. Low carbon conversion has an impact on CGE but, more importantly, results in higher carbon levels in the ash/slag byproduct produced from gasification. This will be discussed in more detail in the Environmental Impacts section of this document.

SGT Delivers World-Class Carbon Conversion on Challenging Coals

Plant	Coal	Conversion
ZZ	20% ash, 12% moisture, Lignite, no FMS	96%
ZZ	27% ash, 2% moisture, SubBit, FMS	>98%
ZZ	38% ash, 5% moisture, Bit, FMS	>98%
ZZ	12% ash, 5% moisture, SubBit, FMS	>99%

SGT is often confused with Simple Fluidized Bed technologies that achieve significantly lower carbon conversion. This is because the simple fluidized bed reactor lacks the sophisticated design enhancements used by SGT, and therefore leaves a significant amount of carbon in the ash/char. In addition to the challenges with ash disposal, approximately 10% higher coal consumption is required for these technologies compared to SGT, to be able to maintain reactor production rates. Furthermore, Simple Fluidized Bed technologies are limited to using highly reactive coals, or their conversion drops even further.

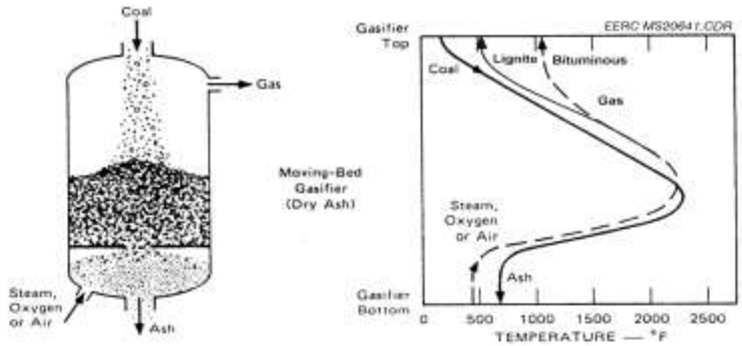
This is in fact the compelling breakthrough for advanced SGT versus other gasification technologies, which has occurred as a result of three decades of research and development and large-scale pilot operations on U-GAS®, the technology on which SGT is built upon, at the Gas Technology Institute in Chicago, and through the continuing technology enhancements including fines recycle system improvements and further ash discharge refinements developed and demonstrated at SES's Zao Zhuang New Gas Company Joint Venture (ZZ) facility and SES's Yima Joint Venture Plant (Yima).

Simply put, SGT has a compelling coal consumption advantage compared to:

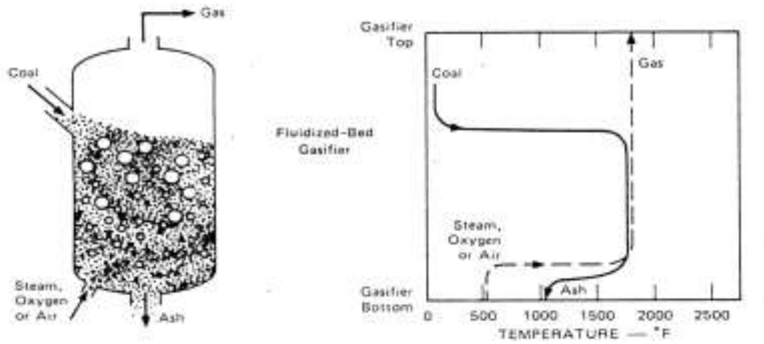
- Simple Fluidized Bed technologies – due to carbon conversion limitations;
- High Temperature Slurry Feed technologies – due to both conversion and the CGE penalty due to water vaporization and high temperature syngas and ash production, and
- High Temperature Dry Feed technologies – due to the CGE penalty due to high temperature syngas and ash production.

Source: NETL Gasifipedia, www.netl.doe.gov

Moving/Fixed Bed

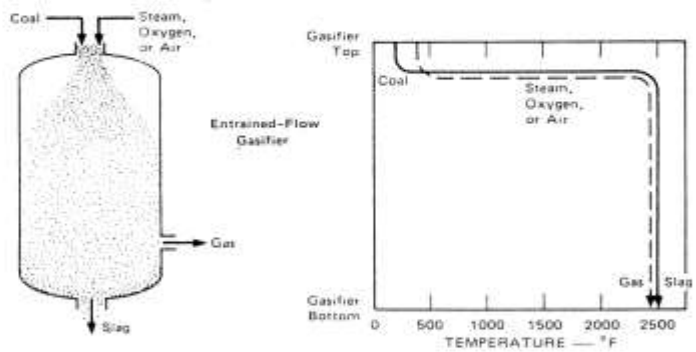


Simple Fluidized Bed

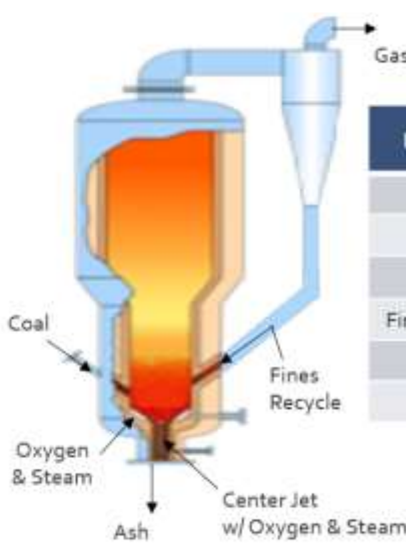


Entrained

High Temperature Dry and Slurry Feed



SES Gasification Technology (SGT)



Materials	Input Temp.	Output Temp.
Coal	25°C	-
Oxygen	150°C	-
Steam	350°C	350°C
Fines Recycle	1000°C	1000°C
Ash	-	150-350°C
Syngas	-	1000°C

Power Cost

A major use of power in gasification is in the air separation unit, the unit that generates purified oxygen from ambient air. At a given pressure the amount of power consumption is directly proportional to the amount of oxygen consumption. Oxygen consumption per unit of syngas is similar for SGT, Moving Bed, Fixed Bed, and Simple Fluidized Bed technologies, and higher for High Temperature Dry Feed gasification due to the oxygen used to heat the syngas and ash to the higher gasifier temperatures. Oxygen consumption is the highest for High Temperature Slurry Feed technologies. For low quality coals, the amount of oxygen consumption increases dramatically for all the High Temperature technologies.

Another large utilization of power is for the compression of syngas as needed for the end product requirements. This can be achieved by raising the pressure of the gasifier and generating the syngas at elevated pressure, compressing the syngas, or both. Since the volume of the syngas generated from gasification is always much larger than the volume of oxygen consumed, less power is used for technologies that can operate the gasifiers at higher pressure. Therefore, the low pressure Simple Fluidized Bed and Fixed Bed technologies, commonly deployed in China, are severely penalized on power cost projects requiring syngas at a higher pressure. For example, to achieve a syngas product at 30 bar using 30 bar gasification versus 2 bar gasification, the power saved is approximately 0.2 kWh/Nm3.[1] With a power cost of 0.10 USD/kW-hr (0.6 yuan/kW-hr) and a plant capacity of 100,000 Nm3/hr, this alone can amount to a difference of approximately $16 million/yr, (approximately 104 million yuan/yr). The annual savings will continue to increase for syngas needed at higher pressures. SES is offering SGT technology up to a pressure of 55 bar.

Power costs present a strong disadvantage to low pressure Simple Fluidized Bed technologies for those applications that use syngas at high pressure (power, SNG, chemicals, ammonia, liquid fuels), and penalize all High Temperature technologies, especially for low quality coals.

Capital Cost

The capital cost advantage for SGT is decisive versus Moving Bed due to the extensive amount of equipment required for processing the Moving Bed by-product tars, oils, napthalenes and phenols, as well as the more complex gasifier internals.

High Temperature Dry Feed and High Temperature Slurry Feed gasifiers have higher capital cost than SGT due to the more severe service conditions (1600°C syngas for Dry Feed High Temperature gasifiers versus 1000°C for SGT's non-slagging fluidized bed) for the gasifier and the syngas cooler, used to cool the syngas leaving the gasifier and to generate high pressure steam. Some High Temperature Slurry Feed technologies use a quench system to reduce cost by eliminating the Syngas Cooler and can achieve capital costs comparable to SGT for large plants and higher quality coal (4400 kcal/kg+), but the quench system significantly increases the environmental impact due to increased wastewater generation, and the lost production of high pressure steam from the syngas cooler is a substantial economic penalty for

---

[1] SES Internal Calculation – based on the power required for 2 bar SGT gasification with syngas compression to 30 bar vs. 30 bar SGT gasification.

larger projects. The quench technology does not meet minimum efficiency requirements recently employed in China for the production of chemicals and SNG.

Combining these factors, the relative syngas production costs for the most cost-effective technologies have been compared. Because SGT is advantaged on coal consumption, advantaged on power cost, and advantaged on capital cost, the total cost of SGT syngas can be as low as 15-20% less than that of the competing technologies on a given coal.[2] What is more difficult to quantify, but is very important, is the impact on "long term" cost of syngas. Over the 20-30 year typical life of a project, many occurrences can impact the price and availability of the original design feedstock. SGT's technology has superior feedstock flexibility (discussed in more detail in a later section), and can adapt to these changes by being able to switch feedstocks during the life of a project to consistently maintain low feedstock cost. This unique fuel flexibility capability will result in a much lower "long term" cost of syngas over the life of the project than can be achieved by other technologies.

Environmental Impacts

SGT and High Temperature technologies have high carbon conversions which allow the ash to be sold into cement and local construction material markets. They also generate no other measurable byproducts, such as tars and oil. Therefore, the overall environmental impact is low. As previously noted, some High Temperature technologies use water quench of the gas to reduce capital cost, increasing their environmental discharges.

Simple Fluidized Bed technologies commonly use water scrubbing for removal of fine ash, and thus generate more wastewater and consume more water. Simple Fluidized Bed technologies operate at 85-91% carbon conversion depending on the coal feedstock, and the resulting ash cannot be used for construction or cement markets. Sales of the ash into typical markets require high conversion, especially for high ash coals, where the ash content in the feed can exceed the carbon content. If the material cannot be sold, it will require landfilling. Some technologies contact the ash byproducts with water as they are being removed. This results in increased volume of discharge and additional challenges with useful disposition of these byproducts.

Due to the generation of tars, oils, napthalenes, and water soluble components such as phenols, and the water quench of the hot gas, Fixed Bed and Moving Bed technologies cannot use syngas coolers on the hot syngas exiting the gasifier. Therefore, energy utilization is low while water consumption and wastewater generation, emissions, and related capital cost for processing and treatment of the by-products are very high. This has recently become a very negative attribute for Moving Bed technologies in the marketplace.

[2] SES Internal Calculation – based on internal knowledge of SGT and publicly available information on other gasification technologies (multiple sources).

Performance and Availability Risk

High Temperature and Moving Bed gasification technologies have significantly greater severe operating conditions. These technologies are part of the older previous generation of gasification and have a large number of installations. Therefore the reliability is well understood and incorporates years of lessons learned. Simple fluidized beds have not been widely commercialized due to their overall poor carbon conversion and high coal consumption. However, they do operate at milder conditions which are less severe on equipment. Similarly SGT has much milder service conditions, is simple, and theoretical reliability is expected to be class-leading as compared to older generations of High Temperature and Moving Bed technologies. This performance advantage will become even more apparent as SGT continues to increase its installed base operating record, now with 12 SGT systems on the ground in China. Further, SES has presented the operating data from ZZ. Although that plant's operations had been constrained by the adjacent methanol plant's poor reliability, the actual ZZ data, when analyzed, clearly supports the expectation of high reliability from SGT. While the ZZ plant has gone through periods of non-operation due to commercial challenges with offtake customers and methanol pricing during an extended period in 2011, ZZ was essentially 100% reliable, providing syngas at all times that the downstream customer was demanding it.

In March 2016, Yima successfully concluded the performance guarantee testing. All aspects of syngas quality, feed consumption and other metrics were passed. SES continues to gather lessons learned from the site, applying continuous improvements and assisting the plant with minor equipment upgrades. SES's joint venture project at Yima has had some early reliability challenges, primarily due to significant deviations from SGT design recommendations and purchase of low quality equipment. Recent improvements in Yima are showing significant improvements in reliability and SES anticipates this to continue to improve over time. Both projects have data which show achievement of single SGT gasifier runs in excess of 90 days. Detailed analysis of this data also shows the outages in both plants have been mostly due to equipment outside, not directly related to the gasifier itself.

The operation of ZZ and Yima have generated many lessons learned. SES has taken the results of these lessons learned and driven improvements into SGT designs that are expected to dramatically improve the reliability of SGT's future projects. In fact, Yima and all new projects are already benefitting from these lessons learned.

SGT HRSGs have significantly lower inlet temperatures than those for High Temperature gasifiers and, when constructed to specification, are more reliable and far less expensive.

Further, the significantly lower capital cost for SGT allows for inclusion of a spare gasifier train for projects of any scale and thus achieves world-class availabilities of greater than 98%.

Operability

Severe service conditions, low reactor inventory, and short residence time make the control requirements for High Temperature technologies demanding and complex. Moving Bed Technologies require stricter controls for management of gas velocities and solid flow than do fluid beds. Due to inventory of well-mixed solids inside the fluid bed reactors, the operating range and simplicity of controls for fluid beds is greatest among all gasifier technologies.

ZZ has run lignites, high ash, low volatile sub bituminous coal, local sub bituminous coals and coal wastes, and long flame bituminous and sub bituminous coals all in the same equipment and at rates from 30% to 100% of capacity. The plant has even transitioned during operation from its normal local coals to test coals while running – by simply changing the coal feed into the coal feed hoppers.

Feedstock Flexibility

As discussed previously, feedstock flexibility can be an extremely important factor in the "long term" cost of syngas over the life of a project. Many gasification technologies claim to have wide feedstock flexibility. What they are often referring to is their ability to design their facilities over a wide range of feedstocks. What is much more important is the flexibility to operate a plant that has been constructed over a wide range of feedstocks. No gasification technology has demonstrated the wide range of post-construction feedstock that SES has demonstrated in the Yima and ZZ commercial operating facilities.

ZZ has run a wide range of coals, in addition to local Shandong coals and coal wastes, under commercial conditions. For SGT as a whole the range of tested coals is unique among gasification technologies.

	Tested Result Range by SGT Site		
Coal Characteristic	**ZZ**	**Yima**	**SGT Total** (including Pilot Plants)
Ash Content (wt %)	10 - 55	19 - 52	1 - 55
Moisture Content (wt %)	4 - 43	1 - 10	1 - 43
Volatile Matter (wt %)	12 - 40	20 - 30	3 - 69
Fixed Carbon (wt %)	24 - 66	22 - 38	6 - 83
Sulfur (wt %)	0.6 - 4.0	0.2 - 2.0	0.2 - 4.6
Ash Softening Temperature (degC)	1,112 - 1,450	1,277 - 1,488	1,040 - 1,460+
Heating Value (kcal/kg)	3,100 - 6,100	2,625 - 5,076	3,050 - 7,700

Due to the high degree of mixing of the solids and the reactor inventory, SGT is far more flexible with respect to a wide variety of coals than are High Temperature, Fixed Bed, and Moving Bed technologies. The SGT feedstock flexibility allows the widest deployment across all regions and coal types, permitting the lowest cost, locally sourced feedstock available in any region. In addition, the ability to use different coals in an existing SGT plant allows unparalleled supplier flexibility for the project once built, leading to significant lifecycle cost savings.

Conclusion

SGT offers a compelling cost advantage, by far the greatest range of feasible and economic feedstocks, low environmental impacts, and the flexibility to use different feeds even after construction which has significant cost benefits over the life of the project. The low water consumption and low capital requirements for SGT are particularly critical in the coal resource-rich yet natural gas-poor developing economies of the world where there is anticipated to be large demand for new, clean energy production.

There is a unique opportunity to leverage the SGT capabilities to grow significant value through the entire value chain of gasification. This will include coal resources, mining and technology, turnkey global EPC, technology licensing, equipment sales and O&M services. In addition, SES plans to capture maximum value by participating in the projects themselves – developing and investing in projects with strong financial strength and selling these projects for attractive multiples on earnings, repeating this cycle for growth.

Synthesis Energy Systems, Inc. | www.synthesisenergy.com