Emerging Gasification Technologies for Waste & Biomass

IEA Bioenergy: Task 33

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ABSTRACT

Gasification is a flexible thermal conversion process with wide-ranging applications in sectors such as heat and power generation, transport fuel and chemicals production. In this report, a methodological framework for assessing the technology readiness of emerging gasification technologies is presented and applied to a selection of ten candidates, chosen to indicate the diversity of technical solutions breaking into the waste and biomass gasification market. The examined technologies are broken down into standardized components, which are assigned a technology readiness level score following established guidelines developed for the purpose. Information is collected for various publicly available sources and used as far as possible to identify process configuration and compile process profiles based on a standard template. Particular attention is paid to technology demonstration as an integrated whole. Scores for individual components are weighed and aggregated to compute a weighted average overall TRL score, which is contrasted with the score for the weakest individual component.

The amount and quality of information publicly available for each evaluation varied greatly between technologies, but from experience, comprehensive structured questionnaires for technology developers face similar limitations in terms of the quality of response.

Identifying the lowest scoring component, i.e., the “weakest link” can show where future development may need to be focused and is considered a good complement to a weighted average score. The use of TRL scoring ranges is recommended in instances where granularity in scoring can be misleading, such as when the evidence available is of a generalized nature. The asymmetry in data and evidence between the different technologies are accounted for in the assignment of scores and weightings to some extent, but care is advised when interpreting the scores. Experience indicates that even commercially available equipment, which it is sometimes argued can be awarded a TRL score of 9 in an emerging configuration requires time and effort for successful integration novel streams in new process environments. This aspect has been incorporated in the methodological framework and is reflected in the scores for some of the examined technology components.

Despite the difficulties in fairly and systematically assessing and comparing technologies from incomplete data, the methodology provided has been successfully applied. It is hoped that this first attempt at a methodological framework for the assessment of emerging gasification technologies can, after further refinements, be more generally used within IEA Bioenergy Agreement Task 33 for similar exercises. One future activity could be the development of a standardized data sheet for technology assessment. Another would be to develop some form of formal guidance on the assignment of weighting for different process units.

EXECUTIVE SUMMARY

The International Energy Agency's Bioenergy Program Task 33 on Gasification of Biomass and Waste is a working group of international experts with the aim of promoting the commercialization of efficient, economically, and environmentally preferable thermal biomass gasification processes.

Gasification is a thermal conversion process with wide-ranging applications in sectors such as heat and power generation, transport, and chemical manufacturing. Several biomass and waste gasification technologies are already well established, but as the field expands and evolves, others continue to emerge on the market.

The scope of the present report focuses on the less established, i.e., "emerging" technologies. The objectives are two-fold: (i) make a first attempt at providing a methodological framework for assessing the technology readiness of emerging gasification technologies that, after further refinements, could also be applied to technologies in other fields, (ii) technically describe, characterize, and evaluate a selection of emerging gasification technologies using the provided framework.

Table 1. Tabular format used for the presentation of technology readiness assessment results.

Step	TRL	Weight	Comments
Feedstock handling system	1-9	10-50 %	TRL scores between 1 and 9. Weights between 10% and 50%.
Gasification reactor with heat supply	1-9	10-50%	TRL scores between 1 and 9. Weights between 10% and 50%.
Product gas separation and cleaning	1-9	10-50%	TRL scores between 1 and 9. Weights between 10% and 50%.
Integrated operation	1-9	10-50%	TRL scores between 1 and 9. Weights between 10% and 50%.
Overall "Weighted Average"	1-9		Weighted average of all individual component scores
Overall "Weakest Link"	1-9		Component with the lowest TRL

In the framework developed for assessing the technology readiness of emerging gasification technologies, the technology under review is represented as an assembly of three essential components (also referred to as steps in the text), each of which is composed of several sub-components:

- A feedstock handling system encompassing feedstock preparation (e.g., drying, size reduction) and feeding;
- A gasification reactor with heat supply; *and*
- A product gas separation and cleaning setup.

Each component is assessed and assigned a TRL score with the aid of definitions from the European Union Horizon 2020 program and the United States Department of Energy Clean Coal Program. The overall score for the technology is determined from the component scores using two complementary approaches: (a) the weighted average approach, (b) the weakest link approach, adapted from [1].

In the weighted average approach, each of the components is assessed for importance and given a weight, which is used to compute a weighted average TRL score. In the weakest link approach, the entire technology is assigned the TRL of the lowest scoring component to account for the possibility that some key components and sub-components may be significantly lagging in development compared to others. The integrated operation, i.e. the demonstration of all parts of the process configuration in an integrated assembly is treated as an independent, separate step. The results of the assessment are provided in tabular form following the structure presented in Table 1.

An initial list of emerging gasification technologies was put together for screening through consultations with subject matter experts, surveys of IEA Task 33 reports, examinations of pertinent conference programs and searches on Google Scholar. Ten examples that indicate the diversity of technical solutions breaking into the waste and biomass gasification market are chosen for closer examination based on publicly available information.

Table 2. Emerging gasification technologies chosen for detailed technology readiness assessments

Technology	Developer	Developer origin	Gasification Technology
Advanced Biomass Gasification Technology	Renergi Pty Ltd.	Australia	Two-stage gasification with integrated catalytic hot gas cleaning
Endeavour Microwave Gasification	Endeavour Energia S. r. l.	Italy	Microwave-assisted ‘Imbert-type’
Heliostorm Gasifier	Cogent Energy Systems	United States of America	Ionic gasification

Technology	Developer	Developer origin	Gasification Technology
MIHG Technology	Wildfire Energy	Australia	Moving injection fixed bed
MEVA Technology	MEVA Energy AB	Sweden	Entrained-flow cyclone gasification
MFC Technology	RWE Power AG	Germany	Entrained-flow gasification
Plasco Gasification & Plasma Refining System	Plasco Conversion Technologies	Canada	Plasma (tar) gasification
RadGas Technology	Advanced Biofuel Solutions Ltd.	United Kingdom	Fluidized-bed gasification
Rotary Gasification	SUNY Cobleskill/Caribo u Biofuels	United States of America	Inclined rotary gasification
TreaTech Hydrothermal Gasification System	TreaTech SARL	Switzerland	Hydrothermal Gasification

The closer examination is intended to elucidate the heterogeneity in emergent configurations and applications as well as draw attention to features that are likely to require additional development attention. In addition to the technology readiness assessment, a technology profile with information on the following aspects has been compiled: technology developer/promotor, feeding system, oxidant, gasification method, principal feedstock(s), principal application(s), intended scale and development status.

The amount and quality of information publicly available for each evaluation varies greatly between technologies. Ideally, evaluations would be based on developer answers to comprehensive structured questionnaires, but experience indicates that such an approach will also face the same limitations in the quality of responses as the use of public information.

In assigning weights to the technical solutions for individual steps, consideration is given not only to how they compare against each other but also to how they measure up against equivalent steps in other gasification technologies. Identifying the lowest scoring component, i.e., the “weakest link” can show where future development may need to be focused and is considered a good complement to a weighted average score. The use of TRL scoring ranges I is recommended in instances where granularity in scoring can be misleading, such as when the evidence available is of a generalized nature.

The asymmetry in data and evidence between the different technologies is accounted for in the assignment of scores and weightings to some extent but care is advised when interpreting the scores. Granularity in scoring does not necessarily make the scores more accurate as an element of subjective judgement is inevitably involved and which increases in subjectivity with increasing gradations.

An aspect of the scoring that can crop up often is when a developer claims that a step does not require validation with the relevant process feeds and can be awarded a TRL score of 9 due to the availability of commercial equipment. This would imply that the equipment has been used under very similar operating conditions and capacity as well as entry and exit process stream quality and specifications. Experience indicates that even commercially available equipment requires time and effort for successful integration of novel streams in new process environments. This aspect has been incorporated in the methodological framework and is reflected in the scores for some of the examined technology components.

Since the examined technology sample consists of ten – rather diverse – technologies and was primarily intended to exemplify and illustrate the method, the evaluation cannot be used to draw long-reaching conclusions. It is worth noting that a comparison where the commercial capacity goal varies from very small scale (on the order of 100’s of thermal kW) to a significantly larger scale (on the order of tens of thermal MWs) is biased in favor of smaller-scale technologies. When comparing technologies based on the TRL, similar capacity ranges would give a more like-for-like comparison.

Two of the ten technologies have the ambition of the recovery nutrients from sludge. Sludge gasification, while also having undergone development in the past to some limited extent, has typically not been in the focus of gasification developers as the feed is, by gasification standards very high in both moisture and ash, thereby limiting the efficiency and gas heating value. But nutrient recovery can be a new demand on sludge systems that may work in the favor of gasification.

Despite the difficulties in fairly and systematically assessing and comparing technologies from incomplete data, the methodology provided has been successfully applied. It is hoped that the exercise provides useful information and can guide others who are charged with the task of evaluating the development of gasifier technologies. As this is a first attempt within the IEA Bioenergy Agreement Task 33 group to establish a formal evaluation framework, there is definitely room for further iterations as well as significant methodological improvements.

List of Abbreviations

Abbreviation	
TRL	Technology Readiness Level
SNG	Synthetic Natural Gas
CHP	Combined Heat & Power
LCV	Low Calorific Value
RED	Renewable Energy Directive
GoBiGas	Gothenburg Biomass Gasification Project
EUP	Ebara Ube Process
FT	Fischer-Tropsch
RDF	Refuse-derived Fuel
RFS	Renewable Fuel Standard
GHG	Greenhouse Gas
SBIR	Small Business Innovation Research

Introduction

The International Energy Agency's (IEA) Bioenergy Program Task 33 on Gasification of Biomass and Waste is a working group of international experts with the aim to promote the commercialization of efficient, economically, and environmentally preferable thermal biomass gasification processes.

The field of biomass and waste gasification is experiencing a structural transformation [2]. In the wake of mounting climate awareness, a global transition to renewable energy sources is taking form. Research and policy interest in efficient resource utilization continues to grow with biogenic carbon becoming a more valuable commodity. Against this backdrop, opportunities open for new gasification technologies that can upgrade low-value biomass and waste streams to higher value-added products.

Gasification is a thermal conversion process that offers excellent feedstock and product flexibilities. Present and potential applications are wide-ranging. Small-scale heat and power generation is an established commercial sector, bulk production of transport fuels remains a promising option, and grid balancing has engendered considerable scholarly interest among newer fields [3].

Several more or less already established biomass gasification technologies are listed in the chapter on the state-of-the-art of gasification. However, the scope of the report targets some of the less-well-established, i.e., "emerging" technologies and an attempt is made to devise a methodological approach for a reasonable and consistent evaluation of the development status of such technologies.

This report is based on research undertaken for IEA Bioenergy Program Task 33 in the 2019-2021 triennium. Task 33 monitors the current status of the critical unit operations and unit processes that constitute biomass and waste gasification. This report is aimed at the technology developers, industrial end users and researchers, as well as the policy makers and the members of the general public interested in following the technical development and commercialization status of emerging gasification technologies.

REPORT OUTLINE

Chapter 1 provides a short background on gasification, lays out the objective and the scope of the report and defines "gasification technology" and "emergence" in the context of biomass and waste gasification.

Chapter 2 presents the methodology and describes how the biomass and waste gasification technologies examined in this work are characterized and evaluated with the aid of technology readiness level (TRL) scores.

Chapter 3 gives a brief overview of the current state-of-the-art in biomass and waste gasification.

Chapter 4 examines in closer detail the technical features, development trajectory and technology readiness of a selected sample of ten gasification technologies in various stages of market emergence.

Chapter 5 discusses and summarizes the principal findings of the study.

OBJECTIVES AND SCOPE

The objective of this report is twofold:

- To make a first attempt at providing a methodological framework for the assessment of emerging gasification technologies that, after further refinements, can be more generally used within IEA Bioenergy Agreement Task 33 for similar exercises in the future;
- To technically describe, characterize and examine a selection of emerging technologies in the area of biomass and waste gasification using the developed framework.

The term "emerging technologies" in the scope and context of this report is relative to the state-of-the-art of gasification of biomass and wastes. The state-of-the-art of gasification of biomass and wastes includes large number of different developers and technologies that are or have been in use at commercial scale (which could be both small and large capacities, depending on the application and market) or in development stages where the commercial scale can be realistically aimed for. It is covered briefly in the next chapter as an orientation. The scope is instead focused on the "emerging technologies", i.e., technologies that are novel or have different characteristics than the state-of-the-art technologies. However, there are numerous biomass and waste gasification technologies breaking out on the market worldwide. A comprehensive annotation and evaluation of these is outside the scope of the present report. Instead, ten examples of "emerging technologies" that indicate the diversity of technical solutions breaking into the waste and biomass gasification market are chosen for closer examination. Other examples of such technologies not selected for a closer examination are (non-exhaustively) listed in the chapter on Other Emerging Technologies.

The closer examination is intended to elucidate the heterogeneity in emergent configurations and applications as well as draw attention to features that are likely to require additional development attention. The question then arises as to how such technologies can be evaluated in a consistent manner. The intention of this work is therefore also to try to develop a more or less general methodology that can be used for such an evaluation and also be refined and further developed for use in other technology fields.

CONCEPT DEFINITIONS

In order to select an appropriate method for closer evaluation, it is necessary to more closely define "gasification technology" and "emergence" in the context of biomass and waste gasification.

A gasification technology can be represented as an assembly of three essential components, each of which is composed of several sub-components:

- A feedstock handling system encompassing feedstock preparation (e.g. drying, size reduction) and feeding;
- A gasification reactor with heat supply; *and*
- A product gas separation and cleaning setup.

The design and arrangement of the components in a gasification technology is to a great extent feedstock and application dependent. In this report, a gasification technology is defined as a gasification system that contains all three of the abovementioned essential components and that has an integrated process configuration deemed to be original in character, with originality being established based on a qualitative evaluation.

As the gas produced and the extent of the gas cleaning and upgrading typically can be used in different applications such as fuel gas for boilers, furnaces and kilns or for use in prime movers such as internal combustion engines and gas turbines as well as for chemical synthesis or extraction of gaseous energy carriers like methane (SNG) and hydrogen with some adjustments to operation of the gasifier operation (oxidant used etc.), the application itself is not part of the assessment. Instead, the status of the operation with all the above parts in an integrated manner, depending on the case also possibly but not necessarily including the end use, was selected.

The conceptualization of what constitutes an emerging technology and how technology emergence should be measured differs greatly between actors [4]. The lack of a common framework implies that attempts at evaluating emergence are typically ad-hoc in nature and built around methods specific to sector and application. Efforts have previously been made by various researchers to develop more systematic frameworks for evaluating technology emergence using methodological approaches that can, for the sake of simplicity, be grouped into three categories: scientiometric, econometric and qualitative [5].

Scientiometric approaches measure technology emergence based on data gathered from the scientific literature. Scientiometric methods are unsuited to the assessment of emergence of commercially oriented gasification technologies as information is likely to be disseminated through webpages, conference material and magazines rather than through scientific literature. Econometric approaches measure technology emergence on the basis of economic or financial data, which can be challenging to obtain in certain jurisdictions and for less developed technologies, or simply because such information is not disclosed for commercial reasons. Even when available, econometric data is typically difficult to extrapolate to the general case as it represents vendor estimates for just a few (one or two typically) installations or based on studies that often have very case-specific features. Qualitative approaches measure technology emergence by qualitatively interpreting diverse indicators that are linked to different attributes of emergence, e.g. the TRL scale, market readiness, manufacturing readiness and financial readiness. As an example, a commonly cited attribute such as radical novelty can be adjudged by comparatively reviewing process configurations, intended applications and the language used in promotional literature. Growth can be approximated by the pace of lab-scale, pilot-scale or commercial development and deployment.

This report assesses biomass and waste gasification technologies using a qualitative approach centered around the use of technology readiness level scores. A waste or biomass gasification technology is defined as emerging if it meets both of the following criteria:

- It is being promoted by either a commercial vendor or an institution
- Public information indicating continuing development is available through news releases or developer updates made in the last two years

Methodology

An initial list of emerging technologies consistent with the scope of the study was put together for screening through consultations with subject matter experts, surveys of IEA Task 33 reports, examinations of pertinent conference programs and searches on Google Scholar using various combinations of search terms including, but not limited to, "biomass gasification", "co-generation", "small-scale CHP", "synthesis gas", "syngas", "plasma gasification", "hydrothermal gasification", "supercritical gasification", "waste gasification". Technologies on the initial list were appraised for emergent attributes, with a particular focus on novelty of technical configuration and/or intended application, data availability and geographical diversity, and ten were taken forward for detailed characterization and assessment of technology readiness based on publicly available information. Developers of the examined technologies were provided with the completed assessments and given an opportunity to comment. Salient points in the resulting feedback are provided in the pertinent technology profiles.

TECHNOLOGY CHARACTERIZATION

For each technology for which the readiness level was examined, a profile with information on the following aspects has been compiled: technology developer/promotor, feeding system, oxidant, gasification method, principal feedstock(s), principle application(s), intended scale (in kg/h or metric tons/h) and development status.

TECHNOLOGY READINESS

Technology readiness was assessed with the help of TRL definitions from the European Union Horizon 2020 program and the United States Department of Energy Clean Coal Program; see the boxes below.

European Union Horizon 2020 TRL scale [9]

TRL 1 – basic principles observed

TRL 2 – technology concept formulated

TRL 3 – experimental proof of concept

TRL 4 – technology validated in lab

TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – system prototype demonstration in operational environment

TRL 8 – system complete and qualified

TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Each of the components in an examined gasification technology was assessed and assigned a TRL score. The overall score for the technology is determined from the component scores using two complementary approaches: (a) the weighted average approach, (b) the weakest link approach, which are adapted from [1]. In the weighted average approach, each of the components in the examined gasification technology were assessed for importance and given a weight, which was used to compute a weighted average TRL score. In the weakest link approach, the entire technology was assigned the TRL of the lowest scoring component to account for the possibility that some key components and sub-components may be significantly lagging in development compared to others.

US DOE Fossil Energy Clean Coal Program TRL Scale [10]

TRL 1 – basic principles observed

Lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples include paper studies of a technology's basic properties.

TRL 2 – technology concept formulated

Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.

TRL 3 – experimental proof of concept

Active R&D is initiated. This includes analytical and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology (e.g., individual technology components have undergone laboratory-scale testing using bottled gases to simulate major flue gas species).

TRL 4 – technology validated in lab

A bench-scale prototype has been developed and validated in the laboratory environment. Prototype is defined as less than 5 percent final scale (e.g., complete technology process has undergone bench-scale testing using synthetic flue gas composition).

TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

The basic technological components are integrated so that the system configuration is like (matches) the final application in almost all respects. Prototype is defined as less than 5 percent final scale (e.g., complete technology has undergone bench-scale testing using actual flue gas composition)

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

Engineering-scale models or prototypes are tested in a relevant environment. Pilot or process-development-unit scale is defined as being between 0 and 5 percent final scale (e.g., complete technology has undergone small pilot-scale testing using actual flue gas composition).

TRL 7 – system prototype demonstration in operational environment

This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Final design is virtually complete. Pilot or process-development-unit demonstration of a 5–25 percent final scale (e.g., complete technology has undergone large pilot-scale testing using actual flue gas composition).

TRL 8 – system complete and qualified

The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development (e.g., complete and fully integrated technology has been initiated at full-scale demonstration including start-up, testing, and evaluation of the system using actual flue gas composition).

TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

The technology is in its final form and operated under the full range of operating conditions (e.g., complete and fully integrated technology has undergone full scale demonstration testing using actual flue gas composition).

Up-to-date process configurations were put together for all the examined technology from publicly accessible sources, such as company websites, patents, journal articles, and reports on demonstration projects and from other sources of information made available by developers. Each process configuration was then split into smaller steps centered on one of the three essential components in a gasification assembly as defined in Concept Definitions, namely, a feedstock handling system encompassing feedstock preparation (e.g., drying, size reduction) and feeding a gasification reactor with heat supply, and a product gas separation and cleaning setup. Several unit processes were found to deploy commercially mature technologies that had either not been used for waste or biomass feedstocks before or had not been used in an integrated assembly. Hence, integrated operation was treated as a separate step.

Each step was assigned a weight based on its novelty, complexity, and its centrality to the overall process configuration. Depending on the clarity, quality, and availability of the relevant technical information, a TRL score was then awarded as either an individual number (e.g., 7) or as a range (e.g., 6-7). In the weighted average approach, the assignment of weights was based on the importance and complexity of each step. The weakest link approach simply used the lowest TRL among the major steps (weight>0.2). In assigning a TRL score to a given step, consideration was given to the novelty of its feed and technology combination. For instance, a step that comprised of a novel feed to a commercially proven technology was awarded a lower TRL score.

OTHER CRITERIA

It was neither possible within the scope of this work nor found meaningful to look at other criteria, although this becomes important when an emerging technology comes to realization, e.g., for the evaluation of economic or environmental performances. This was mainly because the relevant data was not available or, if some information was available, it was not possible to make a general assessment with reasonable effort. Often such information is project- or site specific and presented in such an aggregated form that a comparative analysis is not possible.

State-of-the-art of Gasification

Gasification of solid and liquid fuels, coals, pet coke and petroleum refinery residual hydrocarbons as well as biomass and waste to produce clean fuels, electricity and chemicals is largely a proven energy conversion technology. At present, in roughly 30 countries around the world, 686 gasifiers operating in 272 large-capacity plants have a synthesis gas generation capacity close to 200 GW_{th}, which is equivalent to roughly of almost 200 MW_{th} per gasifier installation [6] A further 74 plants with 238 gasifiers are under construction, adding another 83 GW_{th} of synthesis gas capacity. This is the result of a long-term effort; it has taken over 60 years of worldwide effort to reach this level of gasification production capacity.

The production of (liquid) chemicals and fuels amounts to around 160 GWh_{th}, gaseous fuels, predominantly synthetic natural gas, amount to just below 30 GWh_{th} and power generation amounts to around 10 GWh_{th}.

These impressive number illustrates the maturity as well as the potential of gasification technologies, even if the use of non-fossil feedstocks such as biomass and wastes is more limited and is generally consigned to units with a smaller capacity. In the database cited above, the number of installations using these feedstocks amounts to around 100 units, with a total capacity of some few GW_{th}.

STATE OF THE ART OF GASIFICATION OF BIOMASS AND WASTES

Although the technical viability of biomass gasification and the related environmental benefits are widely acknowledged, the extent of its commercial use has been mostly limited to CHP and district heating and a handful of co-firing applications, driven primarily by a combination of regional or local environmental, climate and economic considerations. To give an impression of the variety in terms of unit capacity, feedstock, technology and applications, a non-exhaustive list of gasification projects and developers, for applications such as CHP/power, fuel gas and advanced biofuels (hydrogen, bio-methane, methanol, ethanol, FT hydrocarbon liquids) is provided in Table 3.

There are literally thousands of small-to medium gasifiers with capacities in the range of 0.02-20 MW_{th}, generating power and CHP by feeding the LCV (low calorific value) or MCV (medium calorific value) gas produced to internal combustion engines. In Germany alone there are already more than 1 000 such units in operation. In addition, and notably in Japan and in the UK, there are also installations ranging from some few MW to tens of MW thermal that gasify wastes to improve the process characteristics and efficiency of conventional incinerator installations for power and CHP.

There are also some tens of stationary and circulating fluidized bed gasifiers at a scale of 10-140 MW_{th} that use various types of biomass residues and wastes to generate LCV product gas for use as a fuel to lime and cement kilns and for co-firing with coal in power plants. In Vaasa in Finland, about a third of the fuel capacity in a 500 MW_{th} peat-fired power plant comes from solid biomass, and in Lahti, a waste and solid biomass plant produces 50 MW_e and 100 MW_{th} district heat for the city.

In China, there are more than 20 installations where waste is used to partially fire cement kilns.

Until recently, the development of advanced processes and broader application of biomass gasification for synthesis gas has been impeded by competition from low-cost fossil fuels combined with policy uncertainty as well as insufficient incentives from policy interventions. This has resulted in an inadequate market pull that has not stimulated partnerships among developers, industry, and other value-chain stakeholders for the development and scale-up of bioenergy and waste conversion technologies. Progress towards industrial scales has therefore been slow for such technologies, e.g., for advanced biofuels based on gasification conversion technologies. There is typically a development sequence from laboratory to bench scale via pilot plant to a demonstration before reaching a first prototype, and where the two last steps in the sequence entails both technical and economic risks and overcoming these within the support and market systems in place has proven to be a bottleneck.

The period between 2010 and 2016 saw the initiation of many gasification-based biofuel project developments within the EU, stimulated by the renewable energy directive (RED) and peaking oil prices at the time. In the EU, except for Gothenburg Biomass Project (GoBiGas) phase 1, none of the projects were however realized, even those that received NER 300 funding. Furthermore, it can be noted that GoBiGas phase 1 was stopped in 2018 for economic reasons [7,8]. The motives for building the GoBiGas phase 1 plant was not its feasibility as a business venture on its own, the main driver was to gain the experience required to de-risk the five-fold scale-up in GoBiGas phase 2. But as this second phase of the project was cancelled in 2015, the motives for continued operation at an economic loss were no longer there.

In 2018, two waste gasification projects, both using the Enerkem technology, were announced in Rotterdam and Tarragona, respectively, but these are still in the planning and permitting stages. In addition, several project studies are being undertaken, but these are less developed than the planned projects. Also, worth mentioning is the project for waste-to-jet fuel project being undertaken by the Fischer-Tropsch (FT) technology company Velocys in the UK.

Table 3. Non-exhaustive list of advanced biofuels and major CHP gasification projects

Project(s)	Technology provider	Product	Feedstock	Country	Status
Various	Burkhardt	Small scale CHP	Wood wastes	Germany	Operational
Various	Spanner RE²	Small scale CHP	Wood wastes	Germany	Operational
Various	Syncraft	Small scale CHP	Woodchips	Austria	Operational

Project(s)	Technology provider	Product	Feedstock	Country	Status
Various	Urbas	Small scale CHP	Wood chips	Austria	Operational
Various	Glock Oekoenergie	Small scale CHP	Wood chips	Austria	Operational
Various	Hargassner	Small scale CHP	Wood chips, pellets	Austria	Operational
Various	Froeling	Small scale CHP	Wood chips, pellets	Austria	Operational
Innovative Environmental Solutions	Chinook	CHP	Autoshredder residues	UK	Operational
Refgas	Refgas system	CHP	Wood waste	UK	Operational
Güssing, Senden etc.	Aichernig Engineering *fka* Repotec	CHP	Forest residues	Austria, Germany	Decommissioned
Lahti	Valmet	CHP	SRF	Finland	Operational
Tees Valley 1 and 2	AlterNRG	Power	RDF	UK	Aborted in commissioning

Project(s)	Technology provider	Product	Feedstock	Country	Status
Various	Biomass Power	Power, CHP	RDF	UK	Operational
Various	Energos	Power, CHP	MSW, ISW	Norway, UK, Germany	Operational
Various	EQTEC	Power, CHP	RDF	UK, Germany	Operational
Villier sous montround	LLT	CHP	RDF	France	Operational
AMERGAS	Essent/Lurgi	Indirect co-firing	Waste wood	The Netherlands	Idling
Lahti	SHIFW	Indirect co-firing	Forest residues, wastes	Finland	Decommissioned
Vaasa	Valmet	Indirect co-firing	Forest residues	Finland	Operational
CEMEX Rüdersdorf	Envirotherm *fka* Lurgi	Fuel gas	SRF	Germany	Operational
ESKA Graphic Board	LLT	Fuel gas	Waste paper	The Netherlands	Operational

Project(s)	Technology provider	Product	Feedstock	Country	Status
Lime kiln gasifiers	Andritz	Fuel gas	Forest residues	Finland, China	Operational
Lime kiln gasifiers	Valmet	Fuel gas	Forest residues	Finland, China, Indonesia	Operational
Ajos BTL	Various (Siemens, Choren, Kaidi)	FT liquids	Forest residues	Finland	Cancelled
Bio2G	Andritz	Bio-methane	Forest residues	Sweden	Cancelled
Choren	Choren	FT liquids	Forest residues	Germany	Decommissioned 2011
Domsjö	Chemrec	Methanol	Brown liquor	Sweden	Cancelled
Waste to methanol	NextChem	Methanol, hydrogen	Wastes	Italy	Study
GoBiGas phase 1	Aichernig Engineering fka Repotec	Bio-methane	Forest residues	Sweden	Op. 2013-2018, idling
GoBiGas phase 2	Not decided	Bio-methane	Forest residues	Sweden	Cancelled

Project(s)	Technology provider	Product	Feedstock	Country	Status
GreenSky	Solena	FT liquids	RDF	UK	Cancelled
Immingham	TRI	FT liquids	Wastes	UK	Study
NSE	SHIFW	FT liquids	Forest residues	Finland	Cancelled
Rotterdam	Enerkem	Methanol	Wastes	Netherla nds	Planning
Rottneros	Chemrec	Methanol	Forest residues	Sweden	Cancelled
Tarragona	Enerkem	Methanol	Wastes	Spain	Announced
UPM Stracel BTL	Andritz	FT liquids	Forest residues	France	Cancelled
Vallvik	Chemrec	Methanol	Black liquor	Sweden	Cancelled
Woodspirit	Siemens	Methanol	Forest residues	The Netherla nds	Cancelled
NOTAR ® gasifiers	Xylowatt	CHP	Forest residues	Belgium	Operational
Movialsa	EQTEC plc [Ireland]	Power	RDF, MSW	Spain	Operational

Project(s)	Technology provider	Product	Feedstock	Country	Status
Värmlandsmetanol	TKI fka HTW	Methanol	Forest residues	Sweden	Planning
Various	Various	Small scale CHP, power	Forest and wood wastes	All continents, mainly Asia and Africa	Operational
Waste gasification	WTEC	CHP	MSW, ISW	USA	Operational
Waste gasification	Various (Nippon Steel, Ebara, JFE, IHI, Mitsui, Takuma, Kawasaki and others)	CHP, power	MSW, ISW	Japan	Operation, idling and decommissioning, depending on the site
Various	PRME	CHP, power, fuel gas	Various	USA, France, Italy, others	Operational
Various	Outotec	CHP, power, fuel gas	Forest and wood wastes	USA, Canada, UK	Operational
Various	Nexterra	CHP, power, fuel gas	Forest and wood wastes	USA, Canada, UK	Operational

Project(s)	Technology provider	Product	Feedstock	Country	Status
Cement plants	Anhui Conch Kawasaki Engineering Co.	Fuel gas	MSW	China	Operational
Alberta Biofuels	Enerkem	Methanol, ethanol	RDF	Canada	Operational
Bayou Fuels	TRI	FT liquids	Forest residues	USA	Planned
Flambeau River	TRI	FT liquids	Forest residues	USA	Cancelled
Ineos Bio	Ineos Bio	Ethanol	Biomass wastes	USA	Decommissioned
New Page	TRI	FT liquids	Forest residues	USA	Cancelled
Pontotoc	Enerkem	Ethanol	RDF	USA	Cancelled
Range Fuel	Range Fuel	Methanol & ethanol	Forest residues	USA	Decommissioned
Red Rock	TC Global	FT liquids	Forest residues	USA	Construction
Riverbank	InEnTec	Ethanol	Orchard residues	USA	Planned

Project(s)	Technology provider	Product	Feedstock	Country	Status
Showa Denko	Ebara UBE Process (EUP)	Hydrogen	Plastic waste	Japan	Operational
Sierra Biofuels	TRI	FT liquids	RDF	USA	Construction
Vanerco	Enerkem	Ethanol	RDF	Canada	Planned
Development units					
Ambigo	Synova Power (Milena, OLGA)	Bio-methane	Biomass residues	The Netherlands	On hold
Bioliq	BioLiq	Gasoline	Agric. Residues	Germany	Operational
BioTfuel	TKI	FT liquids	Biomass residues	France	Commissioning
Comsyn	VTT	FT liquids	Forest residues	Finland	Operational
Gaya	Aichernig Engineering fka Repotec	Bio-methane	Biomass residues	France	Operational
LTU Green Fuels	Chemrec	Methanol, DME	Black liquor	Sweden	Idling

Project(s)	Technology provider	Product	Feedstock	Country	Status
City Refinery Vuosaari	Helen, Lassila & Tikanoja, VTT	CHP, biofuels	Biomass residues	Finland	Planning
SMS Wien-Simmering	SMS Group	FT-liquids	Sewage sludge, paper waste	Austria	Planning
Kew Technology	SEC Technology	Power	Wood wastes	UK	Operational

The situation is similar in a global perspective. There is one plant in Japan using the Ebara Ube Process (EUP), although not for biofuels, that gasifies plastic waste to make syngas, ultimately to produce hydrogen for ammonia synthesis. However, in 2019 it was announced that the EUP technology would form the basis for a cooperation between JGC Corporation, Ebara Environmental Plant Co., Ltd., Ube Industries, Ltd., and Showa Denko K.K. for an EPC business for plastic waste gasification facilities. Sekisui Chemical has worked with a LanzaTech Inc. and has succeeded in developing the gasification of combustible waste into carbon monoxide and hydrogen that is converted to ethanol by gas fermentation.

There is also a plant by Enerkem in Edmonton, Alberta in initial operation, using refuse-derived fuel (RDF). A second plant in Canada is in planning stage.

In the USA, a number of projects have been initiated in the last decade. Two industrial projects, Range Fuel and Ineos Bio, completed construction but were stopped within a few years, seemingly from technical problems. Two other projects, Red Rock Biofuels and Sierra Biofuels, reached financial closure in 2017, and after several years of struggle with planning and financing, both are now under construction. In addition, a biomass-to-FT liquids project by Velocys and a biomass-to-ethanol plant by Aemetis are also somewhere along the project development cycle.

Only four major pilot installations are operating in the EU, one of which, Gaya, is very small, one is under construction, and two, Comsyn and BioTfueL, were started in the period since 2016. The situation in the USA is similar, there are three major operating pilot facilities, one of which is based on the same technology as that used in the Güssing and GoBiGas plants.

The situation with a very slow progress is not limited to gasification technology as such. The same trend is also observed for other forms of biofuels, as many of the causes are in e.g., energy prices and regulatory and policy barriers affecting the market are recurring themes.

There are many things that is in favour of gasification as a technology; the combination of fuel flexibility and product flexibility, high conversion of the fuel, technologies suitable for a variety of scales, etc. are technical aspects that means that gasification has fewer feedstock and technical limitations than other advanced biofuel technologies. This potential is a basic aspect of gasification that keeps the technology on the agenda, despite technical problems in installations in the past.

It should also be realised that the novelty in the technology is the use of biomass in gasification systems and the associated gas cleaning, whereas the upgrading of the gas and the synthesis to products is extensively used in the gas in petrochemical and chemical industries and are thus well-proven. By analogy, the modern form of coal gasification started in the 1970-80´s and went through the learning curve and is today a proven commercial technology with many installations, in particular in China. There is no reason why biomass gasification could not follow in suite to this technology if it can get off the ground in the first installations.

The RED II, and hopefully the follow-up on the renewable fuel standard (RFS2), plus policy interventions in many countries individually, focus on reducing GHG emissions in the transport sector and therefore place more emphasis on advanced biofuels. Such policy- and market-related developments can result in that the market condition become more favourable and gasification-based and other advanced biofuels plant can be economically feasible. The common issues faced by advanced biofuels include the use the framework policies just mentioned to establish conditions, initially for financing developments and market establishment in industrial scale first-of-a-kind plants, and then also more long-term, to establish a commercial framework that leads to more widespread activities and deployment.

Technology Profiles & Technology Readiness Level Assessments

This chapter examines in closer detail the technical features, development trajectory and technology readiness of the selected sample of ten gasification technologies in various stages of market emergence. The sample was selected to capture some of the diversity of the technical options present in the market, technologies are characterized by flexibility in both scale and end product, although the majority are clearly marketed at localized, small-scale applications. Towards the end of the chapter, a non-exhaustive list of emerging technologies that were surveyed but not taken forward for closer examination is also provided.

ADVANCED BIOMASS GASIFICATION TECHNOLOGY BY RENERGI PTY LTD. [AUSTRALIA]

Renergi Pty Ltd's *Advanced Biomass Gasification Technology* has been developed to convert various biomass streams (e.g., forestry wastes and agricultural wastes) to heat and power in CHP applications [1]. According to the company, the technology is characterized by the use of biochar as a catalyst to remove organic and inorganic impurities in syngas, which eliminates the need for liquid-based scrubbing, thereby simplifying syngas treatment, and by a system design that minimizes volatile-char interactions and incorporates advanced energy recuperation principles, thereby improving char reactivity and increasing overall efficiency [1-4].

Table 4. Technology profile for Renergi Pty Ltd's Advanced Biomass Gasification Technology

Designation	Advanced Biomass Gasification Technology
Developer/Promotor	Renergi Pty Ltd. [Australia]
Gasification Method	Two-stage gasification (general classification not provided)
Feeding System	Hooper with an agitator-equipped rotary feeder
Oxidant	Air, steam

Designation	Advanced Biomass Gasification Technology
Principal Feedstock(s)	Forestry wastes, woody plantations, and agricultural wastes
Principal Application(s)	Heat & Power (CHP) by means of an ICE
Scale	100 kg/h feed (demo unit), upper limit unknown (commercial unit)
Development Status	Technical testing in demonstration scale; pending commercialization

Process Description

The subsequent process description is primarily put together from information provided by the developer (a) in response to a request for comment, and (b) in the 100 kg/h demonstration plant project report [3, 4]. Other sources of information consulted include academic articles from a research group at Curtin University responsible for developing the technology [5, 6] and patent reports [7-9].

As a first step, biomass is dried in a conventional dryer to remove part of moisture by using heat recovered from the cooling of syngas. The dried biomass is fed to a pyrolysis zone (presumed to be in the gasifier vessel, although the process description provided by the developer is not explicit on this), resulting in the production of a gaseous intermediate product called volatiles and a solid intermediate product called biochar. The biochar and volatiles enter different zones of a gasifier. Biochar will be gasified with air and steam in the practical absence of volatiles at 850-1000 °C. The gas produced from the gasification of the biochar mixes with the volatiles in the volatile reforming zone of gasifier and is cleaned in a hot gas cleaning and energy recuperation unit. The organic and inorganic impurities such as tar residue and vaporized metallic species (such as potassium) in the raw gasification product gas are either chemically converted or physically removed as the hot product gas is cooled down. Energy recuperation takes place to convert the thermal energy into chemical energy. According to Renergi, the clean product gas meets the quality requirements for use in a gas engine or other types of power generation equipment (e.g., fuel cells) to generate electricity and/or heat [3].

Renergi Pty Ltd's Advanced Biomass Gasification Technology

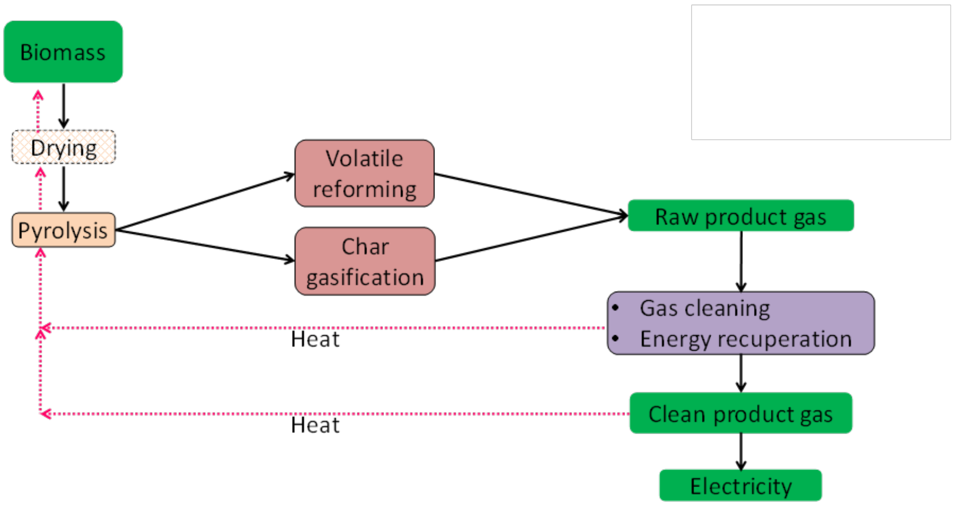

Figure 1. A schematic of the Renergi Pty Ltd's Advanced Biomass Gasification Technology. Based on the schematic diagram provided in [3]

Renergi have developed their own pyrolysis technology to pyrolyze biomass [8]. It is claimed by Renergi that a wide range of biomass resources, like forestry wastes, woody plantations, and agricultural wastes, with a wide range of particle sizes, ranging from microns to centimetres, can be in the same feedstock, reducing the cost of biomass preparation. By minimizing the interaction between volatiles and biochar, the developer claims that the technology can achieve rapid gasification under relatively mild conditions of atmospheric pressure and relatively low temperatures (850-1000°C) and achieve cold gas efficiencies of over 90% (HHV).

According to Renergi, the integrated hot gas cleaning they have developed has made it possible to produce syngas that meets the quality requirement for direct use in gas engine without using a liquid scrubbing process. Biochar, produced in gasifier, has been tested as catalysts in the hot gas cleaning unit. Experiments at the auto-thermal demonstration plant showed that the hot gas leaving the catalyst bed had a tar content below 20 mg/Nm^3 and the HHV of the gas was calculated to be 5.1-6.9 MJ/Nm^3 [2].

Development Status, Applications, Production Scale

The technology has been technically demonstrated in a 100 kg/h auto-thermal demonstration plant in Technology Park, Perth, Australia, which was constructed in part through the financial support of the Australian Renewable Energy Agency (ARENA) [10]. In Renergi's estimation, the demo plant increased the TRL of the technology from 5 to 7-8 and as of 2017 the company was planning to proceed with commercialization [3,4]. The principal application of the clean syngas appears to be combustion in a gas engine or equivalent device for combined heat and power generation, however, combustion in a gas engine was not included in the demo according to publicly available information [2].

Renergi's technology portfolio also contains a grinding pyrolysis technology, which has been developed and demonstrated with a bio-refinery focus on production of non-condensable gases, liquid bio-oil, and solid biochar, with the demonstration plant being rated at 100 kg/h [11,12]

Technology Readiness Level

An assessment of the technology readiness of the Advanced Biomass Gasification Technology is provided in Table 5.

Table 5. Assessment of technology readiness for Renergi Pty Ltd's Advanced Biomass Gasification Technology. Note that a heat and power co-generation application is assumed, and the biochar and heat alternative is not assessed

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	6-7	10	Covers the drying and the hopper-rotary-feeder-agitator-assembly steps. The 100 kg/h demonstration plant was equipped with a biomass dryer and a feeding sub-system, which, in the absence of information to the contrary, are taken to be the same as those included in the commercially offered configuration. Based on the evidence in the public domain and information provided by the developer, the step has been successfully demonstrated as part of the general demonstration of the technology in a 100 kg/h demo unit, although the scale of intended commercial unit is unknown. In response to a request for feedback on the evaluation, the developer proposed a TRL score of 7-8 for the step (as well as for other process steps). However, a TRL score 7-8 supposes that the final design is virtually complete, and that the final configuration has undergone large-scale testing in 5-25% of the intended commercial scale (which could not be ascertained) as well as requires some evidence that the technology in its current state is approaching the end of true system development, which could not be established. Hence, a TRL score of 6-7 is deemed to best reflect the state of development based on publicly available information.
Gasification reactor with heat supply	6-7	30	Covers the pyrolysis, volatile reforming & gasification of the feedstock. Tested in the 100 kg/h demonstration plant. The pyrolysis unit in the demo plant was of Renergi's own design and has undergone testing in a 100 kg/h demonstration unit [11, 12]. Spatially separating the reforming of volatile gases from the gasification of char has a major impact on the effectiveness of the technology. It is assumed that the gasification reactor tested in the demonstration plant is scalable and that the tested

Process steps	TRL	Weight [%]	Comments
			capacity represents at least 25% of the commercially offered capacity. A TRL score of 6-7 is assigned following the reasoning outlined under “Feedstock handling system.”
Product gas separation and cleaning	6-7	30	The design and regulation of the catalyst bed, the choice of the catalyst material and their integration with the gasification vessel and energy recuperation are central elements in the technology. The configuration in the demonstration unit is likely similar to the commercially offered configuration based on project reports and may represent an actual system validation in a relevant environment. The hot gas cleaning has been tested using the biochar produced in gasifier as catalyst. Given the reported syngas quality for its direct use in gas engine and the reasoning outlined under “Feedstock handling system”, a TRL score of 6-7 is assigned.
Integrated operation	6-7	30	The individual technological components in the system configuration aimed at commercial application are known and have been tested in demonstration scale except for the final integration with a gas engine, which was not part of the demo plant. A TRL score of 6-7 is assigned following reasoning outlined under “Feedstock handling system.”
Overall “Weighted Average”	6-7		
Overall “Weakest Link”	6-7		

Developer Feedback

Renergi Pty Ltd responded to a request for feedback on the technology assessment. They provided corrections and clarifications on various technical aspects and a process description based on the 100 kg/h (nominal) demonstration unit. They proposed a TRL score of 7-8 for all the process steps. Their request is addressed in the comment on feedstock handling system in Table 5.

They also noted the following points:

- The technology has been demonstrated at two scales: 4 kg/h and 100 kg/h (nominal). The larger-scale unit has been operated at higher throughputs than the nominal rating. There were significant changes in equipment layout from the 4 kg/h unit to the 100 kg/h unit.
- The Australian governmental agency ARENA carried out a thorough assessment of the TRL of the technology at the end of the 100 kg/h demonstration project and assigned a level of TRL 7-8, which was assessed by external expert.

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ENDEAVOUR MICROWAVE GASIFICATION BY ENDEAVOUR ENERGIA S. R. L. [ITALY]

The *Endeavour Microwave Gasification* technology by Endeavour Energia S.r.l. can be used to upgrade waste and biomass feeds, such as rice and wheat husks, woody biomass, sludge from anaerobic digestion and litter from animal farms to electricity, heat, and biochar. According to Endeavour, the technology is characterized by the use of microwave-assisted high temperature gasification (>1400 °C) together with a simplified filtering system in a setup that does not generate waste in need of disposal [1].

Table 6. Technology profile for Endeavour Energia S. r. l's Endeavour Microwave Gasification Technology

Designation	Endeavour Microwave Gasification
Developer/Promotor	Endeavour Energia S. r. l. [Italy]
Gasification Method	Microwave-assisted fixed-bed 'Imbert-type' downdraft gasification
Feeding System	Rotating helical screw coupled to a feedstock storage vessel
Oxidant	Air
Principal Feedstock(s)	Rice and wheat husks, anaerobic digestion digestate, animal litter, woody biomass
Principal Application(s)	Heat & Power (co-generation), biochar
Scale	100 kWe/150 kWth/100 kg/h (demo unit), 100-200 kWe (commercial unit)
Development Status	Tested in demonstration scale; awaiting first-of-a-kind commercial plant

Process Description

The subsequent process description is based on information provided by the developer in response to a questionnaire, information available on the developer's official webpage and information provided by the developer in a newspaper feature [1, 2, 3].

The first step in the process consists of drying. Residual heat from the cooling of syngas is used to reduce the moisture content in the biomass feedstock to 10 wt. % [1]. Gasification takes place in a fixed-bed vessel of the Imbert downdraft variety. The use of microwaves as a heating agent enables rapid attainment of high temperatures (> 1400 °C). Microwave injection is controlled by a PLC PID algorithm [2]. According to Endeavour, the tar content in hot syngas has been found to be lower than 5 mg/Nm^3, which greatly reduces the cost associated with downstream filtering [1]. Endeavour claim that the tar content is monitored in real time although it is unclear whether this is done through the use of a proxy, such as methane, or by direct measurement. Upon leaving the gasifier, indirect heat exchange with cold air is used to reduce syngas temperature and recover heat for drying. The cooled syngas is subsequently filtered and fed to a gas engine in a heat and power co-generation application.

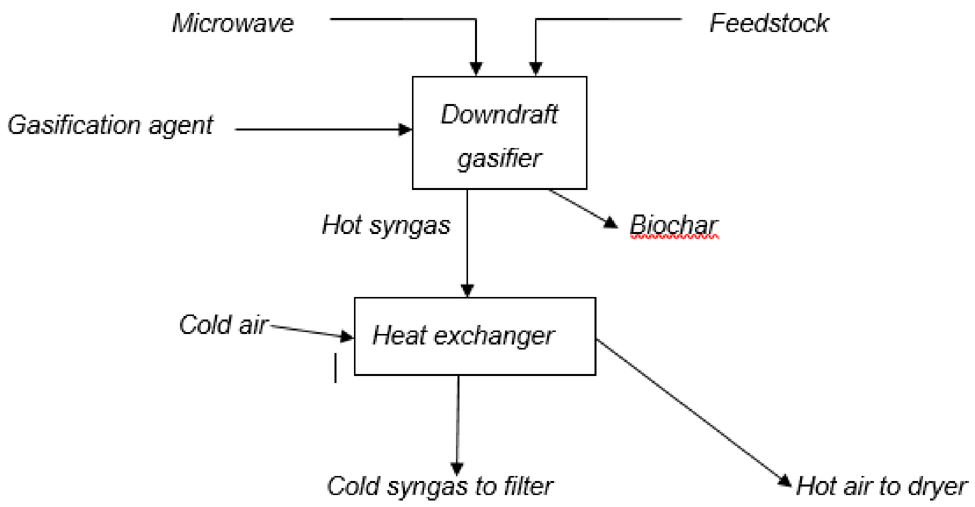

Figure 2. A schematic of the Endeavour Energia S. r. L's Endeavour Microwave Gasification Technology. Supplied by the developer in response to a questionnaire [2].

Development Status, Applications, Production Scale

The Endeavour Microwave Gasification Technology has been demonstrated in a pilot plant that was built to be a 1:1 scale replica of a commercial unit according to the technology developer. Tests were performed with different feedstocks. Syngas and tar samples were taken and analyzed to put together mass balances [2]. The company self-assessed their technology as having a TRL of 6.

Intended commercial applications soon include cogeneration of heat and electricity in anaerobic digestion plants and for specific, identified applications in the food industry. Co-generation of biochar and heat from sewage sludge is an intended long-term application. Current units (on offer) are dimensioned for 100 kW$_{el}$ and 150 kW$_{th}$ but can be scaled up to 200 kW$_e$ [2].

Technology Readiness Level

An assessment of the technology readiness of the Endeavour Microwave Assisted Technology is provided in Table 7.

Table 7. Assessment of technology readiness of the Endeavour Energia S.r.L's Endeavour Microwave Assisted Technology

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	6	10	Covers the dryer and the feeding system to the gasifier. It is assumed that feedstock moisture content requirements (10 wt. %) can be met by standard commercial dryers and that the use of such a dryer was part of pilot testing.
Gasification reactor with heat supply	6	40	The Imbert gasifier is a more-or-less a standard design. According to Endeavour, the gasification reactor has been tested using commercially relevant feedstocks with relevant diagnostic sampling in a full-scale pilot unit (TRL 6).
Product gas separation and cleaning	6	10	Provided that the gasification step functions as intended, the tar concentration in syngas is very low and the cooling and cleaning processes relatively straightforward. It is assumed that cooling and filtering are carried out with standard heat exchangers and filtering technologies and have been tested in the full-scale pilot unit (TRL 6).
Integrated operation	5-6	40	The extent and length to which the complete commercially relevant configuration has been demonstrably tested with both the relevant feedstocks and end-use applications cannot be determined from available information. A ranged TRL score of 5-6 is therefore awarded to accommodate the uncertainty.
Overall "Weighted Average"	5.6-6.0		

Process steps	TRL	Weight [%]	Comments
Overall "Weakest Link"	5-6		

Developer Feedback

Endeavour Energia S.r.L did not submit a response to a request for feedback on the technology assessment.

References

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HELIOSTORM GASIFIER BY COGENT ENERGY SYSTEMS [UNITED STATES]

The *Heliostorm Gasifier* by Cogent Energy Systems is an ultra-high temperature (3000 °C – 10000 °C) ionic gasification technology designed for small-scale (1-5 tons/d) waste to energy applications [1]. According to Cogent, typical applications include the upgrading of agricultural by-products like bagasse and animal manure at farms, the processing of regulated medical waste at hospitals and the conversion of municipal solid waste at military installations and remote communities [1].

Table 8. Technology profile for Cogent Energy Systems' Heliostorm Gasifier

Designation	Heliostorm Gasifier
Developer/Promotor	Cogent Energy Systems [USA]
Gasification Method	Ionic gasification
Feeding System	Hopper
Oxidant	Oxygen
Principal Feedstock(s)	Municipal solid waste, agricultural residue, medical waste
Principal Application(s)	Electricity (off-grid generation), liquid fuels and hydrogen (prospective)
Scale	1-5 t/d (commercial unit)
Development Status	Lab-scale (unknown kg/h) tested, demo (up to 4 tons/d) under development

Process Description

The subsequent process description for the upgrading of mixed waste to electricity in module-based remote applications has been put together using information from the following sources: the company website [1, 2], media reports [4, 6, 7] and a patent application assigned to Cogent Energy Systems in 2019 [5].

Mixed waste is shredded and fed to the gasifier through a hopper and a sealed conveyer. Once inside the gasifier, the waste comes into contact with an active plasma field at temperatures of 3000 to 10000 °C and breaks down into constituent atoms. A patent assigned to Cogent Energy Systems describes the plasma reactor as a DC-DC hybrid plasma system with multiple sets of electrodes placed longitudinally opposite each other within modular units. It appears to have its origin in research on the creation of nanoparticles at Idaho National Laboratory and was developed by Peter Kong, currently the chief technology officer at Cogent Energy Systems.

The plasma processing zone completely fills the gasifier interior and is claimed to produce a syngas free of impurities to the extent that, depending on the application, the only post-conversion cleaning required is passage through a dry or wet scrubber to remove sulfur and/or chlorine if it is present in the feedstock. The produced syngas is cooled through heat exchange and used in a modified diesel engine for power generation.

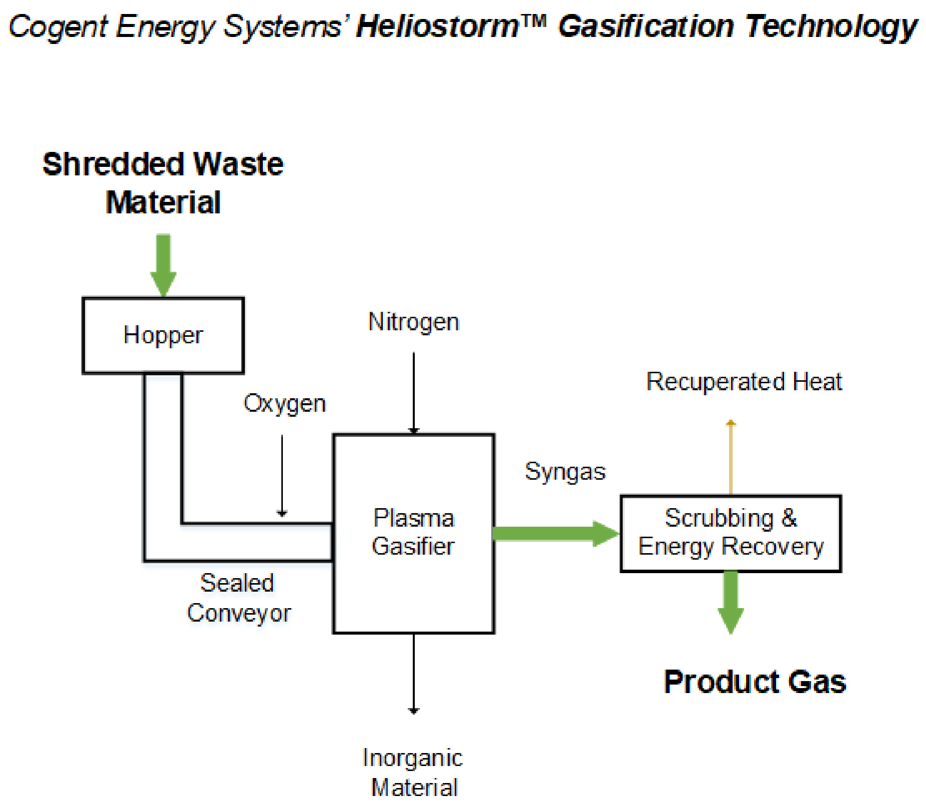

Figure 3. A schematic of Cogent Energy Systems' Heliostorm™ Gasification technology. Adapted from a 2019 presentation of the concept [2]

Development Status, Applications, Production Scale

Cogent Energy Systems and Creare LLC revealed in late 2018 and early 2019 that they were working together to develop a waste-to-energy system for mixed wastes under funding with the U.S. Navy [2]. The aim was to convert up to 4 ton of mixed waste a day into syngas, which would be used to generate 800 kWh of electricity per ton of municipal solid waste in a converted diesel generator. Cogent was supplying the gasification technology and Creare LLC was designing and fabricating the system components for waste preparation and electric power generation.

According to a presentation by CEO in April 2019, the proof-of-concept was demonstrated in 2016. Testing and design upgrades using the R&D unit were performed in 2017 and a commercial-scale unit was constructed, tested, and demonstrated over 2018-2019 [2]. Different feedstocks were tested, and syngas had been found to be free of long-chain hydrocarbons, hazardous chemicals, emissions, and pollutants by independent third-party tests. The same presentation noted that next steps in the development include the completion of testing and optimization of existing system, the integration of the gasifier with feedstock preparation (shredder) and electricity generation (genset), the determination of energy balances from data obtained during long-duration runs and the delivery of the integrated system to military and commercial customers [2]. According to a media article from October 2020, Cogent's partners, Creare LLC were seeking opportunities to conduct a demonstration at a military installation with an operational prototype. A spokesperson was quoted as noting that the company was looking to move the system out of the lab and into a representative operating environment. Whether the system referred to as having undergone lab testing included the shredder and a genset could not be deduced from the article [7]. Integrating of syngas upgrading with the rest of the process appears to be part of the next step in the development process.

Technology Readiness Level

An assessment of the technology readiness of Cogent Energy Systems' Heliostorm™ Gasifier is provided in Table 9.

Table 9. Assessment of technology readiness for Cogent Energy Systems' Heliostorm™ Gasification technology

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	5-6	10	Covers feedstock pre-treatment, such as shredding, and the feeding system to the gasifier. A media article from October 2020 indicates that the waste handling system has undergone detailed design (by Cogent's partner Creare LLC) [7]. Evidence from a SBIR report provided by Cogent in response to a request for feedback on the assessment indicates that the feedstock handling system has been tested as a part of the full-scale, laboratory-grade, prototype system in experimental runs with waste material processing rates of 1 ton/day, which corresponds to 25% of the intended commercial capacity. According to the report, the next step in the development of the system is the automation as well as deployment at an external site for extended

Process steps	TRL	Weight [%]	Comments
			operation and evaluation in a real-world environment. This would, the report argues, enhance the system's readiness level. A TRL of 5-6 is awarded given the successful validation of the complete technology chain in full scale in a lab environment with commercially relevant feedstock.
Gasification reactor with heat supply	5-6	50	Covers the plasma reactor. Available evidence indicates that testing of a full-scale prototype unit similar in configuration to the commercial product has been carried out successfully at part-load (approximately 25%) in lab-conditions using commercially relevant feeds. Following the reasoning outlined for the feedstock handling system, a TRL score of 5-6 is awarded.
Product gas separation and cleaning	5-6	20	Covers the cleaning of syngas including a scrubber and a heat exchanger. Available evidence indicates that scrubbing and heat recovery has been tested in conjunction with other parts in the full-scale lab prototype. Syngas compositions from testing runs indicate very low levels of impurities. Following the reasoning outlined in the comment on the feedstock handling system, a TRL score of 5-6 is awarded.
Integrated operation	5-6	20	A full-scale prototype of the process configuration from feedstock entry to heat recovery and syngas production has been successfully tested at part-load in a lab-scale facility and a TRL score of 5-6 is awarded following the same reasoning as for the other steps.
Overall "Weighted Average"	5-6		
Overall "Weakest Link"	5-6		

Developer Feedback

Cogent Energy Systems responded to a request for feedback on the technology assessment with corrections and clarifications on various technical aspects. They also made available a public report (accessible on request) regarding their system with the aim of providing additional information for the TRL established that was submitted to the US Navy by Creare LLC.

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MEVA TECHNOLOGY BY MEVA ENERGY AB [SWEDEN]

The MEVA technology by Meva Energy AB is a small-scale biofuel cogeneration system built around an entrained-flow cyclone gasifier designed to process crushed pellets and sawdust. According to Meva Energy, the technology is characterized by the use of air instead of oxygen for gasification, which reduces operating cost, and by the production of a high quality, stable syngas with the production of biochar as a side-stream also being a possibility [1].

Table 10. Technology profile for Meva Energy AB's entrained-flow cyclone gasification technology

Designation	MEVA Technology
Developer/Promotor	Meva Energy AB [Sweden]
Gasification Method	Entrained-flow cyclone
Feeding System	Air-assisted pulverized feeding
Oxidant	Air
Principal Feedstock(s)	Crushed pellets, sawdust
Principal Application(s)	Heat and power (co-generation), biochar (prospective)
Scale	5 MW_{th} fuel input, 1.2-2.4 MW_{el} and 2.2-2.4 MW_{th} heat product (commercial unit)
Development Status	5 MW_{th} (demonstration), 2.5-5 MW_{th} (commercial offer)

Process Description

The subsequent process description is put together from information found on the homepage of the developer, in the IEA Bioenergy Task 33 Status Report on Thermal Gasification of Biomass and Waste 2019, in a recent academic study of the technology and from information provided by the developer [1-5].

In the first step, a biomass feedstock such as pellets with a low moisture content is pulverized and mixed with air to provide a continuous co-current feed to an entrained-flow cyclone gasifier through two tangential inlets. A strong spiraling motion causes the biomass particles to tumble downwards towards the bottom of the cyclone. The gasifier is operated at 800-1000 °C. Gasification takes place in a vortex-shaped flow and given the short feedstock throughput times on account of the entrained-flow cyclone design, load changes are immediate, which is advantageous in balancing power applications [2]. The pulverized and relatively dry nature of the particles leads to the release of the remaining moisture at an early stage. In the devolatilization and pyrolysis reactions various gaseous compounds including both light and heavy hydrocarbons are released, leaving behind a solid residue made up of both inorganic and organic components. The latter react with the gases inside the reactor, while the former ultimately exit the reactor as ash, which can be recovered and recycled.

The gasification temperature is relatively low compared to other types of entrained-flow gasifiers and the syngas contains significant amounts of unconverted tar. The hot syngas exits the gasifier at the top and is cooled down to below 100 °C in a water quench. The cooled syngas is conditioned in a two-stage cleaning process: particles and tars are removed in a venture scrubber and the remaining aerosols and small droplets are removed in a wet electrostatic precipitator. The conditioned gas is fed to a turbo-charged internal combustion engine and according to the company electricity and heat efficiencies of 30% and 50% can be achieved when operating with dried and pulverized feedstock [3].

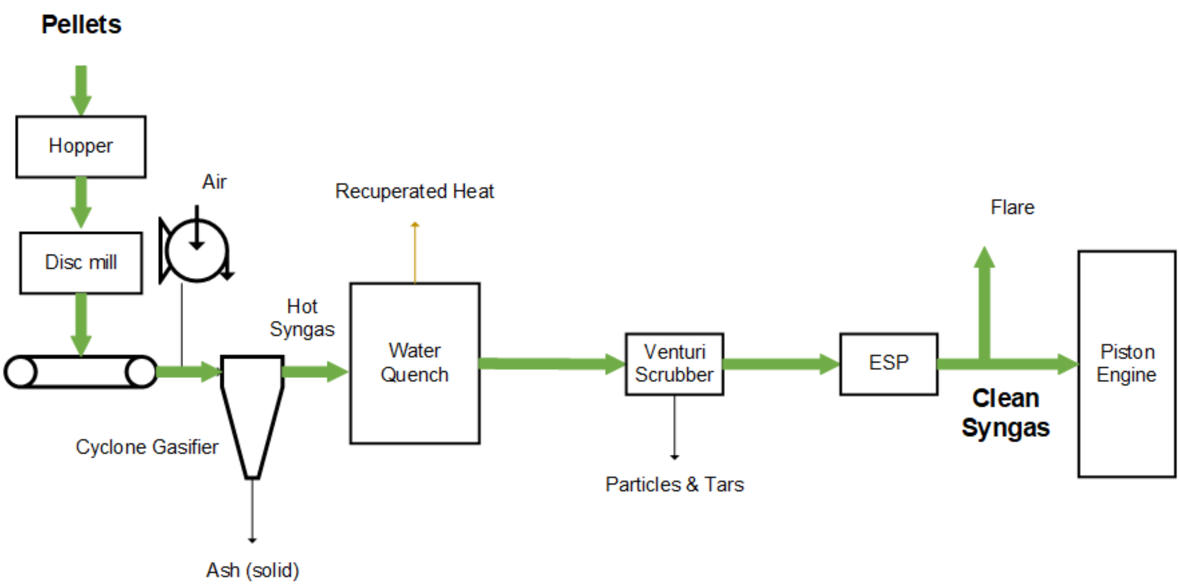

Figure 4. A schematic for MEVA Energy AB’s technology. Adapted in modified form from [4]

Development Status, Applications, Production Scale

The MEVA technology is offered in single and dual unit configurations, which are intended for different market segments [2]. The single unit configuration is estimated to generate 1.2 MW of electricity and 2.2 MW of heat and is intended for small industries or small residential areas with approximately 400 homes. The dual unit configuration provides double the amount of heat and electricity and is intended for larger industries and communities. The Hortlax plant is a single unit and has been operated on crushed wood pellets; operation on sawdust is also possible [1, 3].

The full process configuration from feedstock input to the combustion of syngas in a gas engine has been tested in a 500 kW_{th} pilot plant located at ETC Piteå, Sweden, which was originally commissioned in the 1990's and has undergone several subsequent modifications. A full-scale prototype demonstration plant with a fuel input of 5 MW_{th} and electricity and heat outputs of 1.2 MW and 2.4 MW, respectively, was commissioned in 2012 in Piteå with the local municipality as the end customer for the co-generation products. Power was generated using a 91 litre Cummins V18 engine. Following commissioning the plant underwent various modifications and was eventually purchased back by Meva Energy AB for use as a stand-alone R&D unit. Further details on the development timeline of the MEVA technology (previously referred to as the VIPP system) can be found in the 2019 status report and on the developer's homepage [1,3].

Technology Readiness Level

An assessment of the technology readiness of the MEVA technology is provided in Table 11.

Table 11. Assessment of technology readiness for Meva Energy AB's entrained-flow cyclone gasification technology

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	7-8	20	Covers feedstock pulverization as well as oxidant and feed mixing. Achievement of a continuous, well-dispersed flow has a notable impact on process stability and efficiency targets. Feedstock handling has been technically demonstrated at the Hortlax pilot plant in Piteå as a part of the technical demonstration in full scale. In response to a request for a feedback on the evaluation, MEVA Energy AB proposed a TRL score of 8 for all the process steps. In the methodology chosen in this project, TRL 8 represents the end of true system development, but as the Hortlax plant is currently still being used for development and fine-tuning, a TRL score of 7-8 is considered to better reflect the current state of development based on publicly available information.
Gasification reactor with heat supply	7-8	30	Covers the cyclone gasifier. Technically demonstrated at the Hortlax pilot plant in Piteå in full scale. A TRL score of 7-8 is awarded following

Process steps	TRL	Weight [%]	Comments
			the reasoning outlined for “Feedstock handling system”.
Product gas separation and cleaning	7-8	30	Covers the venturi scrubber and the wet electrostatic precipitator. Technically demonstrated at the Hortlax pilot plant in Piteå in full scale. A TRL score of 7-8 is awarded following the reasoning outlined for “Feedstock handling system”.
Integrated operation	7-8	20	Integrated operation of the full process configuration has been demonstrated at the Hortlax prototype demonstration plant. See the motivation for “feedstock handling.”
Overall “Weighted Average”	7-8		
Overall “Weakest Link”	7-8		

Developer Feedback

Meva Energy AB responded to a request for feedback on the technology assessment. They provided corrections and clarifications on various technical aspects. They proposed a TRL score of 8 for all the process steps. Their request is addressed in the comments on Table 11.

References

[1] http://mevaenergy.com/technology/

[2] http://mevaenergy.com/uploads/Meva-Energy-Brochure-clean-power-and-heat.pdf

[3]http://www.task33.ieabioenergy.com/download.php?file=files/file/publications/T33%20Projects/CHP-operational.pdf

[4] PH. Jafari, A. Wingren, J. GI. Hellström & BR Gebart (2020) Effect of process parameters on the performance of an air-blown entrained flow cyclone gasifier, International Journal of Sustainable Energy, 39:1, 21-40, DOI: 10.1080/14786451.2019.1626858

[5] MEVA Energy AB’s response to an in-project request for feedback

MOVING INJECTION HORIZONTAL GASIFICATION BY WILDFIRE ENERGY [AUSTRALIA]

Wildfire Energy's *Moving Injection Horizontal Gasification* (MIHG) technology is based on a batch process where a sealed bed of unprocessed biomass and waste feedstock is upgraded to syngas by a stream of oxidant moving through the bed [1].

Table 12. Technology profile for Wildfire Energy's Moving Injection Horizontal Gasification technology

Designation	MIGH Technology
Developer/Promotor	Wildfire Energy [Australia]
Gasification Method	Moving Injection Fixed-Bed Gasification
Feeding System	Batch feeding
Oxidant	Air, oxygen (potentially)
Principal Feedstock(s)	Agriculture & forestry waste, green (urban) waste, MSW
Principal Application(s)	Power, Hydrogen
Scale	60 kW_{th} (pilot), 1-7 MW_{th} (off-grid module) to 5-40 MW_{th} (continuous power)
Development Status	Tested in pilot scale, integrated demo funded (2019)

Process Description

The subsequence process description is put together from information provided by the developer on their homepage, in a conference presentation and in a patent application [1-3].

Technology testing at the pilot plant was limited to the use of a single MIHG reactor but a commercial implementation would see two reactors working in tandem. The second reactor is loaded with waste while the first reactor is in operation and a continuous supply of syngas is provided by alternating the sequence.

MIHG technology has been designed to process both as-received and pre-processed feeds. The reactor takes the form of a horizontal fixed-bed chamber. Once the loading of the feedstock is complete and the chamber sealed, the feedstock bed is gasified by sequentially injecting the oxidant through a moveable injection duct or through a series of nozzles along a stationary tube at the bottom of the bed in such a manner that it contacts the biomass at multiple points. Figure 5 demonstrates the movement of the oxidant injection point and corresponding progression of the gasification process [4]. According to the developer, this is a key innovation and enables multiple benefits including reduced or nil feedstock pre-processing, improved gas stability, lower exit gas temperature and reduced tar/particulate loading. Air, oxygen, or a combination thereof are used as oxidants depending on the intended application, although only the former appears to have been tested in pilot scale based on publicly available information. According to the developer, oxygen-blown trials with multiple feedstocks are scheduled for early 2021 after minor modifications to the pilot plant [4].

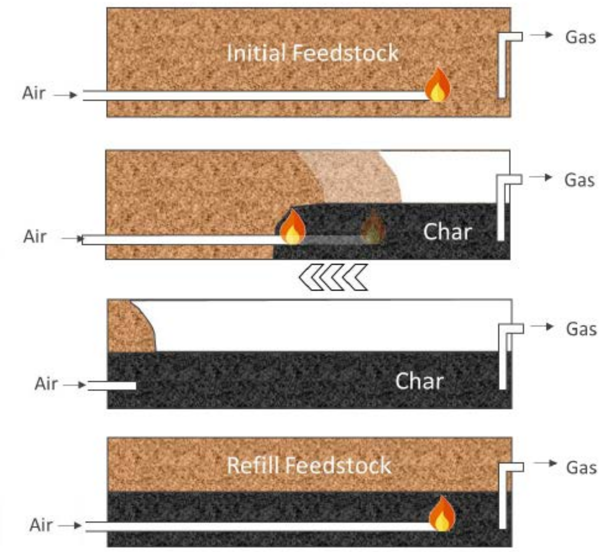

Figure 5. Schematic showing oxidant injection retraction and subsequent gasification front sweeping through the feedstock. Provided by the developer [4]

The reaction chamber is subjected to large temperature gradients, with the temperature closer to the syngas collection pipe being as low as 100 °C. According to Wildfire Energy, ash removal is performed when the gasifier is offline and cooled for reloading using an automated mechanism at the base of the reactor. The developer claims that their chosen approach avoids the need for complex continuous conveying and sealing systems and does not require a water bath [4]. The syngas is sent for cleaning, heat recovery and further treatment. Syngas quality is monitored in real time to regulate oxidant injection.

Once the conversion of the feedstock is complete, the second reactor is activated. The seal on the first reactor is released and the chamber is refilled with fresh feedstock that settles on top of the char layer at the bottom of the chamber. Careful control of the refilling step is necessary to reduce the hazard associated with the exposure of the hot char bed to air and feedstock. According to Wildfire Energy, at the end of each batch operation, most of the char bed has already cooled to moderate temperatures and is force cooled below auto ignition temperature prior to refilling and ash removal [4]. MIHG technology can be configured to use the gasification chamber for pre-drying in a multi-reactor configuration and recirculate the tars back to the reaction chamber [1, 5].

Development Status, Applications, Production Scale

Wildfire Energy has tested the MIHG technology in a 1 t/d (~200 kW_{th}) pilot plant in Brisbane, Australia [6]. The configuration consisted of a single gasification reactor and thus differs from the intended commercial configuration with two reactors working in tandem to ensure continuous syngas supply. According to the developer, a diverse variety of feedstock were successfully gasified over the course of more than forty successful runs. Stable gasifier operation was attained approximately half an hour into operation and maintained throughout the remainder of the run [5]. Syngas composition varied somewhat between the initial fill and the re-fill, with the fresh feed yielding higher concentrations of methane and hydrogen but a lower concentration of carbon monoxide. Injection temperature and temperature at the edge of the reaction zone reached 900 °C and 1100 °C, respectively. Co-injection of the recirculated tar and water with air was shown to affect the gas composition, although the resulting impact on LHV was relatively marginal (a reduction of ~ 5%).

The syngas produced in the pilot experiments was flared. According to Wildfire Energy, a gas clean-up system consisting of the following components (in order) was installed in 2018: ESP for particulate and tar removal, syngas blower, indirect gas cooler and activated carbon bed [4]. The developer is planning to install a gas engine in 2021.

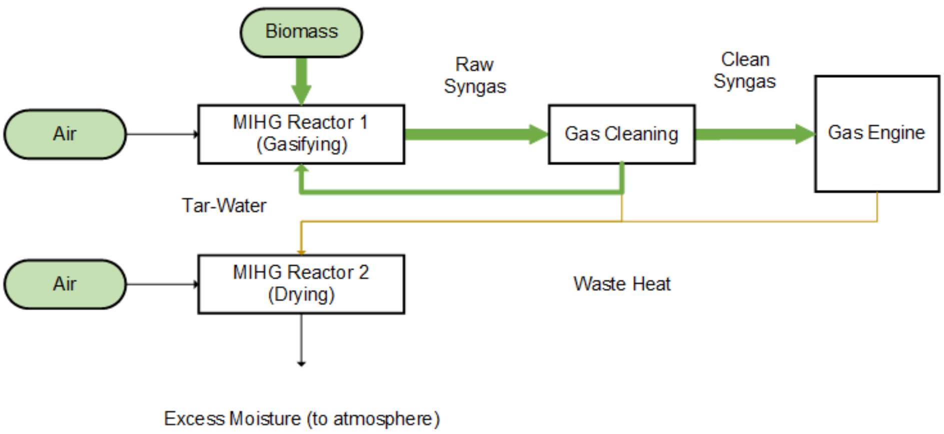

Figure 6. A schematic for the MIHG technology in a dual-reactor biomass-to-electricity application. Adapted from [1]

Wildfire Energy was granted a sum of 0.5 MAUD towards the cost of a demonstration plant set in the Australian city of Ipswich by the province of Queensland [7]. The company is currently developing the project in two stages [8] and provided the following information in response to a comment for feedback on the evaluation: the instantaneous capacity of the MIHG reactors in the first and second stages is expected to be the same, but the annual capacity will be lower for the first stage as the plant is not expected to operate continuously. The original concept was to be field-erected, but the developer is presently targeting a modular design with an initial capacity of 4000 tons/y and an expanded capacity of 20000 tons/y. The intention is to process a wide range of different waste feedstocks and use the syngas to generate electricity in a gas engine (approximately 100 kW_e per 1000 tons/year). Furthermore, a slipstream of syngas may be upgraded to high purity hydrogen [4]. It was reported in November 2019 (article behind paywall) that Wildfire Energy had partnered with waste company BMI to deliver the project and that plans for the demonstration plant were to be lodged with Ipswich city council in 2020 [9].

The intended application for MIHG presently appears to be small scale dispatchable renewable power using gas engines. Wildfire Energy offers MIHG plants in both a modular configuration, with scalable processing capacities in the range 4-20 kt/a (~1.3-6.6 MW_{th}) and continuous electricity production of up to 0.4 MW_e per 4 kt/a of feedstock [10], and as on-site installations, with indicative processing capacities in the range 15-120 kt/a (~4.9-39 MW_{th}) and a choice of electricity, hydrogen, and ethanol as final products [11]. The smallest (modular) and largest (on-site) plants have throughputs of 4 kt/a and 120 kt/a, respectively, which corresponds to thermal inputs of ~1.3 MW_{th} and ~39 MW_{th} assuming the same feedstock and same efficiency as in pilot testing.

Technology Readiness Level

An assessment of the technology readiness of the moving injection horizontal gasification (MIHG) technology is provided in Table 13.

Table 13. Assessment of technology readiness for Wildfire Energy's Moving Injection Horizontal Gasification (MIHG)

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	3-4	30	Covers filling and refilling of the fixed-bed reactor with biomass feedstock. One-reactor operation has been validated. However, tandem operation of two reactors with refilling and with production switching intermittently between the two is the intended commercial configuration but has not been tested in pilot or demonstration scale based on publicly available information. Intended to be demonstrated in the second stage of the planned demonstration unit. In response to a request for a feedback on the evaluation, Wildfire Energy proposed a TRL score of 4-5 for the feedstock handling system since, according to them, only a single reactor is needed to demonstrate all of the features required for the technology. They further claimed that all the steps in the commercial design, namely, loading, drying, purging, ignition, gasification, cooling, ash removal are undertaken at their pilot plant. Given that dual reactor operation is part of the commercial concept, pilot validation of tandem

Process steps	TRL	Weight [%]	Comments
			operation deemed to be a needed for a TRL score of 4-5. Accordingly, a TRL score of 3-4 is awarded to this step.
Gasification reactor with heat supply	4	30	The heart of the process. Covers the MIHG reactor. Pilot testing of a 60 kW_{th} MIHG reactor has been carried out and stable operation was reported to have been achieved. The pilot reactor corresponds to 1-5% of the capacity of the intended commercially capacity range. However, the intended tandem operation has not been tested.
Product gas separation and cleaning	4-5	20	Syngas produced during the initial pilot tests was flared. In response to a request for a feedback on the evaluation, Wildfire Energy proposed a TRL score of 4-5 for product gas separation and cleaning since the pilot has had an operational gas clean up system since 2018. According to the developer, full gas sampling via third party has validated the gas clean up design and the projected emissions are well below the limits specified in the environmental permit. Given these developments, a TRL score of 4-5 has been awarded for this step.
Integrated operation	3-4	20	Integrated operation has been partially validated in pilot testing. Demonstration of tandem reactor operation coupled with syngas cleaning and upgrading could not be established.
Overall "Weighted Average"	3.5-4.2		
Overall "Weakest Link"	3-4		

Developer Feedback

Wildfire Energy responded to a request for feedback on the technology assessment. They provided corrections and clarifications on various technical aspects and future development plans. They proposed a TRL score of 4-5 for the feedstock handling system and the product gas separation and cleaning steps. Their request is addressed in the comments on the respective steps in Table 12.

References

[1] Perkins G, Doucet D, Bollaert G. A Novel Biomass Gasifier for Converting Lump Biomaterials into Renewable Syngas: Pilot Plant Design and Operation. 2016.

[2] Doucet D, Bollaert G, Perkins G. Production of a gas and methods therefor, 2016.

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MULTIFUEL CONVERSION TECHNOLOGY BY RWE POWER AG [GERMANY]

The *Multifuel Conversion* (MFC) technology is being developed by RWE Power AG to test whether recovery of carbon and phosphorous from sewage sludge and other phosphorous-rich feedstocks is possible via gasification. The core process consists of high temperature entrained-flow gasification, optimized to achieve reduction of phosphates to gaseous phosphorous compounds. According to RWE, the MFC technology offers potential to recover phosphorus and carbon in the form of syngas in separate process streams in one single process step. The MFC technology is scheduled to undergo technical demonstration in a 130 kg/h pilot plant with commissioning planned for early 2021 [1-3].

Table 14. Technology profile for RWE Power AG's Multifuel Conversion (MFC) Technology

Designation	Multi-fuel Conversion (MFC) Technology
Developer/Promotor	RWE Power AG [Germany]
Gasification Method	Entrained-flow gasification
Feeding System	Lock-hopper system (pilot), to be determined (commercial)
Oxidant	Oxygen, steam
Principal Feedstock(s)	Sewage sludge, sewage sludge-ash, lignite (near-future); sewage sludge, sewage sludge ash, plastic waste, other biomass waste streams (long-term)
Principal Application(s)	Phosphorus recovery, syngas (power, hydrocarbon upgrading)
Scale	Lab (10-15 kg/h), Pilot (130 kg/h), commercial (125 MW per gasifier unit)
Development Status	Tested in lab-scale, pilot plant under construction

Process Description

The subsequence process description is put together from information provided by the developers (a) in response to a questionnaire and as an additional comment to a request for feedback, (b) on their homepage and (c) in a review of R&D-activities at RWE included in *Verwertung von Klärschlamm 2* [1-4].

Sewage sludge and lignite coal (in its role as a carbon carrier) are dried and finely milled before being co-processed in the gasifier, which is designed and optimized to achieve high process temperatures at minimal oxygen consumption. Steam is used as a co-oxidant [4]. Gasification takes place in an atmospheric, refractory lined, entrained-flow reactor operated at ~ 1500 °C with a dip quench and liquid ash discharge [6]. The process temperature is high enough for the phosphorus to enter the gas phase. The setup of the gasification system at the pilot plant under construction in Niederaussem is not known but the core process has been tested in a lab-scale gasifier divided into two zones with independent oxidant feeding points directly connected by a throat. After entering the gasifier through the throat, the feedstock is entrained into the upper zone by the gas rising from the lower zone, which function as a fixed-bed reactor for the gasification of the char agglomerate. However, according to RWE Power, P-release to the gas phase during lab tests has been observed to be very small, which is presumably due to the technology used not providing sufficiently high temperature and sufficiently low oxygen partial pressure simultaneously. Based on that experience, the design of the pilot plant has been optimized to better achieve high temperature and low oxygen partial pressure at the same time. Syngas cleaning consists of a dip quench and a water scrubber for the main raw gas stream, which is combusted in the boiler of a neighbouring power station and passage through a ceramic candle filter for particle removal and phosphorus separation for a small slip stream.

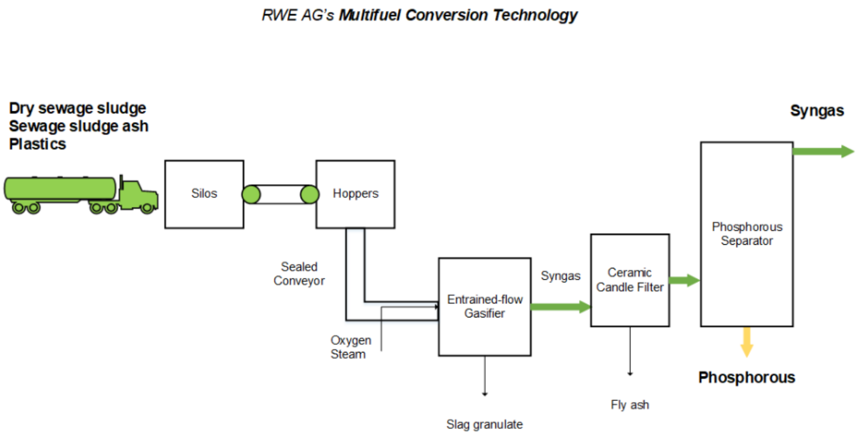

Figure 7. A schematic for the MFC technology-based Niederaussem pilot. Adapted from a presentation by one of the partners in the ITZ-CC project (pilot testing of the MFC technology) [5]

Development Status, Applications, Production Scale

A 130 kg/h pilot plant is currently under construction in Niederaussem, Germany as a part of the ITZ-CC project with start-up scheduled for spring 2021 [1, 6]. The project budget is 6.7 MEUR and the plant is being part-funded by the State of North Rhine Westphalia [6]. Fraunhofer UMSICHT and Ruhr Universität Bochum are partners in the project, DBI Virtuhcon GmbH is responsible for Gasification CFD design and TAF is the main contractor [5]. Recovery of carbon in the form of syngas and phosphorus from sewage sludge is considered to be the first step and the recycling of other, currently unspecified, raw materials is also planned.

The development of the MFC technology was spurred by gasification trials of sewage sludge, sewage sludge ash and dried lignite mixtures in the 10-15 kg/h lab-scale COORVED gasifier at TU Bergakademie Freiberg during which significant P-release was observed in certain test campaigns. However, these promising results could not be reproduced reliably [2, 4]. Research topics for testing trials at the upcoming pilot include optimal feedstock mixes (combinations of sewage sludge and a carbon carried) and processes for introducing said mixes into the gasifier, suitable process and conditions for phosphorus extraction and syngas upgrading [3].

Technology Readiness Level

An assessment of the technology readiness of the MFC technology is provided in Table 15.

Table 15. Assessment of technology readiness for RWE Power AG's MFC technology

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	2-3	20	Covers the storage of feedstocks and the feeding system to the gasifier. Identification of suitable feeding processes for optimal feedstock mixes is part of the research and development outcomes for the upcoming pilot unit. In response to a request for comment on the evaluation, RWE Power AG noted that the storage and feeding system are well-proven commercial technologies with TRL 9. This is true for the case of brown coal but the co-feeding of sludge, lignite and other intended feedstock under the operating conditions foreseen for the gasification has, to the best of the authors' knowledge not been demonstrated. Therefore, according to the methodology used for the present assessment in which the novelty of the feed and the technology combination is explicitly considered, the feedstock handling system is assigned a TRL of 2-3.
Gasification reactor with heat supply	3-4	30	Covers the gasification of the feedstock mixes. Lab-scale testing has been carried out but limited information on whether the lab configuration is the same as the intended pilot configuration mean the TRL of this step is uncertain and a provisional score of 3-4 is thus assigned.
Product gas separation and cleaning	2-3	30	Covers syngas cleaning and phosphorus separation. Information on which streams would be subject to phosphorus separation at the pilot unit (e.g., fly ash) could not be found in available literature. A TRL score of 2-3 is assigned based on current

Process steps	TRL	Weight [%]	Comments
			evidence but would be subject to an upward revision pending the outcome of the planned research on suitable processes for phosphorous extraction at the pilot.
Integrated operation	2	20	The different steps in the MFC process have not been tested as a part of a single configuration. Integrated testing is envisioned for the upcoming pilot plant, which is currently under construction. A TRL score of 2 thus reflect the present state of technology readiness and is subject to an upward revision pending the successful demonstration of integrated operation.
Overall “Weighted Average”	2.3-3.1		
Overall “Weakest Link”	2		

Developer Feedback

RWE Power AG responded to a request for feedback on the technology assessment with corrections and clarifications on various technical aspects. They also observed that storage and feeding system are well-proven, commercially available technologies with TRL 9. Their observation is addressed in the comment on the feedstock handling system in Table 15.

References

[1] Response by RWE Power AB to an in-project questionnaire

[2] Response by RWE Power AG to a request for feedback on technology evaluation

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PLASCO GASIFICATION & PLASMA REFINING SYSTEM BY PLASCO CONVERSION TECHNOLOGIES INC. [CANADA]

Plasco Conversion Technologies' Plasco Gasification & Plasma Refining System is characterized by a three-step process configuration in which municipal solid waste is subjected to moving-bed pyrolysis, the resulting solid fraction is oxidized for heat recovery, while the volatiles are exposed to plasma plumes for cracking resident tars [1]

Table 16. Technology profile for Plasco Conversion Technologies' Plasco Gasification & Plasma Refining System

Designation	Plasco Gasification & Plasma Refining System
Developer/Promotor	Plasco Conversion Technologies Inc. [Canada]
Gasification Method	Plasma gasification of tar
Feeding System	Batch loading (delivery by truck)
Oxidant	Air, oxygen
Principal Feedstock(s)	Unprocessed municipal solid waste
Principal Application(s)	Power (gas engine combined cycle)
Scale	Multiple 200 tpd municipal solid waste modules in series
Development Status	Parts of the configuration tested in a 60 kW_{th} pilot

Process Description

The subsequent process description is put together in the main from information provided on the developer's website [1] and in a recent report on the gasification of waste for energy carriers [2].

MSW is assumed to be unprocessed and is shredded into 12-20 cm pieces, which are separated into a coarse (>5cm) and a fine (<5cm) fraction in an electromagnetic ferrous separation unit and a vibrating screen-type classifier. Both fractions are sent through eddy current separators to remove aluminum after which the coarser fraction is re-shredded, while the fine fraction is delivered to material storage. The MSW enters the gasifier proper on a horizontal moving grate of propriety design heated with sub-stoichiometric air (fed at 300 °C) to 600 °C. The volatile gases released by the devolatilizing and pyrolysis reactions are led to a refining chamber, while the solid fraction left behind is pushed into a 'carbon recovery vessel'. The volatiles from the grate are mixed turbulently with preheated air or oxygen (the company website offers both possibilities) before exposure to plasma plumes. According to Plasco, plasma is used for refining and catalysis to crack tars, not as a primary heat source. Following exposure to plasma, syngas is held in a chamber for five seconds to complete cracking reactions before being sent to a heat recuperator.

The carbon recovery vessel serves multiple functions within the process. The inorganic components in the solid fraction from the grate are brought to a molten state, while the organic fixed carbon fraction is converted to syngas by char gasification. According to Plasco, the process does not generate any residual fly ash secondary waste as the bottom ash from the grate, the particulates from the cyclones and the downstream gas cleaning units are all recirculated back to the 'carbon recovery vessel'.

Plasco Conversion Technologies' ***Plasma Refining & Gasification System***

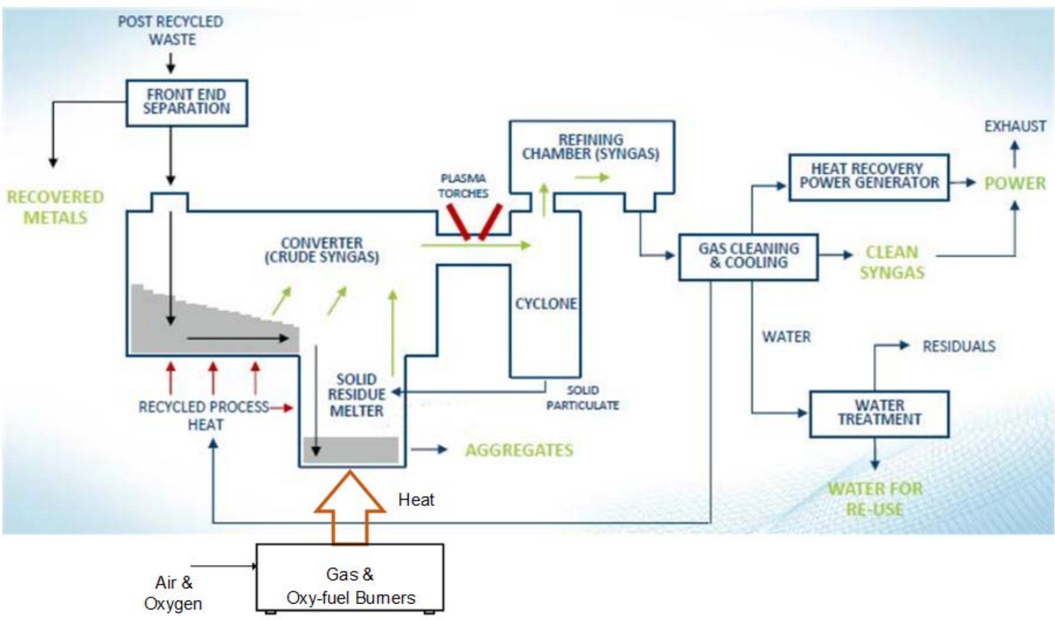

Figure 8. Integrated Conversion & Refining System, taken from [2] and adapted to represent the present heating arrangements for the solid residue melter

Ash from the carbon recovery vessel is sent to the 'solid residues melter' located under the bottom of the carbon recovery vessel and separated from it by a grate. The solid residue melter superheats the molten ash and provides enriched pre-heated air to the bottom of the carbon recovery vessel. The superheated ash is subjected to rapid cooling in a water quench, which produces a non-leachable and vitrified product. In the configuration presented on Plasco's homepage in 2020, heat is delivered to the solid recovery melter by a gas burner running on preheated air enriched with oxygen and supplemented by two oxy-gas burners.

Syngas is cooled to 750 °C upstream of a quench and the heat recovered is used for warming up process air. Some of the process air is used in the gasification process (such as in the carbon recovery vessel), but the bulk of it is available for feedstock drying or steam production. According to Plasco, re-formation of dioxins and furans is prevented by ensuring there is no oxygen in the syngas. Process steps in the gas cleaning set up include a Venturi scrubber, a wet electrostatic precipitator, a sulfur scrubber, and an activated carbon vessel.

Development Status, Applications, Production Scale

The core process steps in the Plasco Gasification and Plasma Refining System were tested and demonstrated in the Integrated Conversion & Refining System (ICARS) at the 135 tpd Trail Road demonstration plant between 2012 and 2015. Subsequent commercial plans fell through. See [2] for more details.

The present configuration offered by the developer differs from the demonstrated configuration in a few aspects, chief among them, a new non-plasma-based design for the solid residue conversion system and updated configurations for syngas cooling and cleaning [1]. The Trail Road facility was simplified, in particular regarding energy optimization and did not include, for instance, a steam bottoming cycle [2].

The cleaned syngas is suitable for a range of heat and power applications, from boilers to IC engines and gas turbines [1]. According to Plasco, each ICARS unit can process up to 200 t/d of MSW and ICARS units can also be operated in parallel for increased capacity.

Technology Readiness Level

An assessment of the technology readiness of the Plasco Gasification & Plasma Refining System technology is provided in Table 17. The TRL score and weight for the relatively complex gasification reactor with heat supply step was calculated by adding up the TRL scores and weights for individual sub-steps as discussed in the comments below.

Table 17. Assessment of technology readiness for Plasco Conversion Technologies' Plasco Gasification & Plasma Refining System

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	6-7	10	Covers feeder and waste inlet to the pyrolysis grate. It is assumed that feedstock handling in the commercially offered configuration is carried out following a configuration similar to that at the Trail Road plant based on the use of commercially established technologies.

Process steps	TRL	Weight [%]	Comments
Gasification reactor with heat supply	5.5-6.5	40	Because of its complexity, the gasification reactor with heat supply step is broken down into the following three sub-steps for the purpose of the evaluation: grate pyrolysis, plasma gasification, solid residue conversion. The overall TRL score and weight for the step is computed by adding up the TRL scores and weights for the individual steps. **Grate Pyrolysis** The (propriety) grate design being offered commercially in 2020 is assumed to be the same as the grate used in the 135 tpd Integrated Conversion & Refining System at the Trail Road pilot plant in Ottawa, Canada. As per [2], the demonstration plant, which had a processing capacity approximately two-thirds of the commercial configuration being offered in 2020 was operated successfully – albeit intermittently and subject to certain technical issues –between 2012 and 2015. Grate pyrolysis is assigned a weight of 10% (of the total process weight) and a TRL range of 6-7 is considered to be best representative of the present state of technology readiness. **Plasma Gasification** The tar-refining plasma gasification unit in the 2020 configuration is assumed to have been demonstrated as a part of the Integrated Conversion & Refining System at the Trail Road pilot plant in Ottawa. Plasma gasification is assigned a weight of 20% (of the total process weight) and a TRL range of 6-7 is considered to be best representative of the present state of technology readiness. **Solid Residue Conversion** While individual elements within the solid residue conversion system are presumably based on commercially established designs, the precise solid residue conversion arrangement chosen by Plasco Technologies Inc. is assumed to be a propriety design. According to [2], ash vitrification in the original solid residue conversion setup at Trail Road was carried out with a 300 kW_e plasma torch. A review of the 2020 configuration shows that heat is delivered to the solid recovery melter by a gas

Process steps	TRL	Weight [%]	Comments
			burner running on preheated air enriched with oxygen and supplemented by two oxy-gas burners [1]. It is therefore assumed that the commercial product currently offered by the company no longer includes the use of a plasma torch. Solid residue conversion is assigned a weight of 10% (of the total process weight) and, in the absence of plant demonstration data for the 2020 design, a TRL range of 4-5 is considered to be best representative of the present state of technology readiness.
Product gas separation and cleaning	6-7	20	It is assumed that syngas cooling and cleaning in the commercially offered configuration is carried out following a configuration similar to that at the Trail Road plant based on the use of commercially established technologies.
Integrated operation	5-6	30	In the original (2006) design at the Trails Road demonstration plant, part of the heat in the syngas was recovered by cooling it down in a process quench vessel, which was later replaced with a recuperator to pre-heat the air by cooling the gas to 750 °C in the 2011 rebuild [2]. Furthermore, the syngas cleaning configuration at the Trail Road plant also differs from that being offered in the 2020 configuration. It is unclear whether the commercial configuration on offer (without the use of plasma torch for the vitrification of the slag and including other modifications) has been demonstrated in an integrated form in commercially representative scale.
Overall "Weighted Average"	5.5-6.5		
Overall "Weakest Link"	5-6		

Developer Feedback

Plasco Conversion Technologies did not submit a response to a request for feedback on the technology assessment.

References

[1] https://plascotechnologies.com/our-technology/

[2] https://www.ieabioenergy.com/wp-content/uploads/2019/01/IEA-Bioenergy-Task-33-Gasification-of-waste-for-energy-carriers-20181205-1.pdf

[3] https://plascotechnologies.com/wp-content/uploads/2018/04/plasco-gprs-2.jpg

RADGAS TECHNOLOGY BY ADVANCED BIOFUEL SOLUTIONS LTD. [UK]

The RadGas Technology by Advanced Biofuel Solutions Ltd. (ABSL) uses a two-stage approach combining an oxy-steam fluidized bed gasifier with a catalytic chamber. ABSL are currently in the process of finalizing the construction of a BioSNG demonstration Plant in Swindon, United Kingdom (UK), which they took over after the original developers filed for administration in 2019 [1, 2, 3]. Although ABSL do not mention it explicitly on their website, according to the introductory note to the environmental permit for the Swindon plant, the catalytic chamber is a plasma converter unit [4].

Table 18. Technology profile for Advanced Biofuel Solutions Ltd.'s RadGas Technology

Designation	RadGas Technology
Developer/Promotor	Advanced Biofuel Solutions Ltd. [United Kingdom]
Gasification Method	Fluidized-bed gasifier
Feeding System	Hopper and belt
Oxidant	Oxygen, steam
Principal Feedstock(s)	Refuse derived fuel (RDF)
Principal Application(s)	Bio-Methane, CO_2, vitrified ash
Scale	22 t/d feed (demo), 60 MW_{th} and ~480 t/d feed (commercial)
Development Status	100 kg/h feed (pilot), 6 MW_{th} (demo plant under construction)

Process Description

The subsequent process description is put together from information found on ABSL's homepage, the introductory note to the environmental permit and a YouTube presentation on waste utilization to produce green natural gas from an expert familiar with the Swindon plant [1, 4, 5].

RDF is delivered to the plant in a moving floor trailer, dried and conveyed to an oxy-steam fluidized bed gasifier. The syngas from the gasifier contains high levels of condensable hydrocarbons, sulfur, and heavy metals, which need to be removed before upgrading. The removal of contaminants is carried out in a high temperature plasma converter. Tars are reformed under the action of high temperature and the inorganic ash forming fraction, including bottom ash separated in the fluidized bed and injected into the plasma converter, is vitrified, and removed. After leaving the catalytic convertor, the syngas is cooled with process steam, filtered to remove particulates, and scrubbed to remove acid and alkali contaminants. The clean syngas is then led to a VESTA methanation unit for catalytically upgrading to bio-methane and CO_2. The latter is captured in a separate stream and liquefied for subsequent export.

The vitrified ash has been tested for construction purposes and a trade name, Plasmarok has been registered.

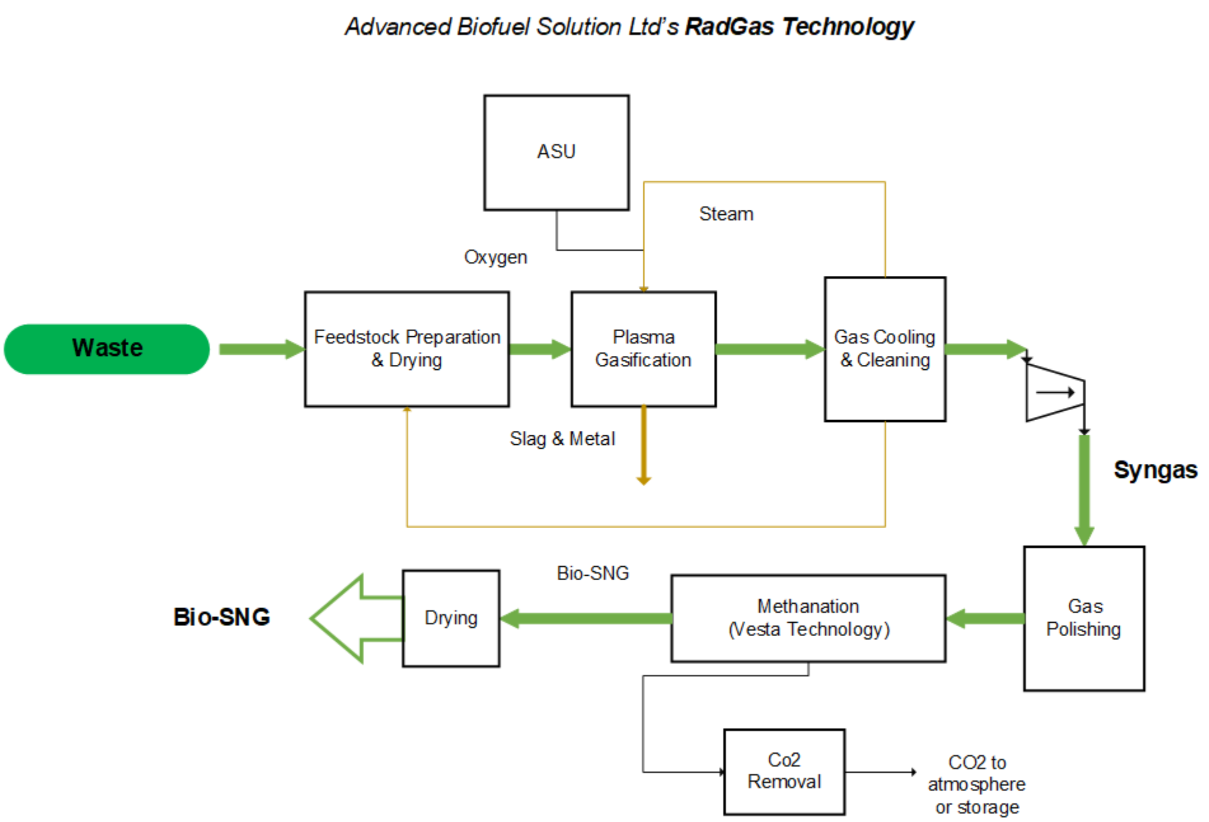

Figure 9. A schematic for the Advanced Biofuel Solution Ltd's RadGas technology as implemented in the Swindon plant. Adapted from a 2016 presentation at a Global Syngas Forum conference by representatives of Advanced Plasma Power (the then project developer) and Amec Foster Wheeler (the methanation system supplier) [7]

Development Status, Applications, Production Scale

A 22 t/d, 6 MW_{th} demo plant to produce BioSNG is nearing completion in Swindon, United Kingdom. Much of the process equipment has been installed [1]. According to a recent update by ABSL on LinkedIn, the cold commissioning of the feedstock handling system took place in the beginning of November 2020 [2]. The construction of the plant was initiated as a joint undertaking by National Grid, Progressive Energy and Advanced Plasma Power under the name of Go Green Fuels. The company entered administration in 2018 and the project was suspended for 14 months before being revived under the name of Advanced Biofuel Solutions Ltd with the support of the UK Department for Transport and gas distributor Cadent [3, 6].

According to the ABSL, the typical scale of a full-sized RadGas line is intended to be 60 MW of thermal input or ~175,000 tonnes per annum of household waste with larger demands being met by multiple lines operating in parallel.

During their time as the developer of the Swindon project, Advanced Plasma Power had referred to their technology as Gasplasma®, which had been tested in a 100 kg/h (~500 kW_{th}) pilot plant in Swindon [7]. The methanation unit for the Swindon plant is being provided by Wood (Amec Foster Wheeler) and is based on the VESTA platform with propriety Ni-based Clariant catalyst tested in a pilot plant in Nanjing, China that started operation in 2014 [8].

Technology Readiness Level

An assessment of the technology readiness of the RadGas Technology is provided in Table 19.

Table 19. Assessment of technology readiness for Advanced Biofuel Solution Ltd's RadGas technology

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	5-6	10	Covers the drying and subsequent conveyance of the prepared feedstock (RDF) to the gasifier. RFD feeding was tested in a pilot unit (< 5% the size of the commercial unit)
Gasification reactor with heat supply	4-5	40	The heart of the process. Covers the fluidized-bed gasifier and the plasma reactor. Demonstrated in a pilot plant (<5% the size of the commercial unit). The fluidized-bed gasifier is being supplied by Metso Outotec Oy. While the company has supplied commercial scale air-blown gasifiers and the gasifier for the APP pilot plant, the full-scale variant would represent the first commercial offering from the company with oxygen as the oxidant [9]. The APP plasma torch is a direct or non-transferred plasma torch, i.e., the slag formed is one of the poles in the electric circuit forming the plasma. The torches are obtained from the previous mother entity Tetronics. Torch longevity and the recharging of the electrodes

Process steps	TRL	Weight [%]	Comments
			during active operation are critical issues.
Product gas separation and cleaning	4-5	20	Covers gas cleaning, methanation and CO_2 separation. The VESTA technology developed by Foster Wheeler is a relatively novel methanation process offered on a commercial basis by Wood plc – an established actor in the business. A demonstration plant has been under operation since 2014. Since it is unclear whether the technology has been employed commercially and whether it has been used for the quality of the syngas stream generated by the cleaning unit in the RadGas technology, a TRL range of 4-5 is considered to be indicative of the present state of technology readiness.
Integrated operation	3-4	30	The integration of the individual technological elements is claimed to be an innovation aspect of the technology. The gasification technology, from feeding to syngas cleaning, have been tested in a pilot plant but evidence for integration with the final use technologies cannot be established. A TRL of 3-4 may best reflect the state of development until the commissioning of the demonstration unit, at which point the TRL for the entire technology would rise to 8.
Overall “Weighted Average”	3.8-4.8		
Overall “Weakest Link”	3-4		

Developer Feedback

Advanced Biofuel Solutions Ltd. did not submit a response to a request for feedback on the technology assessment.

References

[1] https://absl.tech/about-us

[2] https://www.linkedin.com/company/advanced-biofuel-solutions-ltd

[3] https://www.business-sale.com/news/administration/swindon-wastetogas-plant-construction-to-resume-after-administration-219625

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[6] https://www.swindonadvertiser.co.uk/news/18035820.south-marston-energy-plant-will-put-swindon-heart-low-carbon-economy/

[7] https://www.globalsyngas.org/uploads/downloads/2016-11-2-Amec-Foster-Wheeler.pdf

[8] doi: 10.1016/j.egypro.2015.12.092

[9] http://www.ieatask33.org/app/webroot/files/file/2018/Alkmaar-Petten/WS/Waldheim.pdf

ROTARY GASIFICATION BY SUNY COBLESKILL/CARIBOU BIOFUELS [UNITED STATES OF AMERICA]

SUNY Cobleskill's Rotary Gasifier is a portable small-scale gasification unit based on a configuration in which untreated (wet) waste streams, such as municipal solid waste, forestry residue and non-hazardous site wastes can be upgraded to electricity, biofuels and char in an inclined rotary gasifier coupled to a gas cleaning unit [1, 2].

Table 20. Technology profile for SUNY Cobleskill's Inclined Rotary Gasifier technology

Designation	Inclined Indirect Flaming Pyrolysis Rotary Gasification
Developer/Promotor	SUNY Cobleskill/Caribou Biofuels [USA]
Gasification Method	Inclined rotary gasification
Feeding System	Batch loading
Oxidant	Air
Principal Feedstock(s)	Unprocessed municipal solid waste/woody biomass residues/non-hazardous site waste
Principal Application(s)	Power (for military bases), biofuel and biochar (for forestry residue management)
Scale	2 t/d (pilot unit), 0.23 t/h bone dry woody biomass full-scale demo funded
Development Status	Core units tested in pilot scale, funding for demo/commercial unit secured

Process Description

The subsequent process description is based on information provided by the developer in a patent application and in a series of video lectures [1, 2].

Waste streams with moisture exceeding 80% by weight can be processed. In the first step, the wet feed enters a compression chamber where the moisture content in the biomass is reduced mechanically by squeezing. The ideal moisture content for the rotary gasifier is 20-30 wt. %. The feedstock dries as it is pushed half-way up the gasifier, tumbles around and eventually moves downwards to the bottom of the reactor. The gas escapes at the top end of the rotary drum. As the pyrolysis and gasification reactions proceed, the fixed carbon is converted to ash, which is ground to fine powder by the action of a stationary plate at the bottom of the reactor and the rotating ring on the rotary drum and is either discharged to the atmosphere through the air intake clearances or falls into a centrally located collection pen. The major innovation of the gasifier appears to lie in its optimization of the rotation rate and the incline of the rotary vessel, which generates a tumbling motion that continually spreads char particles within the gasifier vessel, thereby facilitating feedstock conversion.

Syngas exits the reactor and is sprayed into a quencher where the organic aerosols condense to a liquid, which is used as the primary liquid to clean the gas in an impingement scrubber. A nozzle at the scrubber inlet generates high velocities, thereby facilitating the mixing of the gas and what the developer refers to as the "oil" stream, which is assumed to be a reference to tars. The tar/oil stream is separated and returned to the gasifier vessel and the particulates trapped within eventually leave the system with the ash. The recirculation and/or introduction of tars/oil into the gasifier vessels leads to the formation of hydrocarbon vapors, which increase the heating value of the gas fraction. The temperature of the syngas leaving the quencher is lower than that of the gas entering the unit as the amount of energy required to re-evaporate the organic vapors and moisture that condense upon spray is greater than the heat that enters the vessel.

Upon exiting the quencher, the syngas undergoes polishing during which it is heated significantly above the pressure dew point using a re-heater. After that it is mixed with combustion air and fed to a diesel engine that drives a generator. In a power-based application, the syngas from the syngas polishing unit is combusted in a diesel engine together with diesel oil with a ratio of up to 80% syngas that drives an electric generator. The exhaust from the engine is used to supply heat to the reactor to increase the temperature of the exiting syngas and superheated steam.

SUNY Cobleskill's ***Inclined Indirect Flaming Pyrolysis Rotary Gasifier***

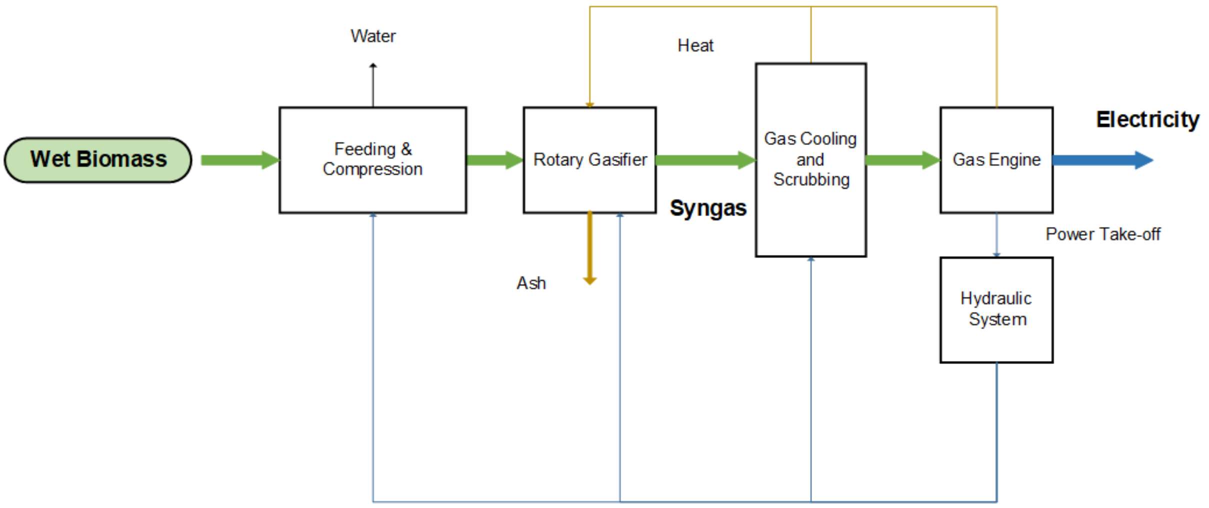

Figure 10. A simplified schematic for SUNY Cobleskill's Inclined Indirect Flaming Pyrolysis Rotary Gasifier based on [1, 2]

Development Status, Applications, Production Scale

The development work on rotary kiln gasification at SUNY Cobleskill goes back to 2009-2010 when the construction of a 2 ton/day, 60 kW_{el} pilot unit was initiated with financial support from the US department of energy and the US department of defense [3]. The pilot was based on the TURNW2E™ technology developed by W2E USA Inc. and shared with SUNY under license [4]. In recent years, development has been led by SUNY Cobleskill. A patent application for an inclined rotary gasifier waste to energy system originally filed in 2015 was recently (September 2020) assigned to Research Foundation of State University of New York [1]. In 2018, SUNY Cobleskill received a 1.6 MUSD grant from DOD and EPA to build and demonstrate a fully automated, mobile rotary gasifier waste-to-energy system at a domestic military base [5, 6]. In 2019, The Research Foundation for SUNY entered an agreement with Caribou Biofuels, Inc. to develop and commercialize a rotary gasifier that turns combustible waste into biofuels and a soil supplement on behalf of SUNY Cobleskill [6, 7]. In May 2020, SUNY Cobleskill announced that it had received 5.8 MUSD from the CAL FIRE program to develop and deploy a 500 lbs/h (bone dry) woody biomass conversion unit to complement fire reduction efforts [6].

Technology Readiness Level

An assessment of the technology readiness of the Inclined Indirect Flaming Pyrolysis Rotary Gasifier technology is provided in Table 21.

Table 21. Assessment of technology readiness for SUNY Cobleskill's Inclined Indirect Flaming Pyrolysis Rotary Gasifier

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	5-6	20	Covers pre-treatment and feeding. It is inferred based on a talk by the developer that the feeding system in the commercial offer has been tested in the 2 t/h pilot unit at SUNY Cobleskill [2]. 2 t/h is approximately 40% capacity of the commercial offerings and the pilot can be viewed as a prototypical system for testing in a relevant environment. A patent by the developers includes no mention of a limestone feeder, which was included as an optional configuration in the report on the demo unit based on the TURNW2E™ gasifier [1, 3]. Since information on the present configuration is scarce, a TRL range of 5-6 is assigned.
Gasification reactor with heat supply	5-6	30	Based on news reports and a talk by the developers, it is inferred that the gasification reactor in the current commercial offer is likely functionally the same as in the testing prototype. A score of 5-6 is assumed to be reflective of the current status of development following the reasoning presented above.
Product gas separation and cleaning	5-6	30	Covers the cleaning of syngas. A score of 5-6 is assigned assuming that separation and cleaning has been part of the prototype tests.
Integrated operation	5-6	20	The technology appears to have been demonstrated in an integrated form for the purpose of power generation and the results have been reported in the literature, although a paywall meant that only the abstract was consulted in this project [8]. It was not possible to ascertain conclusively that the retrieval of oil/tars was part of the integrated testing of the configuration. A demonstration of the setup for the purpose of biofuel production and/or char retrieval could not be found in publicly available literature. A TRL score of 5-6 is assigned for the power generation application only. The TRL for other applications is estimated to be lower.

Process steps	TRL	Weight [%]	Comments
Overall "Weighted Average"	5-6		
Overall "Weakest Link"	5-6		

Developer Feedback

SUNY Cobleskill/Caribou Biofuels did not submit a response to a request for feedback on the technology assessment.

References

[1] https://patents.google.com/patent/US10760016B2/en [Inclined rotary gasifier waste to energy system – US Patent]

[2] https://www.youtube.com/watch?v=welK07i3WL0 [SUNY COBLESKILL Gasification Project: Lecture with Professor Dave Waage]

[3] https://digital.library.unt.edu/ark:/67531/metadc835292/

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TREATECH HYDROTHERMAL GASIFICATION SYSTEM BY TREATECH SARL [SWITZERLAND]

The Hydrothermal Gasification System by TreaTech SARL can be used to upgrade liquid wastes, such as sewage sludge, to clean water, biogas and mineral salts [1]. The technology enables the disposal of wastes that are typically landfilled or incinerated to higher value products, such as phosphoric acid [2]. According to TreaTech, the technology is characterized by a compact design – it fits inside a 30 m^2 shipping container – and an efficient salt separation process, which allows effective recovery of phosphates [3].

Table 22. Technology profile for TreaTech Hydrothermal Gasification System

Designation	TreaTech Hydrothermal Gasification System
Developer/Promotor	TreaTech SARL (in partnership with Paul Scherrer Institute) [Switzerland]
Gasification Method	Hydrothermal Gasification (supercritical)
Feeding System	Pressurized slurry feeding
Oxidant	Supercritical water
Principal Feedstock(s)	Sewage sludge
Principal Application(s)	Bio-Methane, mineral salts (phosphorous)
Scale	500-1000 kg/h feedstock (commercial unit)
Development Status	Lab-scale (1 kg/h) tested; pilot (100 kg/h) in construction; demo (1-2 kg/h) planned

Process Description

The subsequent process description for sewage sludge-based bio-methane implementation is based on information from the company website [1, 3] and in interviews with the founders [4, 5].

Sewage sludge with a dry matter content of 10 wt. % is taken from a wastewater treatment plant (WWTP) and heated up to 400 °C under high pressure (300 bar) in a salt separator. As their solubility decreases, the mineral salts in the sewage sludge start to precipitate from the brine, and the solids are removed from the vessel for further processing. The design of the salt separator is proprietary to TreaTech SARL and is likely similar to that described in a 2015 parent filed by Paul Scherrer Institute on which the chief technology officer of TreaTech SARL is noted as the first author [6].

Following salt removal, the sewage sludge passes through a sulfur removal step before being upgraded to high-pressure biogas in a gasification reactor with the aid of a ruthenium-based catalyst. The share of CH_4 in biogas is 50-85%, while the share of CO_2, H_2 and other gases is 15-50%. The liquid phase left behind after the separation of gas is composed of nitrogen-rich water. It likely also contains dissolved organic and information on whether and how it is treated and recycled could not be found. The biogas is purified and injected into the natural gas grid, although whether that is done at gasification pressure or after a pressure let-down could not be ascertained.

TreaTech's ***Hydrothermal Gasification System***

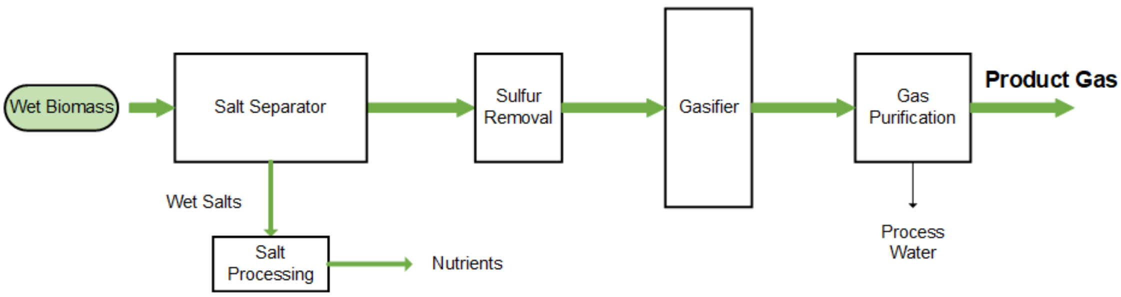

Figure 11. A simplified schematic for TreaTech's Hydrothermal Gasification System

Development Status, Applications, Production Scale

The technology has been tested in bench-scale (1 kg/h) [7]. A pilot plant with the capacity to process 100 kg/h of sewage sludge is under construction and was expected to be completed by the end of summer 2020. Whether the pilot plant is to be operated as a continuous or a batch unit could not be ascertained from the available information. The goal is to launch a 500-1000 kg/h demonstration unit as soon as possible [4].

Technology Readiness Level

An assessment of the technology readiness of the TreaTech Hydrothermal Gasification System is provided in Table 23.

Table 23. Assessment of technology readiness for TreaTech SARL's TreaTech Hydrothermal Gasification System

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	3-4	40	Covers the production of biomass slurry and the separation of salts with subsequent treatment. The method of separating salts for recovery is a proprietary design of TreaTech SARL and the step is key to the overall process, which has been tested in a 1 kg/h bench-scale reactor [7]. Testing details are not provided on the company website, though as TreaTech's research is being supported by Paul Scherrer Institute, it is likely that testing was carried out in collaboration. At 1 kg/h, the bench-scale reactor represents less than 1% of the commercial product capacity and is probably not a continuous reactor. Pumping material into the reactor and the through the let-down valves is a challenge and extended operation is needed to satisfy the requirements for a TRL score of 5. A TRL score between 3 (active R&D is initiated) and 4 (a bench-scale prototype has been developed) may best reflect the present development level.
Gasification reactor with heat supply	3-4	30	Covers the catalytic gasification of the feedstock after the salts have been removed. Important aspects include the choice of catalyst and the process settings for gasification. Detailed analysis of syngas yields, and balances is not available on the developer's website. It is worth noting that the catalyst, Ruthenium, is extremely rare, with annual production in the order of 30 tons/y globally and expensive, with costs around 1500 USD/kg and a consequent requirement for very high levels of catalyst recovery. A TRL of 3-4 may best reflect the development status and future challenges.
Product gas separation and cleaning	2	10	Provided that gasification functions as intended, the separation of bio-methane from other constituents in the biogas such as CO_2 can be carried out with established technologies, e.g., membrane separation and pressurized swing absorption. However, in the absence of information on syngas composition and on whether the syngas from the gasifier has undergone purification and if so at what pressure, the step

Process steps	TRL	Weight [%]	Comments
			remains at TRL 2. Once proof of testing is available, the TRL score could be revised upwards to 8-9.
Integrated operation	2	20	There is little evidence or proof available for integrated testing of all of the relevant process steps for a commercial unit, including the separation of phosphorous and/or other elements in bench-scale, which is likely also impractical. This will likely change once the pilot plant is commissioned but until then a TRL score of 2 (applications are speculative and examples are limited to analytical study) may best reflect the development level of integrated operation.
Overall "Weighted Average"	2.7-3.4		
Overall "Weakest Link"	2		

Developer Feedback

TreaTech SARL did not submit a response to a request for feedback on the technology assessment.

References

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[2] https://solarimpulse.com/companies/treatech-sarl

[3] http://trea-tech.com/app/uploads/2017/09/201707_TreaTech_GWI.pdf

[4] https://www.sccer-biosweet.ch/sccer-biosweet-interview-with-frederic-juillard/

[5] https://www.youtube.com/watch?v=UNgDafL9UTg

[6] https://patents.google.com/patent/US10472267B2/en

[7] http://www.grtgaz.com/fileadmin/plaquettes/en/2020/Hydrothermal-Gasification.pdf

OTHER EMERGING TECHNOLOGIES

A non-exhaustive list of technologies that made it to the initial list for screening but were not taken forward for the TRL evaluation is provided in Table 24 for reference. Reasons for their exclusion varied from lack of information and limited novelty to similarity in technical configuration with an examined technology.

Table 24. List of biomass and waste gasification technologies included in the initial list for screening but not taken forward for the TRL evaluation

Technology	Developer [Country]
Al-Shrooq skid-mounted gasification unit	Al Shrooq Green Energy [United Arab Emirates]
Ankur downdraft gasifiers	Ankur Scientific Energy Technologies Pvt. Ltd. [India]
Biomass pyro-gasification (WoodRoll®)	Cortus Energy [Sweden]
Bright Circular supercritical waster gasification	Bright Circular [The Netherlands]
Fixed-bed downdraft gasifier	Zeropoint Cleantech [United States]
Fluidized-bed gasification	Hysytech [Italy]
GreenE gasification technology	Greene Waste to Energy Spain]
Hyrothermal gasification	Osaka Gas [Japan]

DISCUSSION AND CONCLUDING REMARKS

A methodological approach aiming at a consistent evaluation of the development status of relatively less well-established waste and biomass gasification technologies has been devised and applied to a sample of ten emerging technologies. The approach is centered on the assignation of discrete technology readiness level (TRL) scores to the essential process sub-steps common to all gasification technologies, namely, feedstock handling, gasification reactor with heat supply, product gas separation and cleaning, integrated operation.

Information from various sources has been collected and used as far as possible to identify process configuration and compile process profiles based on a standard template.

The major findings and takeaways can be framed in terms of two broad questions: is the devised methodology fit for purpose? What insights have the individual evaluations provided that may be applicable to the aggregate field?

The method devised breaks each technology down into four sub-steps with integrated operation being treated as category in its own right as interfacing process units adds complexity. Each of the four steps is then assigned a TRL score and a percentage weight. Since generalized TRL scoring guidelines, such as those put together by the EU or the US Department of Energy are available, maintaining internal consistency is easier for the assignment of TRL scores than for the assignment of weights.

The category of gasification reactor with heat supply is given the largest weight in most instances but in this work, weightings still entail an individual assessment of not only how each step compares against the others in the same process chain but also of how it measures up against equivalent technical processes in other gasification technologies. In this context, identifying the step with the lowest score i.e., the “weakest link” and providing it as a complement to a weighted score is motivated and serves to direct attention to the focal points for future development work. An aspect of the devised methodology is the use of TRL ranges, which are recommended for use in instances where granularity in scoring can be misleading, such as when the evidence available is of a generalized nature. It is also when the information is patchy that the effectiveness of the devised approach, particularly with regards to the assignment of weightings, is particularly reliant on the experience and subject matter expertise of the assessor.

The amount and quality of information publicly available for each evaluation varied greatly from technology to technology. But publicly available information is sometimes only a limited part of the data and know-how of a developer. Developers have very different policies regarding the extent to which they are disseminating results and are willing to release information on request, which will directly influence the possibility, and more importantly, the accuracy of the assessment. Ideally, the assessment should be based on a template questionnaire fully completed by the developers, but, from experience, such an approach will face the same limitations in terms of the quality of responses as the use of public information.

The asymmetry in data and evidence between the different technologies was accounted for in the assignment of scores and weightings to some extent in this work and an attempt has been made to highlight the lack of information where relevant. Nonetheless, care must be taken when interpreting the scores, particularly since in some cases, resolving the ambiguity in the exact development status can lead to significant shifts in TRLs. Integrated operation was the weakest link in the case of some technologies where, for instances, the gasification reactor itself was at a higher level of technology readiness. This supports the utility of a methodological approach that can provide differentiated insights into the development trajectories of emerging technologies.

A particular example is when a developer claims that some part of the process does not require some form of validation, as there is commercial equipment available. If this is the case, then the score is TRL9. This would imply that the equipment has been in used under very similar operating conditions and capacity as well as entry and exit process stream quality and specifications. Nevertheless, in many instances the developer refers in more general terms to specific equipment more or less off the shelf, for example scrubbers, filter, electrostatic precipitators, that may also have been used in other gasification processes. However, experience from many projects indicate that although such equipment is available, it takes time and efforts to get the integration of such off-the-shelf equipment to work as intended a new process environment and only then can one arrive at fungible equipment specifications for future vendor procurement. So, when referring to the use of commercial equipment, this can also be a sign of that the developer does not have enough insight and experience to realize the process integration problems ahead. This could be seen on the other end of the scale, i.e., as a status of having formulated a concept, which is only TRL2. Judging between these extremes, when there is actually very little specific information available, puts a high demand on the assessor.

Regarding the insights resulting from the assessment, the comparison of technologies where the commercial capacity goal varies from very small scale, say magnitude of 100 kW thermal to larger scale maybe going to tens of MW thermal in scale gives a positive bias for the smaller scale technologies. The TRL scoring of a development unit at some intermediate size, e.g., 50 kW thermal, will be higher for the technology aiming for a smaller commercial capacity. So, when comparing technologies based on the TRL, the comparison should be for similar capacity ranges to become more like-for-like.

In this work, the sample consisted of only ten, and also very diverse technologies. The limited number of technologies addressing the same feedstock and application prevents drawing any conclusions on the status of different types of gasification systems and application.

However, it can be noted that two systems at least addressed sludges with the ambition to recover nutrients. Sludge gasification, although also being developed in the past to some limited extent, has typically not been in the focus of gasification developers as the feed is, by gasification standards very high in both moisture and ash, thereby limiting the efficiency and gas heating value. But nutrient recovery can be a new demand on sludge systems that may work in the favor of gasification.

Concluding Remarks

Despite the difficulties faced in making an assessment without complete data, the methodology was successfully applied, and hopefully gave some useful information as well as a guide for others who are charged with the task of evaluating the development of gasifier technologies.

Nevertheless, this was a first attempt within the IEA Bioenergy Agreement Task 33 group to make some kind of formalized evaluation such that there is definitely room for further iterations and refining of the methodology.

One way forward could be the development of a standardized data sheet for technology assessment. Another way could be to have some form of formal guidance on the assignment of weighting for different process units. Academic literature often uses various so-called emergent attributes, such as coherence, novelty, growth, prominence and potential to operationalize emergence. Translating these attributes into a practical quantitative or qualitative benchmarking framework can represent one way of ranking technologies in a structured manner.

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