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Review

Barriers to Success: A Technical Review on the Limits and Possible Future Roles of Small Scale Gasifiers

Giulio Allesina and Simone Pedrazzi *

BEELab-Bio Energy Efficiency Laboratory, Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via Vivarelli 10/1, 41125 Modena, Italy; beelab@unimore.it
* Correspondence: simone.pedrazzi@unimore.it; Tel.: +39-059-2056-2229

Abstract: Literature and manuals refer to biomass gasification as one of the most efficient processes for power generation, highlighting features, such as residual biomass use, distributed generation and carbon sequestration, that perfectly incorporate gasification into circular economies and sustainable development goals. Despite these features, small scale applications struggle to succeed as a leading solution for sustainable development. The aim of this review is to investigate the existing technological barriers that limit the spreading of biomass gasification from a socio-technical point of view. The review outlines how existing technologies originated from under feed-in-tariff regimes and highlights where the current design goals strongly differ from what will be needed in the near future. Relevant market-ready small-scale gasification systems are analyzed under this lens, leading to an analysis of the reactor and filtration design. To help understand the economical sustainability of these plants, an analysis of the influence of capital expenditures and operating expenditures on the return of investment is included in the discussion. Finally, a literature review on prototypes and pre-market reactors is used as a basis for spotting the characteristics of the system that will likely resolve issues around fuel flexibility, cost efficiency and load variability.

Keywords: biomass; gasification; biochar; bioenergy; CHP

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1. Introduction

Biomass-to-power technologies are often addressed as key actors in the socio-technical transition which is aimed at reaching global sustainability goals and driving sustainable development [1]. Among the heterogeneous biomass-to-power technologies, small scale gasification systems are considered to be promising solutions due to their good power density over footprints and their satisfactory global biomass-to-electricity efficiency.

A review of the literature showed that there is no univocal definition of a "small scale" gasification plant. The maximum power output may range from 100 kW [2] to 500 kW as the limit of the fixed bed reactor architecture [3,4], however some authors set the limit to an average 200 kW [5,6]. In order to use the broadest definition, a gasification CHP (combined heat and power) plant is here considered to be "small scale" if the nominal electrical power output is below 500 kW. On average, small scale gasifier biomass to electrical production efficiency is above 20%, even for micro-scale generators that are designed to deliver only a few kW of electrical power [3,4].

However, complex control systems are required to maintain constant gasification reactions under the intrinsic biomass moisture, size and quality variability that characterize real case scenarios. Variable running conditions force gasifiers to step outside of their design parameters, resulting in the producer gas starting to show high tar contents [7]. Tar consists of a mix of high molecular weight hydrocarbons, mostly Polycyclic Aromatic Hydrocarbons (PAH), that can be found in a vapor phase when exiting the reactor along with the hot producer gas [7].

Almost all small scale gasification power plants use an Internal Combustion (IC) engine coupled to either a synchronous or asynchronous generator for the final conversion stage [4]. Using the socio-technical multi-level-perspective approach suggested by Geels [8], it is possible to understand why IC engines easily reached a dominant position for the final conversion stage in gasification systems: they can be easily repaired and maintained using well-spread existing know-how and, additionally, the use of IC engine technology as the dominant solution for powering transportation over several decades has increased the availability of spare parts [4].

IC engine utilization forces the gas to be cooled in order to prevent knocking and efficiency losses [4]. At these temperatures, tars partially condensate and need to be filtered out to prevent them from sticking to valves or other engine components. The described scenario, analyzed using the filter of system innovation [9], may lead to unsolved questions, including: if small scale gasification systems are such a good fit for society's needs and goals, why is this technology not yet in common usage? Why is gasification not leading the transition towards sustainability?

This review tries to answer these questions. The discussion covers two major aspects: context analysis and an exploration of the available market-ready technologies. A final overview on literature and academic innovative solutions is then added to the discussion. The basis of the multi-level-perspective approach demonstrates how the transition towards sustainability is not only led by technology, but also needs to coexist with various social and environmental factors [9]. In this section, the development of gasification technologies, alongside the social needs that triggered innovation in this field, is covered. Parallel to the development of the gasification technology two important socio-technical aspects must be considered in order to understand the role of small scale biomass power systems in the transition towards sustainability.

First, it is fundamental to find a common definition of sustainability. This paper refers to the "classical" definition of sustainable development as defined in the report "Our Common Future", published in 1987 by the United Nations and broadly known as Brundtland's report [10], and then finalized in the World Summit on Sustainable Development during 2002. This classical definition outlines the three pillars "social, environmental, economic" which represent the summit motto "People, Planet, Prosperity" [11].

The key to the sustainability of the technological solutions that will be discussed in the following paragraphs must be examined considering social economical and environmental sustainability [12].

Some of the technologies analyzed were developed in countries (mostly within the EU [13,14] and Japan [15,16]) due to a notable push from the presence of consistent subsidies and feed-in-tariff economic strategies that temporarily broadened the boundaries of economical sustainability. For example, from 2012 to 2016, Italy's feed-in-tariff was 229 €/MWh for small scale biomass power plants, with a 30 €/MWh bonus in case of low emissions and a 40 €/MWh bonus in case of high efficiency Combined Heat and Power (CHP) [17]. The temporarily generous added value for the kWh of electrical power that was fed to the national grid shifted reliance on economically disadvantageous solutions to advantageous ones, characterized by high power plant complexity (and, therefore, high cost per installed kW) or solutions requiring highly selected (and, therefore, expensive and often not locally-sourced) biomass [13]. More details on these aspects can be found in the description of the different technologies discussed below.

The technical analysis is presented in the next paragraph, while the socio-economical analysis mentioned before needs to be translated into specific goals that are necessary to overcome the barriers that limit the widespread use of gasification technology. Economic, social and environmental sustainability need to be evaluated for each gasification technology. The technical solution widely used in the EU in recent years, which can be summarized as "a gasifier running at peak power, with selected fuel," is, therefore, the offspring of a feed-in-tariff driven product development. Changing the framework to scenarios without subsidies causes a change in the major goals that drive product development. Going forward, it will be important to design reactors that are capable of efficiently using locally sourced by-products. A few attempts were made to use wood chips [18], corn cobs [19,20], coconut shells [21], vine prunings [22,23], walnut shells [24], and giant reeds [25], among others.

Off-grid use of these systems, as well as smart load management in smart-grid scenarios, needs to move away from the installation of power systems designed to run at peak power only. The power production needs to follow the applied load in off-grid configurations or to respond to a specific energy demand from smart grid management systems [26]. Most of the existing technologies are not capable of running at below nominal power [7].

Lastly, the combined cost of the power plant, the fuel cost and the operation and maintenance costs need to be lowered to reduce the payback time of these systems, as well as creating solutions that approach the cost-effectiveness of photovoltaic power systems. In the conclusion of this paper, the socio-technological framework that feed-in-tariff subsidies provided, over the years, are discussed, along with the technological advantages for complex systems operating with selected fuel. Using a multi-level-perspective lexicon, we investigate how new drivers are now creating pressure on the socio-technical regime of small scale gasification, with the double purpose of showing how the existing systems do not fit within these new requirements and setting the following apparently irreconcilable targets for future gasification system development: (i) fuel flexibility; (ii) cost efficiency; and (iii) load variability. Section 2 reviews the existing technologies in light of these three targets and, then, as concluding remarks, a projection of future out-of-the-box applications of small scale gasification technology is discussed.

Socio-Technical Aspects of Distributed Biomass Power Production

The transition from centralized to decentralized energy production has resulted in a fragmentation of project deployment, with that result that each project is characterized by a universe of stakeholders orbiting around each deployed case.

Following the transitional thinking approach proposed in the Climate KIC Toolbox [27,28], stakeholders participate actively or passively in co-creation/co-destruction processes during the transition to new energy scenarios. Some will benefit from the deployment of a power generation plant (i.e., in terms of energy independency, by-products reuse, or new job opportunities) while others will be damaged (i.e., by reducing the traditional energy production and distribution profits, or creating a real/alleged threat to an area, an ecosystem or just the quiet of a neighborhood).

Therefore, the fragmentation of projects radically increases the complexity of the framework (known as socio-technical regime). Dòci et al. define the regime for renewable energy communities' transition as an interdependent complex system composed of numerous combinations of subsystems that are combined in different ways, which determine the fitness of the regime [29]. This increased complexity is also investigated in the work of Juntunen and Hyysalo [30]:

> "Production of renewable energy is becoming multifaceted and clear demarcation lines between centralized and decentralized, grid-connected and off-grid, and producer and consumer, are increasingly becoming blurred. New configurations consist of different sizes of networks that underpin the energy consumption of consumers and communities [. . .]".

In 2008, Watson et al. [31] described the transition that was happening: As micro-generation is gaining momentum, new types of actors and ways of organizing around micro-generation are emerging. Within this framework, gasification should play a major role. Micro biomass-to-power generators perfectly suit the purposes listed by Wolsink in 2012 in [32]. They can produce added value for the community, helping energy consumption and material usage to be controlled and regulated by the community itself. Other social and technical benefits of biomass power systems are listed by Manara and Zabaniotou [2]:

- Support of the agricultural and forestry sectors by providing solutions for additional income to farmers and forest managers.

- Ecological impact reduction via biomass pathways for energy production (water and soil protection, biodiversity, air quality, etc.).
- Increasing the share of biologically generated fuels within the energy market.
- Reducing fossil fuel consumption and substitution of imported energy flows.

On the other hand, the analysis proposed by Watson empowers the local stakeholders with control, material provision, and energy use roles, while they have also to be significantly involved in all of the operations that are required for power plant maintenance. As reported in [30,33], local key actors take care of functions, such as generation, distribution network, ownership, operation, management service, and the consumer-supplier relationship chain. In these aspects, existing biomass gasification systems do not stand out, as they require daily maintenance operations (while solar or wind power systems require monthly or yearly based maintenance) and impose very tight requirements around fuel quality that reflects on the availability of specific supply chains.

2. Review of Commercial Small Scale Gasification Power Plants

In this section the most relevant commercial power plants are described. An existing system is here discussed and labelled as "commercial" if it satisfies all of the following requirements:

- commercial availability;
- allows continuous feeding;
- allows continuous discharge of char/ashes.

While the first condition is quite self-explanatory, and it exudes all those unique installations that may work quite well but are not available on the market, the second and third conditions are intended to guarantee that the chosen technology is designed to withstand long runs and continuous operation. All of these conditions are set in order to ensure the maturity of the technologies which are analyzed.

2.1. Architecture Similarities and Thomas Reed's Legacy

Despite very few exceptions, which not mentioned in this review, most small scale gasification power plants are designed similarly. A gas generation unit takes care of the thermochemical conversion of the solid biomass. The syngas is then cooled, filtered and sent to an internal combustion engine for electrical power production.

The choice of using an IC engine obligates the system to feature a gas cooling stage in order to prevent knocking and efficiency losses [4]. While the gas temperatures decrease, tars partially condensate and must be filtered out to prevent them from sticking to valves and other engine components.

In 1998, Prof. Thomas B. Reed [34], one of the "fathers" of modern fixed bed gasification, gave his personal review about gasification system development, stating,

> "The typical project starts with new ideas, announcements at meetings, construction of the new gasifier. Then it is found that the gas contains 0.1–10% of 'tars'. The rest of the time and money is spent trying to solve this problem".

Unfortunately, this brutal process continues today, often fueled by the minimum effort required to convert biomass to gas, which obscures any deep understanding of the complex phenomena that are required to design a system that works properly and continuously. As previously discussed, over the decades, gasifier manufacturers found two major common strategies to avoid Reed's prophecy:

- Narrowing of the boundary operating conditions (selected fuel running at specific load): stabilization of the gasification reactions and operating conditions through reduced fuel and load variability, leading to the reliance on highly selective and expensive dry biomass within power plants which are designed to run at nominal power only [35,36].
- Robustness and overabundance of gas filtration systems: this strategy consists of preserving the IC engine through extensive gas filtration stages. Filters, such as water,

oil or solvent wet scrubber, high voltage electrostatic candles, ceramic, metal mesh and baghouse filters are often used alone or in combination to prevent soot and tars from reaching the engine intake manifold [37,38]. These solutions allow fewer restrictions on the fuel choice and operating conditions but lead to the high cost and complexity of the power plant, together with high operational costs for filter maintenance and filter by-product disposal.

Regardless of the chosen solution, in the end, the Capital Expenditures (CAPEX) and Operating Expenses (OPEX) of gasification power plants are often too high to self-sustain the investment without high subsidies for electrical energy production.

2.2. Commercial Small Scale Gasification Power Plants

The following sub-paragraphs alphabetically list the most widespread commercial solutions for small scale gasification systems. After the description of each technology investigated, Table 1 resumes and compares the aforementioned technologies in terms of peculiarities, advantages, disadvantages, CHP efficiency and number of installations.

2.2.1. Ankur Scientific Energy Technologies Pvt. Ltd.

Ankur Scientific produces gasifiers in a wide range of nominal electrical capacities, from 10 to 2000 kW [39,40]. Ankur Scientific gasifiers are designed to be fueled with various types of woody biomasses. Depending on the specific gasifier model, the woody biomass must be properly sized. For all the reactors, the moisture content must be kept below 20%. The reactor consists of single-throat, downdraft architecture. The filtration system is composed of a particle separator, a gas cooling scrubber, with water and tars condensation, and a final stage with a demister and saw dust filter.

2.2.2. Burkhart GmbH

Burkhardt is the world leader of wood pellet gasification. All of their CHP plants use a patented partially fluidized bed rising co-current reactor [41]. This architecture differs significantly from the other systems presented in this work, warranting a specific description of the process as reported in the producer datasheet [42]:

> "In this process, the wood pellets are fed into the reactor from below. An updraught cocurrent flow gasification takes place there while forming a stationary fluidised bed. This is generated with an airflow over a side-channel compressor. A bed material is not necessary here, since the fuel stabilises by itself. Rising means that the stages of gasification (drying, pyrolysis, oxidation and reduction) are passed through from the bottom to the top. The aim is to transfer the highest possible proportion of energy inherent in the solid fuel to the combustible synthesis gas".

The Burkhardt gasifier uses EN plus A1 wood pellets. The standard Burkhardt model is a Wood gasifier V 3.90 equipped with the CHP ECO 165, able to reach a nominal electrical power output of about 165 kW. Recently, Burkhart developed a smaller 50 kW CHP unit fueled with the same wood pellets (Wood gasifier V 4.50 coupled with the CHP smartblock 50 T). Burkhart uses a dry filtration solution for the particle matter.

2.2.3. Costruzione Motori Diesel CMD s.p.a.

The CMD ECO20X gasifier is a moving bed, single throat, downdraft gasifier with a nominal electrical power output of 20 kW [43]. CMD gasifiers can be fuelled with 13 different types of ligno-cellulosic fuel biomass with maximum 20% moisture and typical dimension P45 [26]. Its innovative reactor design provides for such high fuel flexibility [44]. The filtering system is composed of a cyclone, a syngas cooler and a biological filter [43].

2.2.4. ESPE s.r.l.

ESPE is an Italian company that manufactures the CHIP50 biomass CHP unit [45]. The gasifier architecture is a single throat moving bed downdraft gasifier, while filtration is based on a baghouse system. CHIP50 is installed inside a technical shell (container) to reduce dependency on environmental (weather) conditions. The nominal electrical power production is about 50 kW. The gasification char is extracted from the grate at the bottom of the gasifier. The higher temperature inside the single throat gasifier reaches values of around 1100 °C, increasing tar thermal cracking; however, high quality wood chips are required to run the facility (manufacturer suggests P45 W10 [46] woodchip from conifer).

2.2.5. Fröling GmbH

Fröling is a world leader producer of wood boilers and wood stoves. The company also produces a 50 kWel gasifier (the CHP50 gasifier [47]) fed wood chips. The reactor architecture is a single throat, moving bed downdraft gasifier. The syngas is cooled down to 110 °C in a tubular water/gas heat exchanger before the filtering process takes place in a fabric filter with mechanical cleaning.

2.2.6. Glock-Ökoenergie GmbH

Glock wood gasification plants have a nominal electrical power production of 18 kW (GGV 1.7 model) and 50 kW (GGV 2.7 model) [48]. The reference fuel is P16–P31 [46] wood chips with a 30% maximum moisture content. No sieving is necessary, as around 15% of bark and fines are allowed. This peculiarity of fuel flexibility is given by the patented solution [49], where ceramic candles are used as particle filter elements and zeolite powder is injected into the gas line. Zeolite is capable of adsorbing long-chain hydrocarbons, removing those from the filter elements.

2.2.7. GRESCO Power Solution GmbH

Gresco gasifiers are designed to produce 300 and 500 kW of nominal electrical power [50]. The architecture is a downdraft moving bed. The reactor runs with P50–P100 W10 [46] wood chips. P100 is an uncommon size that requires special chipping equipment. The syngas is cooled down and filtered in a vegetable oil scrubber before entering the engine.

2.2.8. Holz Energie UK

Holz Energie produces two models of CHP systems: a 65 kWel and a 125 kWel unit. Both gasifiers use wood chips with a length of 50–70 mm without fines and with a residual moisture lower than 10% [51]. The gasifier architecture consists of a moving bed downdraft reactor. The filter system is a patented solution [52]. It is composed of several sintered stainless steel candles working around 400 °C. The syngas is finally cooled down to 70–80 °C before entering the engine.

2.2.9. Kuntschar Energieerzeugung GmbH

Kuntschar gasifiers are characterized by a nominal electrical power production of 150 kW. They have two key features that differ from other gasifier manufacturers. First, the reactor architecture is based on a patented solution describing a cylindrical vessel, where the combustion is forced to take place within a conical chamber equipped with a grate [53]. Second, the filtration system is made of several ceramic filtering tubes [54] as depicted in Figure 1. On the ceramic candles a partial cracking of the heavy hydrocarbons takes place. This filtration strategy works at a high temperature; therefore, a cooling stage will likely be present in the upstream of the engine.

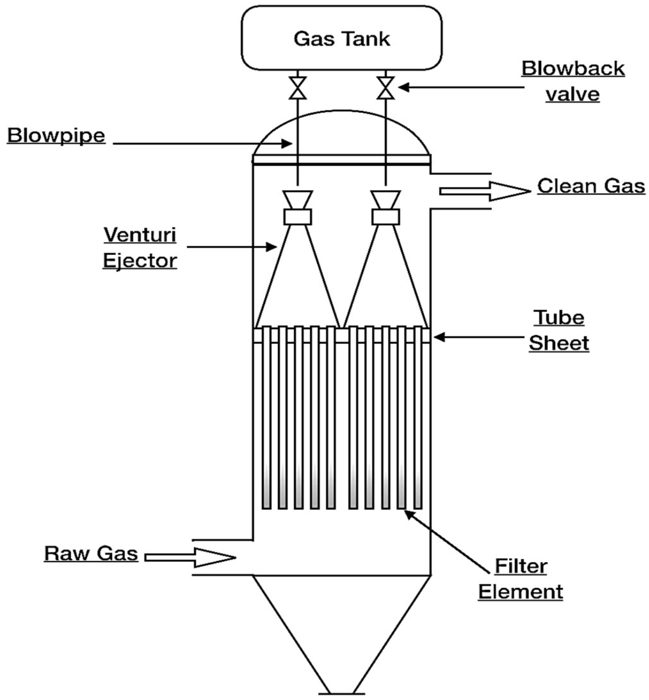

Figure 1. Scheme of a filter system with single tubesheet design (adapted from [36]).

2.2.10. LiPRO Energy GmbH

LiPRO Energy produces a double stage gasifier with a nominal electrical power of 30 and 50 kW [55]. In the first stage, pyrolysis takes place in the fuel auger. The auger is heated by the raw syngas that cools in an external jacket. Pyrolysis gases then combust and char reduction take place in a cylindrical reactor. The syngas can be used in an industrial engine without extensive gas cleaning; only a gas cooling heat exchanger and a baghouse filter are used. However, LiPRO power plants use medium quality wood chips: P45 W15 with low fines (10 mm) < 30%.

2.2.11. RESET s.r.l.

RESET Syngasmart gasifier is a fully automated CHP plant with a nominal electrical capacity of 35 and 60 kW [56]. The system is patented [57] and it runs with low and medium quality biomass: chipped wood residues, nut shells, briquetted-waste wood and briquetted organic biomass. The maximum biomass moisture allowed is 12% and the filtering system is composed of a cyclone, a candle filter, heat exchangers and a final biomass filter.

2.2.12. Spanner Re^2 GmbH

Spanner is the widest installed small scale gasification system [13]. Its Holz-Kraft gasifier is produced at various nominal electrical powers (9, 35, 45, 49, and 70 kW). The architecture, identical in all models, is based on a single throat, moving bed downdraft gasifier [58,59]. Spanner gasifiers must be fed high quality wood at a low moisture content (<13% wt.) and low fines content (<30% of fines below 4 mm). The gas conditioning stage consists of a simple standard tube-in-tube heat exchanger to cool down the gas and a bag filter to separate fine char and tar particles from the gas stream.

2.2.13. Stadtwerke Rosenheim GmbH

Stadtwerke Rosenheim (Rosenheim Municipal Utilities) introduced its own wood gasifier: a double stage gasifier with a pyrolysis stage and a fluidized rising bed stage where combustion and reduction reactions take place [60]. Like other solutions from Stadtwerke Rosenheim GmbH, the syngas does not need severe filtration: it is cooled down and filtered in a baghouse filter before entering the engine. The nominal electrical power of the gasifier is 50 kW and the biomass fuel requirements are: dimension P45, moisture W10 and fines amount <5%.

2.2.14. Syncraft GmbH

Syncraft gasification technology is a double stage patented process [61]. The fuel input is medium quality P45 W10 wood chips that can also contain wood bark. The biomass is pyrolyzed in the first reactor (co-current moving bed) and then gasified in the second reactor (floating moving bed). The division of the two phases facilitates better control of the system and greater fuel flexibility. The syngas filtering and conditioning system is composed of dry and hot ceramic candles that separate the particulate matter (char and soot), a gas cooler and a water scrubber where light tars and water vapor are condensed. This filtering process is efficient and reliable and works properly also with a raw gas that contains high impurities given by the medium quality biomass that is used as fuel. Syncraft produces power plants with electrical capacities from 200 kW to 1 MW [62].

2.2.15. Urbas Energietechnik GmbH

Urbas Energietechnik develops and produces systems for generating electrical and thermal energy from biomass [63,64]. Urbas gasifiers have an electrical nominal power that ranges from 150 to 250 kW [64] and a standard single throat moving bed downdraft reactor architecture. A peculiarity of Urbas technology is the biomass requirements that need high quality P100 W10 [46] wood chips. Furthermore, a sophisticated filtering system is adopted. The filter is composed of a series of ceramic candles that work at around 250–300 °C. A defined amount of $Ca(OH)_2$ is injected into the syngas line after the filter to help the filter cleaning mechanism The $Ca(OH)_2$ injection simultaneously reduces CO_2 content in the producer gas due to the reaction between the carbon dioxide and the injected powder. After dust and particle filtration, the syngas is cooled down in a tube and shell heat exchanger and the condensed water and light tars are collected and disposed of.

2.2.16. Volter Oy

Volter is a company that produces a fully automated 40 kWel gasifier that works with high quality P30 W15 wood chips [65]. The same plant can be installed indoors or outdoors in a customized container. The gasifier is a patented downdraft architecture [66]. The syngas exiting from the reactor is cooled down to 180 °C before the filtration stage in a baghouse filter.

2.2.17. Xylowatt S.A.

Xylowatt produces the patented NOTAR gasifier [67]. The system is scalable from 150 to 750 kW electrical power using medium and low quality biomass wood chips [68]. A gas condition unit is composed of a first gas cooler with a particle filter and a second gas cooler with a scrubber [69].

Table 1. Commercial small scale gasification power plants comparison.

Gasifier Producer	Peculiarities	Advantages	Disadvantages	CHP Efficiency [%] Declared	Grid Feeding Plants
Ankur Scientific Energy Technologies Pvt. Ltd.	Extensive syngas treatment and conditioning system	High biomass flexibility	Tarry condensate disposal	70 (CGE) [40]	8 (Worldwide) [39]
Burkhart GmbH	Updraft fluidized bed reactor fueled with pellet	High number (more than 200) of installation, therefore presumed high reliability	Extremely selected feedstock required (A1 en Plus Pellets)	77	200 (DE, AT, CH, IT, SI, GB, LU, JP) [70]
Costruzione Motori Diesel CMD s.p.a.	Double stage syngas filtering	High biomass flexibility	- [1]	60	8 (IT) [71]
ESPE s.r.l.	Compact design, high integration with auxiliaries	High temperature tar cracking	High quality fuel required	75	18 (IT) [71]
Fröling GmbH	Containerized and indoor systems installation	High wood to electricity efficiency	- [1]	85	5 (DE, AT, SI) [71]
Glock-ökoenergie GmbH	Patented filtering system	Above average fuel flexibility and efficiency	- [1]	90	13 (AT, DE, CH) [70]
GRESCO Power Solution GmbH	Vegetable oil scrubber	High nominal capacity (up to 500 kW)	High quality fuel required	84	N.D.
Holz Energie UK	High temperature filtering system	Robust design, no tar condensation	High quality fuel required	N.D.	120 (EU, JP, CA, ID, CH) [70]
Kuntschar Energieerzeugung GmbH	Patented gasification reactor	Catalytic tar cracking, no tar condensation	High quality fuel required	N.D.	N.D.
LiPRO Energy GmbH	Double stage gasification reactor	Simple gas filtering architecture	Required biomass low in fine particles	78	9 (AU) [71]
RESET s.r.l.	Final stage biomass filter	Above average biomass flexibility	- [1]	64	19 (IT) [71]
Spanner Re^2 GmbH	External char combustor	>700 existing grid-connected plants	High quality fuel required	80	700 (Worldwide) [71]
Stadtwerke Rosenheim GmbH	Double stage updraft gasification reactor	Simple filtering stage	- [1]	85	2 (DE, IT) [70]
Syncraft GmbH	Double stage gasification (1 reactor for pyrolysis and 1 for gasification)	High biomass flexibility	Power plant complexity	83	6 (DE, AU, IT, JP) [70]
Urbas Energietechnik GmbH	Filtering system with ceramic candles and $Ca(OH)_2$ injection	Robust design and no tar condensation	High quality fuel required	75	27 (Worldwide) [70]
Volter Oy	Containerized and indoor systems possibility	High performance patented reactor, simple filtration system	Low power output	84	20 (Worldwide) [65]
Xylowatt	Double stage patented gasifier	High capacity ranges	Tarry condensate disposal	90	6 (BE, FR) [68]

[1] Few existing data available, insufficient data to draw conclusions.

3. Review of Adopted Reactors and Filtration Choices and Their Impact on Power Plant Operation

3.1. Reactors Design

Based on commercial power plant technical analyses, three common designs are used for gasification reactors:

1. "Imbert" type downdraft gasification: Ankur Scientific, CMD, ESPE, Fröling, Glock-ökoenergie, Holz Energie, Kuntschar, RESET, Spanner, Urbas and Volter companies all use a single throat reactor design. This system is often referred to as an "Imbert" gasifier after its designer, French chemical engineer Georges Christian Peter Imbert [72,73]. The literature and technical history recognize the various advantages of the "Imbert" design and its evolutions: these reactors are robust and inexpensive in their fabrication, with low levels of tar production and an acceptable turndown ratio [74,75]. However, the reactor architecture causes low fuel flexibility. The architecture relies on a combustion zone that is generated through a crown of nozzles above the throat, placed at a precise level in the reactor. The homogeneity of the combustion zone is obtained through a proper penetration of the air injected by the nozzles. As a result, there will typically be few combinations of particle sizes and air flow rates where the combustion zone reaches peak homogeneity, thus producing an adequate tar cracking that is virtually free from pyrolysis vapors. The moisture level needs to be low (as discussed in the commercial application review, often the requirements impose a moisture level below 10%). The fuel ash amount must also be low to prevent slagging in the combustion and reduction zones. According to the explanation on how the Imbert reactor works [72,73], it is easy to understand how the acceptable wood chip size depends on the gasifier's thermal power output, growing with the reactor's nominal power. Some producers push this concept to the limit, requiring P100 wood chips, which are difficult to source and produce. For most reactors, fines below 10 mm or 2 mm are not allowed. These restrictions increase the cost of the fuel, as well as the amount of required pre-treatments like drying and sieving. There are producers (Ankur Scientific, CMD, Glock-ökoenergie, RESET) whose reactors have a higher fuel flexibility, but require more complex and expensive filtering systems that are able to process the syngas that is produced in non optimal conditions, with a higher tar content. From a socio-technical point of view, single throat "Imbert" reactors represent a suitable solution only when high fuel quality is guaranteed. It is unlikely that "Imbert" reactors, in their present version, will lead the transition towards a wider use of agro-industrial byproducts, such as corn cobs, vine prunings, nut shells, crop stalks, and fruit pits. Agro-industrial byproducts are characterized by a low heating value, a high size variability and often a high inorganic (ashes) content. These characteristics drive researchers to look into different reactor strategies.
2. Double stage moving bed gasification: LiPRO and Xylowatt gasifiers have a double stage architecture. The pyrolysis stage takes place in a separate vessel using an external heat source (LiPRO) or an internal heat source with a partial combustion of the inlet biomass (Xylowatt). This separation allows for a more efficient and complete drying and pyrolysis process of the inlet biomass [76]. Furthermore, the pyrolysis gas combustion occurs at a high temperature that increases the kinetics of the reduction reactions between the char and exhaust gases [76]. If the system is well balanced, biochar quality is higher compared to standard "Imbert gasifiers" and syngas contaminants are lower. Double stage gasifiers accept medium quality biomass like W15 wood chips with bark and maximum 30% fines. They do not need intensive gas cleaning mechanisms. However, in order to further increase fuel flexibility, Xylowatt uses scrubbers. Therefore, the separation of pyrolysis and combustion/reduction can be set as a winning strategy for increasing gasifier spread, allowing for a higher fuel flexibility. By contrast, phase separation will also bring a series of difficulties to the technical discussion: the most apparent difficulty is the necessity of gas-tight or quasi-gas-tight devices to separate the zones, such as knife

valves, rotary valves and so on. The second challenge is fuel level sensing in areas that are characterized by high temperatures, tar vapors, ongoing combustion, etc. The best solution is to obtain phase separation using a reactor whose architecture does not include valves. Unfortunately to date, very little work has been done on this, with the exception of the remarkable work of Susanto-Beenakers and Van Den Aarsen, as well as a patent from James Mason [77–79]. None of these architectures have reached the commercial stage within the development socio-technical regime that currently exists. If the next few years will be characterized by increasing social pressures to find fuel-flexible solutions to agro-industrial use as biofuel in small scale reactors, these architectures may play a major role in the process.

3. Single stage and double stage rising bed/fluidized gasification: the Burkhart gasifier has a unique updraft co-current, partially fluidized bed architecture optimized for a standardized biomass fuel: EN Plus A1 pellets. The fluidization stage must take into account specific fluid-dynamic fuel properties (drag force), imposing even higher size restrictions compared to the single throat reactors described above. Burkhart reactors are highly optimized for EN Plus A1 pellets only. This makes them a good fit for energy production business plans, where very little concern is paid to local fuel sourcing or overall installation sustainability. These reactors may have a role if they can work around fuel restriction issues once they are capable of processing low grade pellets. Industrial pellets are now forbidden in several parts of the EU for household heating systems due to air pollution restrictions [80,81]; these new regulations apply to stoves and boilers only, creating market opportunities in the legacy of those businesses producing low grade pellets that, today, have lost a relevant portion of the market. Furthermore, even if pelletization is an energy-demanding preprocess, it can bring back the possibility for a list of biomasses otherwise excluded from gasification due to fuel managing issues, i.e., vine prunings, cotton stalks, spent coffee grounds, and even digestate or cattle manure [22,23,82–84]. Different from Burkhardt's solution, Stadtwerke Rosenheim and Syncraft use a double stage gasifier: an auger pyrolysis reactor that uses an external heat source (Stadtwerke Rosenheim) or an internal heat source (Syncraft) coupled with a fluidized co-current bed reactor, where pyrolysis gas combustion and reduction reactions take place. In comparison with the double stage moving bed gasifier, this solution has a higher fuel flexibility and a higher capacity. However, the OPEX cost is high in this plant because of the complexity of the floating bed reactor, which is more difficult to properly control. Therefore, floating bed reactors need a sophisticated control system. In addition, the materials adopted for the fabrication of fluidized gasifiers need to be more resistant to the wearing phenomenon.

3.2. Filter Design

Five common strategies are used for syngas filtering and conditioning:

1. Syngas cooling and baghouse filter: Burkhart, ESPE, Fröling, LiPRO, Spanner, Stadtwerke Rosenheim, Volter and Xylowatt all use a similar strategy, which is syngas cooling and a baghouse filter. Filters reach an average temperature of 110 °C (Fröling) to 180 °C (Volter), as reported by the manufacturers. This filtration strategy is cheap and quite simple. The drawback is that these filters have a high sensitivity to the operating temperature [85]. High temperatures damage the fabric of the filter, while low temperatures initiate various tar compound condensation that abruptly clogs the fabric. When not clogged or damaged, the bag filter can usually be regenerated via mechanical methods (mostly shaking) or pneumatic pulsed jets, and can be reused a finite number of times [54]. During the regeneration process, char particles and the filtering cake collect at the bottom of the filter itself. Another advantage of this filtering solution is the absence of tarry condensate; however, the char extracted from the filter will have adsorbed and collected a significant amount of tar content, limiting

the possibility of mixing it with the quasi-tar-free char that is commonly extracted from the reactor [7].

2. High temperature filtering followed by gas cooling: Glock-ökoenergie, Holz Energie, Kuntschar, Urbas gasifier producers adopt a similar filtration strategy, which is high temperature syngas filtering, followed by syngas cooling in a heat exchanger. High temperature filtration takes place above tar condensation [86]. In some applications a specific chemical additive can be entrained in the flow prior to high temperature filtration to enhance tar cracking, tar absorption or CO_2 reduction [7]. Glock-ökoenergie uses zeolites powder and Urbas uses $Ca(OH)_2$ powder. Pulsed N_2 flows on the top of the candles are used for filter regeneration. Common high temperature filtration solutions use steel (sintered or mesh) or ceramic candles. Ceramic is resistant to higher temperatures compared to metal mesh or sintered steel candles. Conversely, ceramic filters are more prone to cracking due to thermal cycling. This issue magnifies one of the more significant drawbacks of this filtration strategy: these filters require a long start-up time to reach proper operating temperatures. Looking at this restriction in the framework of transition towards a more widespread use of gasification technology, this filtration strategy does not allow for an intermittent use of the gasifiers, and thus forces the power plant to run at nominal power for as long as possible. These operating conditions, perfectly aligned with a feed-in-tariff regime, cannot stand an intermittent use of the system with variable load demand.
3. Use of gas scrubbers combined with other filters: GRESCO adopted a vegetable oil scrubbing stage. Syncraft uses a combination of high temperature filtration followed by gas washing in a water scrubber. Wet filtration usually exceeds dry filtration performances. Other fluid, i.e., oil or biodiesel, can be used to run the scrubbing process at higher temperatures [87]. Two major disadvantages are associated with this technology: the high cost of the equipment (when compared to fabric filters) and the final cost of the exhausted liquid disposal.
4. High temperature filtering followed by gas-cooling and final biomass filters: CMD and RESET use this filtration strategy: first, particle separation at a high temperature through a cyclone and candle filter (only Reset technology), then gas cooling with a tube-and-shell heat exchanger, and final gas filtering with an adsorbent biomass media filter. With this solution, biomass flexibility is higher compared to strategies one and two. This solution is a fair compromise between complexity and flexibility. On the other hand, further investigation is required to understand the load flexibility. This filtration solution is effective when every stage operates at a fixed temperature; dry filtration above tar condensation, and the final stage at the lowest temperature possible. Load variation changes the gas flow rate and the amount of sensible and latent heats that need to be managed by the filtration layout [88].
5. High temperature filtering, scrubber, demister and final biomass filter: as a final example, depicted in Figure 2, the Ankur Scientific gasifier uses a series of filtration stages composed of a high temperature particle separator, a gas cooling in a water scrubber, final filtration with a demister and a saw dust filter. The complexity of this filter train allows high biomass flexibility and an efficient filtration performance. The disadvantages of this system are the complexity and the constant production of tarry water from the scrubber unit. This byproduct has a high disposal cost.

3.3. Cost Efficiency

The previous paragraphs listed the technical characteristics of the most common small scale commercial gasifiers available on the market. Design choices were examined from a transitional thinking point of view, looking at the limits of the offered solutions to the widespread use of gasification technology as a dominant solution for distributed power generation from agro-industrial residues. The first paragraph also introduced the concept of sustainability, including the economic aspects in its definition.

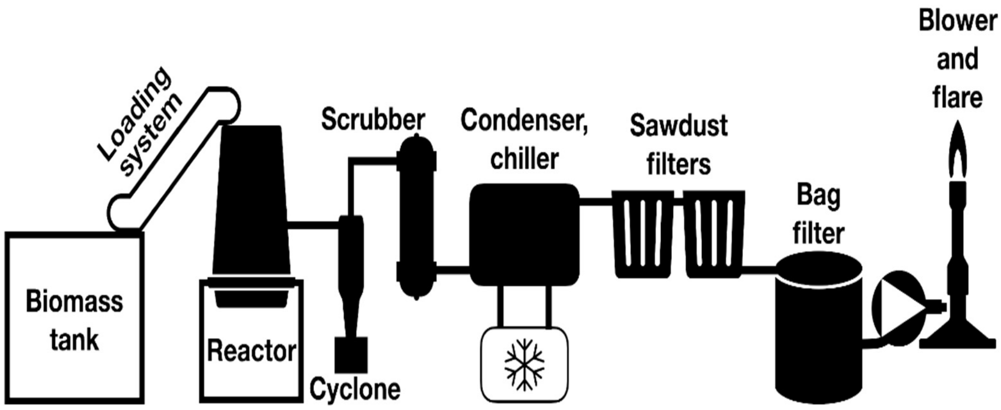

Figure 2. Ankur Scientific filtration system (adapted from [40]).

Several gasification manufacturers are hesitant to publish the cost of their equipment, making it difficult to compare them from an economic point of view. This reluctance is justified by the fact that most of these power plants need to be "tailored" around a specific application, which adds further costs, such as biomass storage, chipping and drying stages. These stages may or may not be necessary, consequently causing the cost of the purchase to vary. In this work, the economic analysis of small scale gasification systems is carried out with two distinct approaches: first, using a literature review, a general cost-benefit analysis was performed.

The authors then generated a CAPEX vs. Internal Rate of Return plot that allows readers to evaluate a specific case in terms of economic sustainability or feasibility.

Several studies tried to evaluate the economic profitability of biomass gasification CHP plants [89–94]. Colantoni et al. [89] used Montecarlo simulation to evaluate important economic indicators, like Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Time (PBT), of three different gasification CHP power plants (13.6 kW, 136 kW, and 1.9 MW nominal electrical capacity). Small scale CHP sizes (13.6, and 136 kW) showed a PBT of 13.6 and 6 years, respectively. Pedrazzi et al. [90] evaluated the economic feasibility of a small scale CHP plant of 20 kW nominal electrical capacity applied to an indoor hemp greenhouse. In this case, a PBT range for 3.5 to 5.5 was evaluated. Cardoso et al. [91] assessed the energetic valorization of forest biomass blends in the archipelago of the Azores through small scale biomass gasifiers. The results showed that 100 kW units were economically impracticable, while the 1000 kW units were found to be economically feasible with an NPV of 486 k€, IRR of 17.44% and PBP of 7.4 years.

Seo et al. [92] performed an economic analysis of a 500 kWel CHP plant using forest biomass in the Republic of Korea. PBT ranges from 4 to 20 years as a function of the electricity selling price and forest biomass price change.

Huang et al. [93] published a comparative techno-economic analysis of biomass fuelled CHP plants for commercial buildings. The study considered two CHP technologies with the same electrical nominal capacity of 150 kWel: Organic Rankine Cycle (ORC) based and biomass gasification systems. The results of the economic analysis demonstrated that the breakeven electricity selling price (BESP) for the ORC-CHP systems varies from 40 to 50 £/MWh and for the biomass gasification based CHP systems was between 87 and 97 £/MWh.

Copa et al. [94] presented a comparative techno-economic analysis concerning the deployment of small-scale gasification systems in dealing with various fuels from two countries, Portugal and Brazil, for electricity generation in a 15 kWel downdraft gasifier. The viability of the projects was predicted for an NPV set between 18.99 to 31.65 k€, an IRR between 16.88 to 20.09% and a PBP between 8.67 to 12.61 years.

Starting from these references, this paragraph intends to define how the boundary conditions within a gasification system will create economically sustainable or even profitable results. The analysis is carried out in economic scenarios where the only sources of income are electrical energy self-consumption, the thermal power production and the biochar sale, without any added subsidy or feed-in-tariff.

Therefore, CAPEX and OPEX need to be balanced with the earnings derived from the above-mentioned sources of income. To do so, financial institutions evaluate the feasibility of the investments using the IRR [95]. As a common guideline, the financing of a biomass power plant is granted if the IRR is higher than an expected value that ranges from 6% (low risk) to 11% (high risk) [96]. In this paper, a variable Net Present Value (NPV) analysis [97] is performed by varying the OPEX and CAPEX of a hypothetical biomass gasification power plant. The objective of this analysis is to find the maximum CAPEX of the investment, considering a constant IRR of the financial institution and a specific OPEX suggested by the gasifier manufacturer. The following hypotheses are taken into account in the NPV analysis Lifespan of the investment:

- Lifespan of the investment: 20 years;
- Internal rate of return (IRR): from 5% to 15% at 20 years [96];
- Electricity prices for non-household consumers: EU average value of 0.1254 €/kWh [97];
- 100% of on-site electricity self-consumption;
- Cost of district heat: average EU value 0.069 €/kWh [98];
- Heat utilization: 50% for biomass drying and 50% for district heating;
- Biochar selling price: 0.3 €/kg [99];
- Biochar production: 2.5%wt. of the inlet biomass [7];
- Standard P45 W10 wood chips cost: 0.1 €/kg [100];
- Biomass specific consumption: 1 kg/kWhel [7];
- OPEX (operation, maintenance and spare parts) specific cost: from 0.03 to 0.07 €/kWh [90];
- Annual running hours: 7500 h;
- Thermal power produced is double the electrical power production.

The results of the variable NPV analysis are depicted in Figure 3. Here, three investment CAPEX over IRR at different specific OPEX are plotted. Figure 3 also shows an example of how to use the graph as a tool for the evaluation of a maximum allowable CAPEX. First, a chosen value of IRR (9%) and a given value of specific OPEX (0.05 €/kWh) are set. The maximum investment CAPEX (3900 €/kW) is then derived from the *y*-axis.

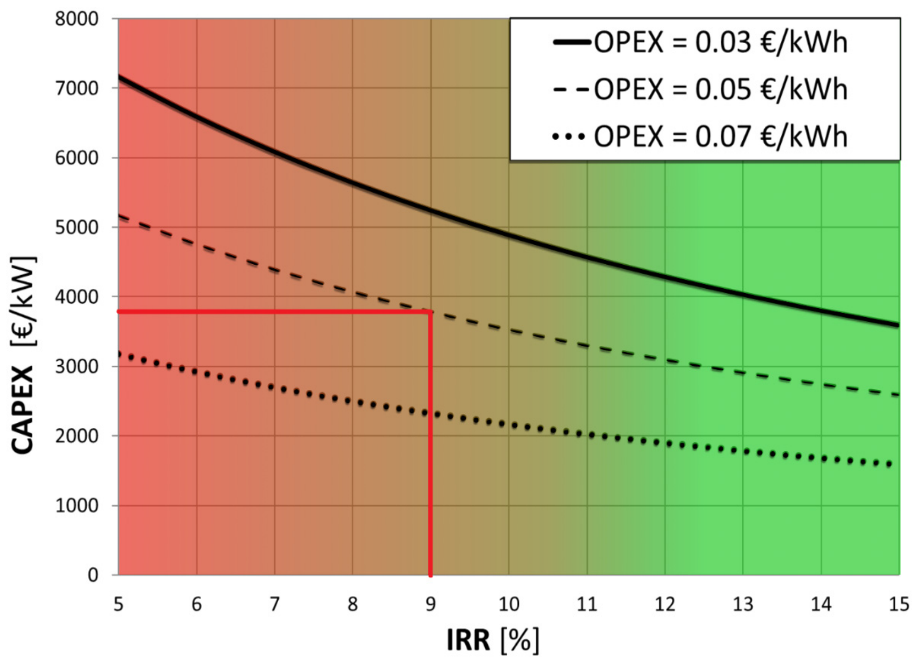

Figure 3. Results of the variable NPV analysis.

A consequence of this analysis is the quantification of the common sense conclusion that the higher the cost of the maintenance (usually associated with complex reactors or filtration designs), the lower the maximum initial cost of the power plant needs to be. Following the opposite path, knowing both the initial cost of the power plant (e.g., 3900 €/kW) and the specific OPEX for that power plant (e.g., 0.05 €/kWh), it is possible to evaluate the IRR of the investment (here 9%). Figure 3 shows the effectiveness of the investment (IRR) using a quantitative chromatic scale, where green represents a highly profitable investment and red represents a not-profitable investment. To reduce the complexity of the results, Figure 3 considers a fixed electrical power production. Small scale gasifiers can also be used in smart grid applications at variable power output [26,32]. In such a case, the evaluation needs to be performed for each load step utilized or for different annual overall energy production.

4. Research and Future Applications

Research about small scale gasification is mainly focused on gasifier design in order to enhance fuel flexibility [101–104] and tar reduction through primary and secondary methods [35,36,105]. Several moving bed and fluidized bed gasifier prototypes have been developed throughout the last decades without reaching market readiness. Among them, there are few reactors that deserve to be discussed. In 1996, Susanto and Beenackers [78] developed a gasifier with internal recirculation and separate pyrolysis gas combustion. The prototype, depicted in Figure 4a, was able to produce a syngas with a low tar content <0.1 g/m3 and a valuable gas higher heating value of 4.5 MJ/Nm3. Pyrolysis gas (D) is recirculated using the Venturi effect of an ejector (E). Recently (2020, depicted in Figure 4b) this architecture has been optimized in a second prototype reactor designed by Rahman et al., reaching even lower levels of tar [79]. As previously discussed, these two systems represent a laudable attempt to create separation between the pyrolysis, combustion and char reduction without using physical separators, i.e., valves, or multi-stage architectures. As previously mentioned in the reactor architectures discussion, a better separation of the phases leads to more complete gasification under load and fuel quality variability; these are two of the three goals set for future success of this technology.

A few years after the Susanto gasifier, Brandt et al. [76] developed the Viking double stage gasifier (Figure 5). The system was fully characterized during 465 h of experimental tests [106]. Here the separation of the phases takes place in different parts of the system. It is also remarkable in terms of heat flow management: the pyrolysis auger is jacketed with engine exhaust gases which are further heated in an exhaust-syngas heat exchanger. This solution allows the jacket to run at high temperatures using a gas that has very little or no PAH condensation issues or particulate content. A more recent evolution of the original Viking research can be found here [107]. An analog double stage architecture was also used by LiPRO for their commercial gasifiers. Despite the promising results of the Viking gasifier, this architecture never reached the commercial stage. Its complexity suggests a high CAPEX that is difficult to counterbalance with proper earnings from the power plant.

The literature also shows several attempts to reduce heat dispersions of the reactors, as well as recover heat from the downstream processes [108]. The fundamental role of thermal loss control for gasification efficiency is discussed in the literature since the first appearance on the market of commercial-ready systems. In 1941, Lutz already listed a series of suggestions for increasing the performances of downdraft gasifiers that, even today, some manufacturers forget to follow [109]. Another strategy to increase gasification efficiency and fuel flexibility is the utilization of concentrated solar energy to heat up gasification agents [110] or gasifier external walls [111].

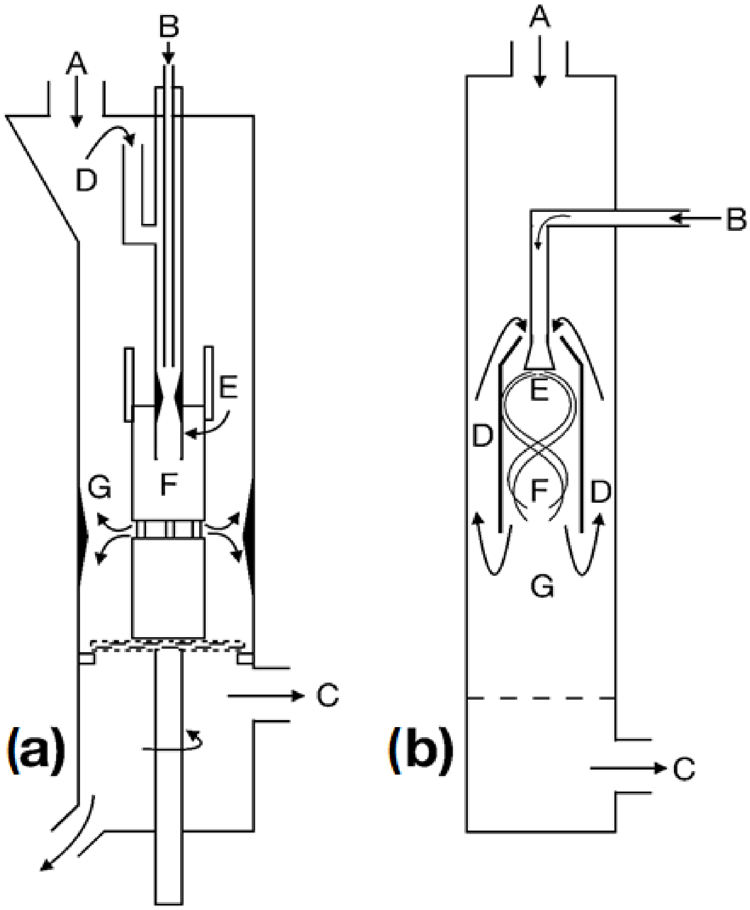

Figure 4. (**a**) Susanto–Beenackers gasifier (adapted from [78]); (**b**) Rahman et al. LTB gasifier (adapted from [79]).

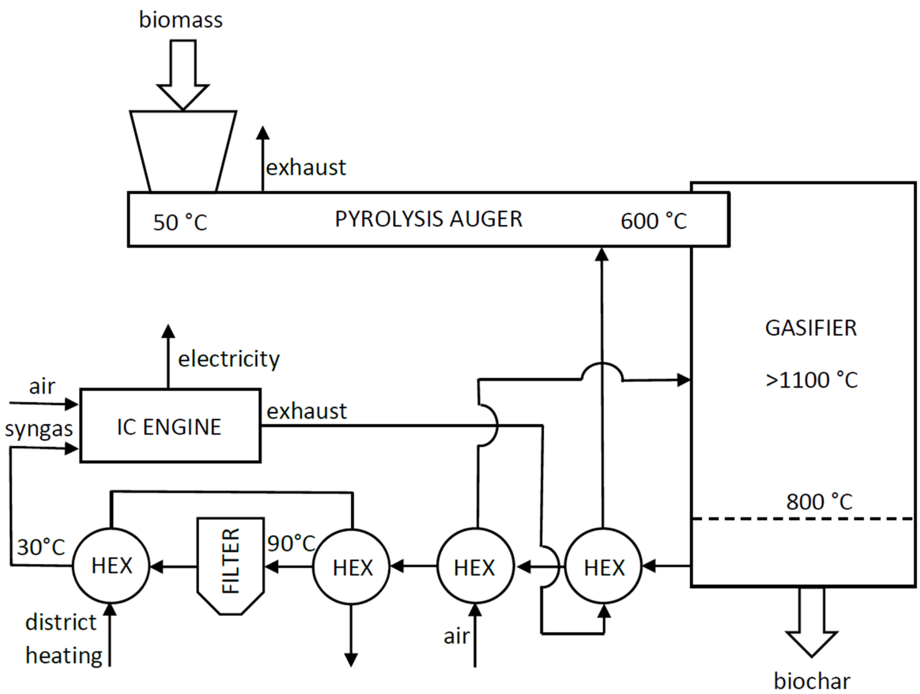

Figure 5. Viking gasifier with several heat exchangers (HEX) (adapted from [107]).

In the last decade, a US-based company, ALL Power Labs [112], has developed a prototype gasifier that uses several heat recovery strategies. The syngas heat is used to perform the drying stage in the fuel auger that connects the hopper to the reactor itself. After this, the top part of the reactor is jacked, and here engine exhaust gases are used to enhance biomass pyrolysis. Finally, a single throat reactor completes the gasification. Several patents [77,113,114] show the evolution of the product. The separation of the phases, combined with a specific bottom reactor design [112,114], allow this gasifier to use a wide range of biomasses [115]. Despite its promising features and the numerous installations reported on the manufacturer website, this product has not yet reached full maturity for continuous 24/7 operation. It still shows a fuel hopper, a legacy design for discontinuous use, and there is no add-on to have a continuous discharge of the biochar, which is collected in two vessels.

Other relevant studies for small scale gasifier development used exhaust gas recirculation from the IC engine to partially or totally substitute the gasification agent or as control mechanism to modify the gasification reaction according to the load variations [116–118].

Between the small and micro scale experimental facilities, it is important to acknowledge the double stage open top gasifier developed at the Indian Institute of Science, Bangalore (India) [119,120]. This reactor was used in a series of researches on fuel flexibility [121–123]. The results of the work on this pilot scale gasifier were partially exported to full scale facilities [101]. Table top size reactors can be a valuable test-bench for testing possible future designs of commercial gasifiers [124–126].

In conclusion of the literature review of the scientifically proposed solutions, it is worth mentioning that a completely different "out of the box" way of solving some of the power plant problems consists in removing the engine and using externally fired solutions, such as ORC, EFGT or Stirling engines [127–129]. These solutions are far from being market-ready for small scale applications due to the difficulties in making EFGT or Stirling engines economically competitive for limited power sizes.

Outcomes of Socio-Technological Analysis of Micro Scale Gasification Use

The analysis proposed in this work clearly stated the existence of a multitude of commercially available solutions that arose from a socio-economical framework where continuous high power operativity was awarded, among other possible features. Somewhat differently, academia is widely fighting to create more flexible prototypes by working on reactor design, innovative reactions management or other "out-of-the-box"solutions. The previous paragraph stated the important features that need to be developed in future biomass-to-power systems, such as fuel flexibility, cost per kW and power modularity. The pursuit of the mentioned goals must be researched, together with other socio technical aspects. Sovacool, in 2009, stated that the proper and healthy growth of renewable energies derive from a broad, effective and wide promotion of the technologies only if this promotion is placed side by side with increasing public understanding of energy systems and challenging entrenched utility practices [130].

This statement outlines a further reason why the existing gasification technologies are inadequate: as long as users and communities expect to deal with and use gasification technologies the same way they operate other renewable energy sources, their expectations will not be met. Gasification requires higher maintenance and different approaches to be correctly used. Therefore, the previously discussed technological inadequacy, combined with an inadequate perception of the technology, leads to major barriers to its development. The future of gasification is, therefore, to be searched in power generation plants capable of using locally sourced by-products, to be active parts of smart-grid systems, coexisting with local communities that are adequately trained and instructed about opportunities and the limits of gasification technologies.

5. Conclusions

The present work aimed at reviewing the existing small scale gasification technology solutions, with the final goal of investigating the socio-technical factors that currently limit the diffusion of biomass gasification. Despite the promising features that perfectly fit gasification within circular economy and sustainable development goals, such as residual biomass use, distributed power generation and carbon sequestration using biochar, this review outlined how existing technologies are the offspring of design drivers of feed-in-tariff regimes. Most existing technologies work properly with selected feedstock at a defined power output, giving little chance to adopt these solutions to close local circular economy loops or to be effectively used as primary generators in a variable load regime such as a smart grid. The economical analysis performed in this review showed further boundaries to the economical sustainability and profitability of small scale biomass-to-power installation. Complex architectures that lead to high OPEX and CAPEX costs struggle to produce profitable results under a framework lacks feed-in-tariff subsidies. Finally, referring to the solutions in various research papers, it is possible to outline how development efforts need to address internal heat recovery and also simplify the separation between pyrolysis, combustion and reduction, producing more clean gases, even with low grade biomasses. Eventually, local communities would benefit from distributed biomass based power generation, if the users understand the potentialities as well as the limits of these solutions.

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