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Costs of Gasification Technologies for Energy and Fuel Production: Overview, Analysis, and Numerical Estimation

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Abstract: During recent years, gasification technology has gained a high potential and attractiveness to convert biomass and other solid wastes into a valuable syngas for energy production or synthesis of new biofuels. The implementation of real gasification facilities implies a good insight of all expenses that are involved, namely investments required in equipment during the project and construction phases (capital expenditures, CapEx) and costs linked to the operation of the plant, or periodic maintenance interventions (operational expenditures, OpEx) or costs related to operations required for an efficient and sustainable performance of a gasification plant (e.g., feedstock pre-treatment and management of by-products). Knowledge of these economic parameters and their corresponding trends over time may help decision-makers to make adequate choices regarding the eligible technologies and to perform comparisons with other conventional scenarios. The present work aims to provide an overview on CapEx associated with gasification technologies devoted to convert biomass or solid waste sources, with a view of reducing the carbon footprint during energy generation or production of new energy carriers. In addition, an analysis of technology cost trends over time using regression methods is also presented, as well as an evaluation of specific capital investments according to the amount of output products generated for different gasification facilities. The novelty of this work is focused on an analysis of CapEx of existing gasification technologies to obtain distinct products (energy and fuels), and to determine mathematical correlations relating technology costs with time and product output. For these purposes, a survey of data and categorization of gasification plants based on the final products was made, and mathematical regression methods were used to obtain the correlations, with a statistical analysis (coefficient of determination) for validation. Specific investments on liquid biofuel production plants exhibited the highest decreasing trend over time, while electricity production became the least attractive solution. Linear correlations of specific investment versus time fitted better for electricity production plants (R^2 = 0.67), while those relating the product output were better for liquid biofuel plants through exponential regressions (R^2 = 0.65).

Keywords: gasification; cost; investment; evolutionary investment trend

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1. Introduction

There is a significant and growing need to develop clean and renewable energy sources to achieve carbon neutrality by 2050 [1]. Biomass gasification is the only method that uses completely renewable resources and offers a range of advantages in terms of its associated environmental impact and carbon neutral characteristics [2]. Thus, it is critical to increase the production capacity of renewable gases from gasification processes. Various innovative gasification technologies are being developed, which offer improved efficiency and cost-effectiveness. These technologies include plasma gasification [3], entrained flow gasification [4,5], dual fluidized bed gasification [6,7], and sorption enhanced gasification [8–10], while other recent developments have been a resurgence in research into oxidizing agents, using air, steam, oxygen, carbon dioxide, or a combination of them [11–15]. It is expected that the hydrogen economy will co-produce large amounts of oxygen as a by-product that could be deployed in oxy-gasification through increasing the syngas LHV by reducing atmospheric N2 dilution, and facilitating carbon capture and storage (CCS) [16,17]. Biomass and waste gasification technologies are being used to convert a wide range of biomass feedstocks, municipal solid waste, sewage sludge, and industrial waste into syngas [18–23]. However, this waste-to-energy approach has recently been criticized by activist groups [24]. Overall, there is a shift in research interests, from waste to energy, towards gasification for chemical production through thermo-catalytic synthesis. To achieve this goal, research are focused on achieving effective syngas clean-up and purification and the development of new catalysts [25–29]. Gasification technology is being used to produce a variety of chemicals such as methane, methanol, ammonia, hydrogen, and sustainable aviation fuels [30–36], which can help reduce the reliance on fossil fuels for chemical production. This approach, coupled with CCS technology to capture and store carbon emissions, has the potential to significantly reduce greenhouse gas emissions from the chemical and energy sector [16].

However, large-scale gasification processes are currently having problems penetrating the market. Several plants have been closed or are still in a planning phase, mostly due to their high investment costs and economically unattractive commercial operations [37].

The most pressing issues in the economic sustainability of large-gasification plants are related to biomass availability and heterogeneity, as considerable amounts of homogeneous feedstock are required to support the operations in these plants. Moreover, according to a report from IRENA (2019), the costs of transporting feedstocks from great distances to gasification plants larger than 50 MW_{th} are not economically viable [38]. Regarding biomass availability, the substantial amounts of feedstock that are required in large-scale gasification plants can lead to the shifting of food crops to unused lands, thereby leading to the conversion of forest areas to arable lands. This shift has a very negative impact on biodiversity and greenhouse gas (GHG) emissions [39]. These aspects need to be addressed in the implementation of these gasification systems by researching different solutions such as using exclusively wastes as feedstocks (e.g., forestry wastes, agricultural wastes, municipal solid wastes), or by mixing different wastes in the feedstock (co-gasification) [37,39,40]. These solutions also have the advantage of increasing waste management sustainability and national energy provision, due to the copious amounts of different waste streams that are produced all year round. Furthermore, feedstock prices can also be reduced when considering waste feedstocks, as the price of input fuels is a key issue in large-scale gasification plants [41]. In addition to feedstock, there are other strategies available to improve the economic viability of large-scale gasification, namely, retrofitting existing fluidized-bed boilers to reduce capital expenditures (CapEx), char and ash valorization, or polygeneration approaches to yield more than one product [40].

Additionally, in what concerns gasification's final products, catalytic synthesis is known to require very high-quality producer gas, meaning that it is mandatory to have proper, and usually expensive, gas cleaning and upgrading processes (e.g., scrubbers, filters, and water-gas shift reactors). These equipment tools are responsible for the significant increases in CapEx and operational expenditures (OpEx) in large-scale gasification plants [42]. This can be improved with different strategies, such as the development and implementation of innovative gas upgrading processes, for instance high-temperature gas cleaning technologies combined with catalytic treatments integrated at the exit of the gasifier. This solution has the advantage of keeping the high temperature of the gas without losses of heat and water vapor, and which are relevant for further high-temperature applications such as fuel cells and catalytic processes for hydrogen and methane production. Moreover, carbon deposition in catalysts may be minimized, and therefore OpEx becomes lower [43]. Furthermore, catalysts for tar reforming and cracking should be further studied, specifically low-cost and regeneratable catalysts such as the gasification by-products (e.g., ash and char) [42,44]. Demonstration plants, such as the GoBiGas plant, can also give precious insights regarding promising operational strategies, production stability, and market prospects, that all have potential to be used for the design and operation of future gasification plants, thereby minimizing the risks of a new installation [45,46]. This is of utmost importance, as realistically, the gasification technology and producer gas cleaning technologies are still in a demonstration phase, presenting various technical and non-technical risks [47]. In addition, the operation and expertise gained in demonstration plants may provide fruitful knowledge regarding marketing strategies for the different products generated (e.g., energy, and liquid and gaseous fuels).

This document aimed to present an overview of several large-scale gasification plants, using different feedstocks and technologies, to establish relationships between their investment costs and outputs throughout the years, from an evolutionary perspective of technology implementation. The novelty relies on the compilation and analysis of CapEx associated with demonstration and commercial gasification plants producing different products (heat, electricity, and other liquid and gaseous fuels), and to establish the mathematical correlations that relate technology costs with the year of implementation and product output. These studies may have a relevant contribution in the activities of decision makers (e.g., government bodies, technology manufacturers, and project developers) that work with similar technologies.

2. Overview of Capital and Operational Expenditures Associated with the Different Stages of Gasification

Regarding CapEx values focused on the scale of gasification technologies, the literature reported that fixed and fluidized bed gasifiers may have total installed capital costs between 1965–5235 €/kW, while gasifiers with CHP systems may have costs between 5115–6010 €/kW [48].

For product gas cleaning modules, there are a variety of technologies developed with this purpose, however the most sold are cyclones, filters, electrostatic precipitators, and wet gas scrubbing. Cyclones can remove up to 90% of the larger size particles at a reasonable cost (0.5–1.5 k€ for a gas flow of 1000 m^3/h). However, high temperature ceramic or sintered metal filters (1–2 k€ for gas flowrates of 1000 m^3/h) must be incorporated, or even electrostatic precipitators to remove small-sized particles (22–110 k€ for gas flows of 1000 m^3/h) [49,50]. Another commonly considered option is wet gas scrubbing, which can remove up to half of the tar present; when used in combination with a venturi scrubber, the device can remove up to 97% of tar (23–70 k€ for saturated gas flowrates of 17,000 m^3/h) [51]. OLGA's tar removal process uses several scrubbers, and effectively recycles almost all the tar contained in gas to the gasifier. The investment may be between 150–1750 € (gas flowrate of 1 m^3/h) [52].

Finally, fixed OpEx for gasifier plants typically range from 3–6% of initial CapEx per year, while variable OpEx are around 3.4 €/MWh [48].

More information on thermochemical process costing is available in the Supplementary Materials, which contains Tables S1–S4 compiling information on OpEx and CapEx estimates according to gasifier type, oxidizing agents, syngas cleaning technology, and syngas applications.

3. Description of Methodology Analysis

3.1. Survey of Information Regarding Real Gasification Plants Producing Energy or Renewable Fuels

A thorough collection of information about existing operational plants, including those that entered operation in the past and meanwhile ceased working was performed. These additional non-operational plants were integrated in the study as they allow to increase the sample size for several product categories, and to provide useful data insights about similar facilities that eventually will be projected and built in the next years. Information that was retrieved for each plant (whenever possible) included its owner company, location, year, raw materials and products, output capacity, technology readiness level (TRL), and CapEx. Several sources were considered for data collection such as institutional reports, databases, and scientific articles, and the temporal period considered for this survey was between 1996 and 2021. The specific cost of each plant was calculated considering the ratio of total CapEx and the output capacity (expressed in mass or energy flow units, as appropriate), and updated through to 2020 through the application of producer prices in industry indexes, as published by Eurostat [53]. In addition, units that were considered to express power and fuel flow as output results were uniformized and converted to kW and t/y, respectively, to provide consistent relationships and estimations.

3.2. Categorization of Gasification Plants According to the Final Product Type

A classification for the different gasification plants based on the final product type was proposed to differentiate the available production technologies, process complexities, and capital investments required for each solution. The list of gasification plants and their corresponding products collected from the survey performed in Section 3.1 allowed to propose the following classification: products obtained from energy generation (electricity, heat, and combined heat and power (CHP)), from renewable gases generation (SNG), and from liquid fuels generation (ethanol, methanol, gasoline, and FT fuels). Therefore, a total of three product classes and eight product subclasses were established to group the facilities retrieved during the analyzes and discussions about capital investments. All surveyed plants in Section 3.1 were thus grouped according to this classification, based on the final products obtained.

3.3. Correlation Equations and Their Graphical Representations to Elucidate Evolutionary Trends of Plant Costs over Time, and Economy of Scale

Lastly, this work entailed the creation of graphical representations between the relevant variables, in particular specific investment vs. year and product output. These representations provided a way to identify and exclude several outlier points that would negatively interfere in the analysis, and then to determine correlation equations using regression methods. These equations aimed to relate the variables involved, and to estimate the specific costs inside and outside the range of the sampling period (1996–2021), or the range of product output. Linear and exponential regressions were then used to define the relationships between the specific cost and year, as well as the specific cost and output, respectively. Such correlations can therefore be used to identify trend patterns and to analyze the evolutionary trend of CapEx with time and scale, concerning gasification plants.

Figure 1 summarizes the complete methodology of analysis that was followed in the present work. As far as we know, the complete methodology proposed here presents an innovative approach to evaluate and predict capital investments in gasification technologies and was not identified in other works as of yet.

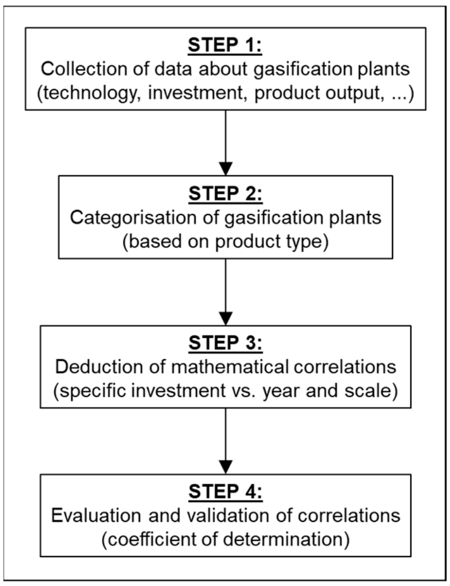

Figure 1. Summary of the methodology analysis proposed in the present work.

4. Analysis on the Evolutionary Trend of Gasification Plant Investments

Several small and large-scale gasification plants able to process biomass and solid wastes into energy, biomethane and other liquid biofuels were identified in fourteen different countries. Most of the plants are in the USA (seven units), UK (six units), France (five units), and Finland and Canada (four units for each one). These facilities use different conversion technology approaches, and Table 1 presents a list containing information regarding these units.

Table 1. List of gasification plants with the relevant information included in the technology cost analysis and classified according to the product type.

Product	Plant Company Owner	Technology Description	Product Output	Specific Investment (Updated)	Refs.
Electricity	Plasco Energy Group	Feedstock: MSW (85 t/d); Conversion pathway: moving grate gasifier + gas engine; TRL: 4.	4 MW_e	11,800 €/kW_e	[47]
	Taylor Bioenergy *	Feedstock: MSW, wood waste, and construction and demolition waste (900 t/d); conversion pathway: circulating fluidized-bed gasifier + gas turbine.	20 MW_e	12,991 €/kW_e	[47]
	Tahoe Regional Power Company	Feedstock: forestry waste; conversion pathway: gasification + internal combustion engine.	2 MW_e	5240 €/kW_e	[54]
	PHG Energy	Feedstock: waste wood, scrap tires, and sewage sludge (58 t/d); Conversion pathway: downdraft gasifier.	300 kW_e	10,031 €/kW_e	[54]
	M&W Group	Feedstock: refuse-derived fuel (RDF, 40,000 t/y); conversion pathway: fluidized-bed gasifier.	12.5 MW_e	10,598 €/kW_e	[54]
	EERC	Conversion pathway: entrained-flow gasifier.	300 kW_e	2318 €/kW_e	[55]
	CoGen	Feedstock: waste wood (67,000 t/y, updraft gasifier; 72,000 t/y, updraft gasifier; 157,000 t/y, fluidized-bed gasifier);	10.3/10.6/ 26.5 MW_e	7987/6073/ 5395 €/kW_e	[56]
	Mitsubishi Materials and Kawasaki Steel	Feedstock: MSW (51,000 t/y); conversion pathway: high-temperature gasification + fusion of waste materials.	2.4 MW_e	215,211 €/kW_e	[56]
Heat	Vicat	Feedstock: wood and RDF (3 t/h); conversion pathway: fixed-bed gasifier + direct burn of gas.	6.4 MW_{th}	710 €/kW_{th}	[56]
	ESKA	Feedstock: wastepaper and plastics (3.5 t/h); conversion pathway: circulating fluidized-bed gasifier + steam generation.	12 MW_{th}	1231 €/kW_{th}	[57]
	Stora Enso	Feedstock: plastics; conversion pathway: fluidized-bed gasifier + steam generation.	40 MW_{th}	624 €/kW_{th}	[47]
	Lahti Energia Oy	Feedstock: forestry biomass (50–55 truckloads per day); conversion pathway: circulating fluidized-bed gasifier + steam generation.	190 MW_{th}	868 €/kW_{th}	[47]

Table 1. *Cont.*

Product	Plant Company Owner	Technology Description	Product Output	Specific Investment (Updated)	Refs.
CHP	Dall Energy	Feedstock: wood, garden, and forestry wastes; conversion pathway: updraft gasifier + thermal oil heater + internal combustion engine; TRL: 8.	800 kW_e (electricity) 5000 kW_{th} (heat)	1528 €/kW	[47]
	Babcock&Wilcox Volund	Feedstock: woodchips; conversion pathway: updraft gasifier + gas engine; TRL: 9.	1 MW_e (electricity) 3 MW_{th} (heat)	4501 €/kW	[58]
	H. H. Käser GmbH	Feedstock: woodchips, forestry waste, and short rotation plants (133 kg/h); conversion pathway: downdraft gasifier; TRL: 9.	140 kW_e (electricity) 240 kW_{th} (heat)	1807 €/kW	[59]
	Josef Bucher AG	Feedstock: woodchips (15 m^3/d); conversion pathway: downdraft gasifier + gas engine; TRL: 9.	130 kW_e (electricity) 260 kW_{th} (heat)	3658 €/kW	[59]
	Energie Oberwart	Feedstock: woodchips; conversion pathway: circulating fluidized-bed gasifier + gas engine; TRL: 9.	2.8 MW_e (electricity) 4.1 MW_{th} (heat)	2436 €/kW	[59]
	Emamejeriet AB	Feedstock: forestry wastes; conversion pathway: gasifier + gas engine; TRL: 8.	40 kW_e (electricity) 100 kW_{th} (heat)	2184 €/kW	[59]
	Lahti Energia Oy	Feedstock: solid recovered fuel (SRF, 250,000 t/y); conversion pathway: circulating fluidized-bed gasifier + steam turbine; TRL: 9.	50 MW_e (electricity) 90 MW_{th} (heat)	1127 €/kW	[59]
	Spanner Re^2	Feedstock: pellets, briquettes, and woodchips; conversion pathway: downdraft gasifier.	450 kW (electricity + heat)	4709 €/kW	[59]
	Vaskiluodon Voima	Feedstock: biomass + coal; conversion pathway: downdraft gasifier.	140 MW (electricity + heat)	289 €/kW	[47,59]
	Royal Haskoning DHV	Conversion pathway: bubbling fluidized-bed gasifier.	10.5 MW (electricity + heat)	5201 €/kW	[60]
SNG	Go Green Fuels Ltd.	Feedstock: RDF and waste wood; conversion pathway: fluidized-bed gasifier + water-gas shift + methanation; TRL: 8.	1500 t/y	18,589 €/(t/y)	[61]
	Goeteborg Energi	Feedstock: woody biomass; conversion pathway: fluidized-bed gasifier + methanation; TRL: 6–7.	11,200 t/y	13,419 €/(t/y)	[62]
	Engie	Feedstock: wastes of wood, straw, forest, agriculture, paper industry, and SRF; conversion pathway: fluidized-bed gasifier + catalytic methanation; TRL: 4–5.	100 kg/y	606 M€/(t/y)	[59]
Ethanol	Enerkem	Feedstock: MSW; conversion pathway: gasification + methanol synthesis + ethanol conversion; TRL: 8.	30,000 t/y	3397 €/(t/y)	
	Enerkem	Feedstock: MSW; conversion pathway: gasification + methanol synthesis + ethanol conversion.	35,000 t/y	1879 €/(t/y)	[63,64]
	Woodland Biofuels	Feedstock: wood and crop wastes; conversion pathway: gasification + catalytic synthesis.	601 t/y	14,899 €/(t/y)	[65]

Table 1. *Cont.*

Product	Plant Company Owner	Technology Description	Product Output	Specific Investment (Updated)	Refs.
Methanol	Varmlands Methanol	Conversion pathway: gasification + alcohol synthesis.	92,000 t/y	3384 €/(t/y)	[65]
Gasoline	GTI Gas Technology Institute	Feedstock: woodchips and pellets; conversion pathway: pressurized fluidized-bed gasifier + methanol/dimethyl ether synthesis + gasoline synthesis; TRL: 4–5.	27.9 t/y	929,757 €/(t/y)	[63]
FTfuels	Total	Feedstock: straw, energy crops, and forestry waste; conversion pathway: gasification + FT synthesis; TRL: 6–7.	8000 t/y	23,750 €/(t/y)	[66]
	Fulcrum	Conversion pathway: gasification + FT synthesis.	30,360 t/y	5764 €/(t/y)	[63,67]
	CHOREN Fuel Freiberg GmbH	Feedstock: woodchips and residual forestry wood; conversion pathway: gasification + FT synthesis; TRL: 6–7.	13,500 t/y	17,684 €/(t/y)	[59]
	Red Rock Biofuels	Conversion pathway: gasification + FT synthesis.	47,270 t/y	6325 €/(t/y)	[65]
	BioTfuel Demo	Feedstock: straw, energy crops, and forestry waste; conversion pathway: gasification + FT synthesis + hydrotreating/hydrocracking; TRL: 6–7.	8000 t/y	23,750 €/(t/y)	[59]
	Karlsruhe Institute of Technology	Feedstock: straw; conversion pathway: gasification + FT synthesis; TRL: 6–7.	968 t/y	57,965 €/(t/y)	[65]
	Tubitak	Feedstock: forestry waste; conversion pathway: gasification + gas clean-up and conditioning + FT synthesis; TRL: 4–5.	250 t/y	33,702 €/(t/y)	[63]

* Under construction.

A first look at the output and specific investment columns from Table 1 revealed the existence of several outlier values that were too high, and were therefore removed from the economic study. This adjustment was deemed to be necessary as such values may provide inaccurate results and inconsistent estimates in the next stages of the study. Gasification facilities defined as outliers were Mitsubishi Materials and Kawasaki Steel (located in Japan), GTI Gas Technology Institute (USA), Engie (France), PHG Energy (USA), EERC (USA), Karlsruhe Institute of Technology (Germany), and Total (France).

Most facilities with available economic information are in Northern America and Northern Europe and process a variety of feedstocks that include forestry and wood wastes, municipal solid wastes (MSW) and its derivatives, sewage sludge, polymeric wastes, and energy crops. The calculated specific costs were relatively high in plants producing liquid or gaseous fuels, which were directly related to the complexity of the production process (values between 1800–34,000 €/(t/y)). These plants started to come out particularly in the last six years, thus justifying the low technological maturity and the high investment costs that were associated with them. Inside the group of energy production plants, those that generate electricity alone were deemed to be more expensive compared to heat production or CHP alternatives (5200–13,000 €/(t/y)). This occurrence may be justified by the higher efficiency of energy extraction from input feedstocks. Concerning liquid fuel plants, these presented a larger flexibility in terms of the list of final products, which include ethanol, methanol, gasoline, and various Fischer-Tropsch (FT) fuels (e.g., diesel, gasoline, and naphtha). The FT reaction mechanism is the most implemented, however, in some cases, major investments are still required. Plant scales ranged from 140 kW–190 MW for those dedicated to energy production, and 250–92,000 t/y for gaseous or liquid fuel production.

Table 2 gives a brief overview of both the variation and average specific costs of gasification facilities, as according to the final product.

Table 2. Average specific costs of gasification plants according to the final product type.

Plant Type	Variation of Specific Costs	Average Specific Cost
Electricity	2318–12,991 €/kW_e (Output range: 2–26.5 MW_e)	8583 €/kW_e
Heat	624–1231 €/kW_{th} (Output range: 6.4–190 MW_{th})	858 €/kW_{th}
CHP	289–5201 €/kW (Total output range: 140–140,000 kW)	2744 €/kW
Synthetic natural gas	13,419–18,589 €/(t/y) (Output range: 1500–11,200 t/y)	16,004 €/(t/y)
Liquid fuels	1879–33,702 €/(t/y) (Output range: 250–92,000 t/y)	10,879 €/(t/y)

As evidenced by the presented data, electricity and SNG production plants have the highest costs in the general categories of energy and fuel production (8583 €/kWe and 16,004 €/(t/y), respectively). However, the dispersion of results for specific costs was significantly higher in the case of liquid biofuels, a fact that may be explained by the large spectrum of fuel products (ethanol, methanol, gasoline, and diverse FT fuels), and by the diversity of conversion technologies that were involved.

Given the number of plants found in each product category, mathematical correlations were established for those producing electricity and CHP, once these categories contained a significant number of points to generate robust correlations. Moreover, all liquid biofuel production plants (ethanol, methanol, and FT fuels) were combined, again to provide a relevant number of points to deduce correlations (the gasoline production unit was excluded from the analysis once this was considered an outlier as previously declared). Therefore, a total number of three categories (electricity, CHP, and liquid biofuel production) were considered for the determination of the individual mathematical correlations.

Graphical representations and linear regression equations for specific investment vs. year for electricity, CHP, and liquid fuel production units are shown in Figure 2 and Table 3, respectively.

Table 3. Linear regression equations that relate the specific investment with the year for electricity, CHP, and liquid fuel plants.

Plant Type	Equation	R^2	Notes
Electricity	$SI = -531.01 \times Y + 1{,}077{,}364.19$	0.67	SI—specific investment (k€/kW for electricity and CHP; k€/(t/y) for liquid fuels)Y—year of the plant
CHP	$SI = -120.03 \times Y + 244{,}214.06$	0.21	
Liquid fuels	$SI = -933.29 \times Y + 1{,}891{,}578.92$	0.29	

All specific investments presented a decreasing tendency over time for the three plant types. The linear correlation fitted better to data regarding the electricity production plants, with a coefficient of determination (R^2) of 0.67. The other two plant typologies exhibited values lower or equal to 0.29. This was explained by the higher dispersion of points associated with the heterogeneity of specific costs, and potentially also due to the higher diversity of conversion technologies found in both CHP and liquid fuel production facilities (i.e., different gasifier types combined with various energy production pathways, gas cleaning technologies, and fuel synthesis processes).

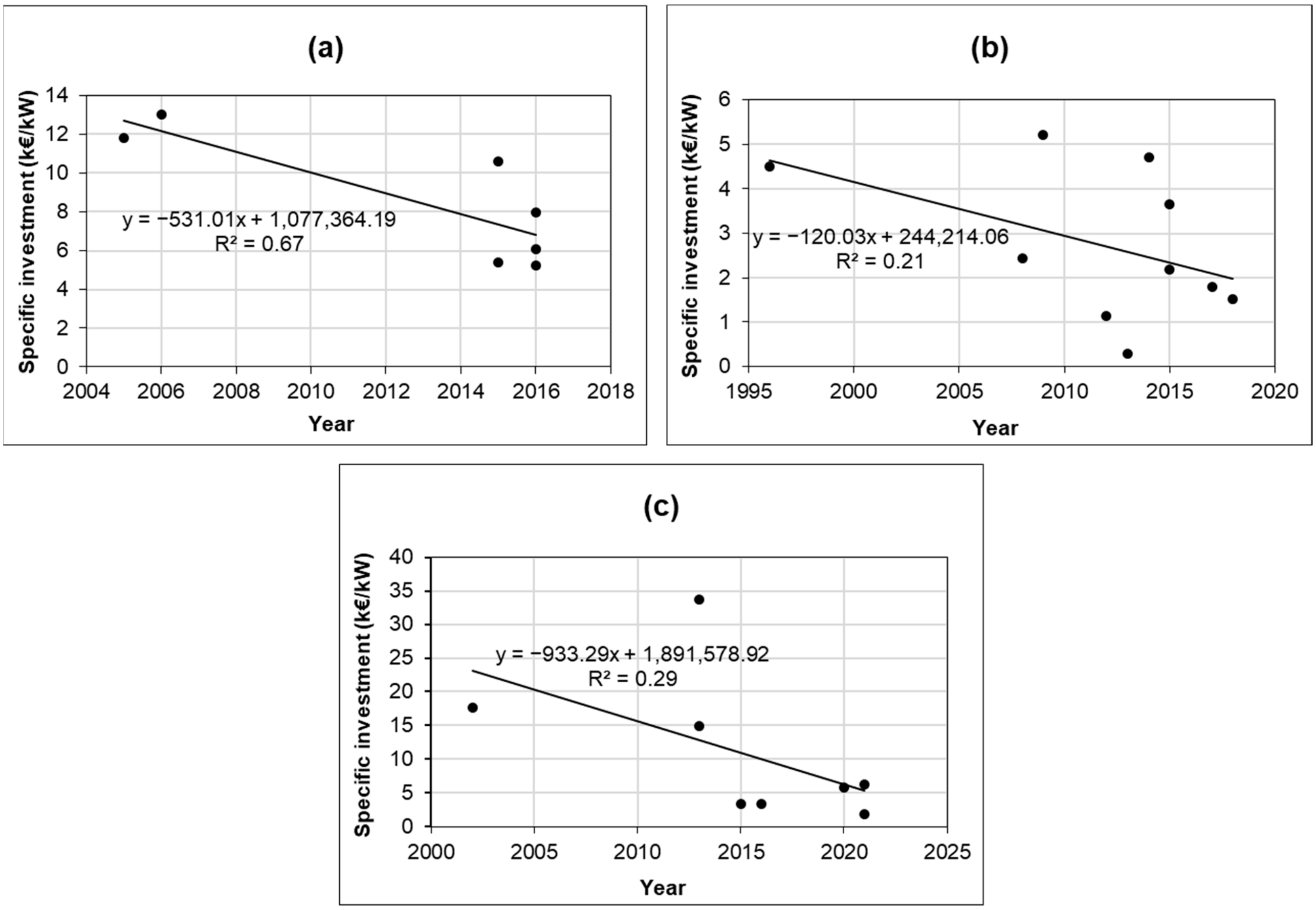

Figure 2. Relationship between the specific investment and year, and the corresponding linear regression equations for (**a**) electricity, (**b**) CHP, and (**c**) liquid biofuel gasification plants.

The linear correlation of the data for the liquid fuel production plants has a lower coefficient of determination (R^2) with a value of 0.29. This was expected, as these technologies presented global reaction yields below 50% and a wide variety of products that can be obtained. The literature reported gasifiers with capacities ranging from 4.8–393 MW_{th}, using different types of biomass residues from wood, wood chips, forest residues/wood pellets/straws, and rice straws with associated FT processes; yields of synthetic fuels achieved between 16.5–53.5% [68–71]. In addition to the operating conditions and the nature of biomass wastes, the type of catalysts applied in the FT processes also have an impact on the yields and the products distribution [26,72–74].

Liquid biofuel facilities presented a higher decreasing trend in specific investments with time due to the higher slope of the regression line in absolute terms (933.29 k€/(t/y)). The reason for this occurrence was related to the weaker maturity and recent emergence of these technologies with a strong potential for implementation in a near future, contrary to what happens with electricity or CHP plants that are well established and more developed solutions. All correlations were valid between the years 2005–2016 (electricity plants), 1996–2018 (CHP plants), and 2002–2021 (liquid fuel plants), respectively, as all facilities were retrieved during these periods. Extrapolation beyond these ranges can be admissible, but with some margins of error in the calculated estimates.

Heat and SNG production facilities were not included in the regression study, since the number of points were not considered sufficient to obtain a more robust analysis for these cases (only four and two production units were identified in the survey, respectively). However, preliminary assumptions can be established for these two groups: the specific cost associated with heat production was the lowest among all plants (average of 859 k€/kW), while SNG synthesis is currently very expensive (average of 16,004 k€/(t/y)). Considering that SNG will be an attractive fuel source in Europe, and will complement biomethane production from anaerobic digestion plants, financial incentives and subsidies are required for further developments in SNG synthesis technology (presently with a TRL between 4–8), and to disseminate and decentralize the construction of similar plants in the future.

Figure 3 illustrates the evolutionary trend of economies of scale (graphics of specific investment vs. output) associated with the different types of gasification facilities (electricity, CHP, and liquid biofuels).

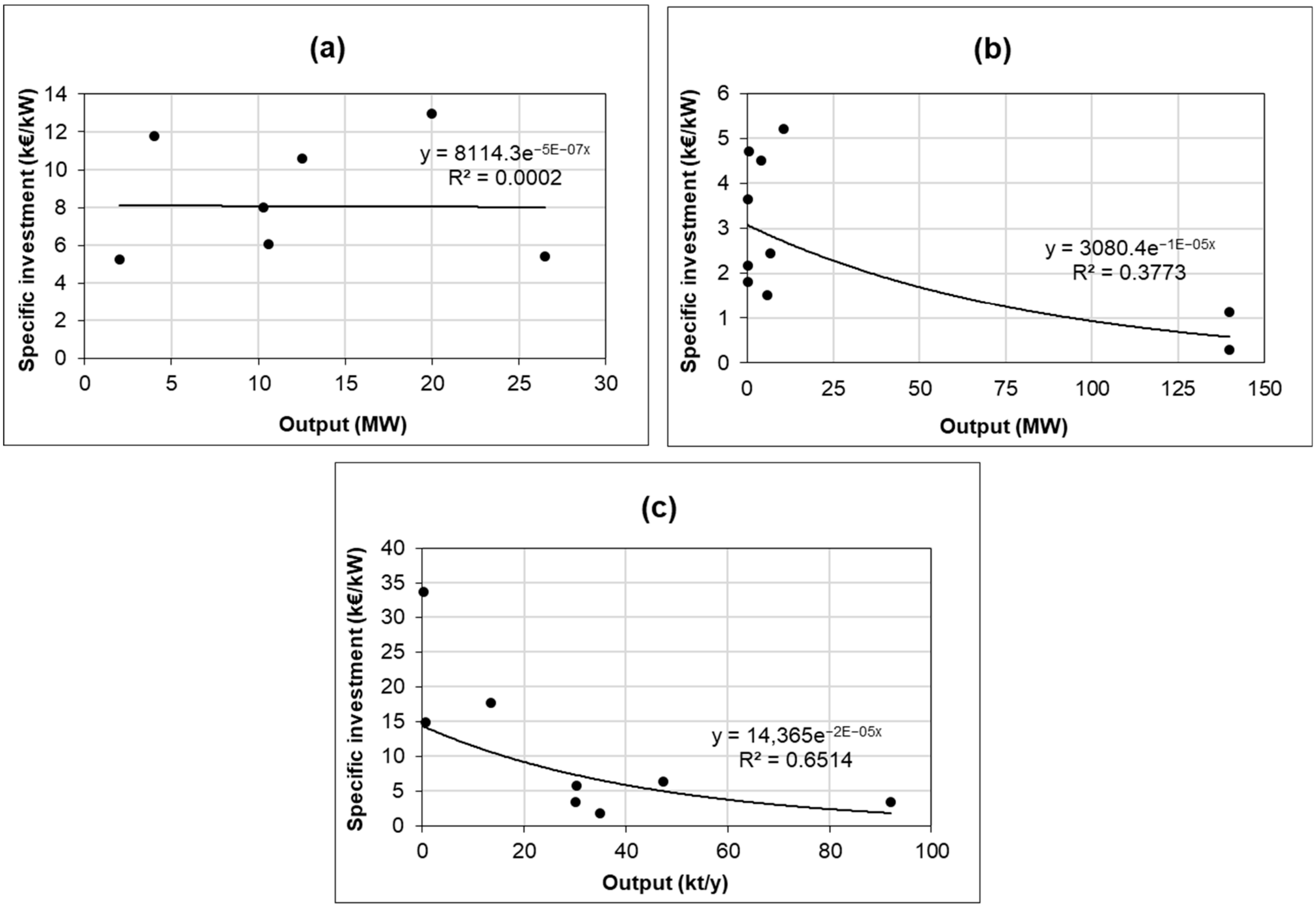

Figure 3. Relationship between the specific investment and output flow, and the corresponding linear regression equations for (**a**) electricity, (**b**) CHP, and (**c**) liquid biofuel gasification plants.

Higher specific investments were obtained for plants with lower product outputs, which was evidenced by the distribution of points, particularly for the CHP and liquid biofuel plants. Exponential correlations presented a better fit for these two latter cases, with coefficients of determination between 0.3–0.7. This demonstrates the decreasing effect of specific investment, with output as the main rule in the economy of scale observed in gasification plants. However, facilities based on electricity production exhibited randomly distributed points, which complicated the establishment of a precise exponential correlation (R^2 = 0.0002) and the definition of a trend that rules the economy of scale. Anyway, the deployment of electricity plants is presently a less sustainable option due to the lower efficiency for energy extraction (typically less than 40%) [75]. The economic attractiveness and competitiveness of these plants became low in recent years, as evidenced by the lack of information in the survey since 2016 (see Figure 2).

In the specific case of CHP plants, the two isolated points located on the right-hand side of the middle graphic in Figure 3 correspond to gasification plants located in Finland. In this country, there seems to be a trend to implement large-scale gasification to produce district heating and fuel gas for the pulp and paper industry [44]. Research and development (R&D) on gasification was initiated in the late 1970s, aiming to decrease the dependence of the Finnish economy on imported oil. Throughout the 1980s, continuous governmental support in R&D focused on syngas applications was conducted, including the construction of a gasification plant for heat production [76]. These R&D efforts have established Finland as a major player in gasification technologies and services, offering solutions to meet the needs of various power and process industry sectors. Finland has bet on the modification of existing boilers or industrial kilns to be integrated with new gasification plants, which may achieve several hundreds of megawatts in output size. Additionally, existing fuel systems can be left as operational in parallel or for backup, some of which admit fossil fuels. As a result, Finnish gasification plants presented lower specific investment high outputs for CHP.

5. Conclusions

To compete with fossil-based technologies, large-scale gasification installations still require significant technological development, supporting economic subsidies and incentives, and efficient operational strategies. The mathematical regression analysis performed in this paper showed that specific investments tend to decrease over the years, particularly for gasification plants dedicated to producing electricity, CHP, and liquid biofuels. The latter group presented the highest decreasing trend, mainly due to the lower technological maturity, the recent emergence and interest in the production of biofuels, and global policies pressing for the adoption of carbon-neutral solutions. Economies of scale were more prevalent for CHP and liquid biofuel plants, evidencing the decrease of specific investments with product output through a downward exponential pattern. SNG production plants showed specific costs that were almost comparable to those of liquid biofuels. However, the consumption of these fuels, as well as their economic interest, was expected to increase with further technological developments and optimization. On the other hand, gasification plants producing only electricity presented a lower attractiveness for deployment in recent years.

These results, along with the variability of gasification technologies (e.g., specific gasifier design) and producer gas cleaning systems employed in large-scale gasification plants show that the technology is not mature, and still has to find its niche in the market. This uncertainty is the main cause of the lack of confidence from investors, delaying this technology's commercial maturity as a cost-efficient and reliable operation has yet to be fully demonstrated in practice. Nevertheless, this study offers several perspectives to boost the stakeholders' confidence in large-scale gasification plants. Data on the costs and expenses are useful to highlight areas where technological innovation can improve and reduce costs, allowing better decision-making, cost optimization, and improved project planning. However, full access to information on previous gasification plants is required to optimize these technologies and help with the development and operation of future plants. Learning effects from past endeavors are critical to making more informed choices about which final products from gasification to invest in and whether they are economically viable. Indeed, as gasification technologies continue to evolve and mature, it will be increasingly important for the technology to find its role in the transition to a more sustainable energy system and focus on high-value final products and specific industrial applications.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling8030049/s1, Table S1: Estimates for CapEx and OpEx according to gasifier type; Table S2: Estimates for CapEx and OpEx according to oxidizing agents; Table S3: Estimates for CapEx and OpEx according to syngas cleaning and tar cracking technologies; Table S4: Estimates for CapEx and OpEx according to syngas application. References [77–150] are cited in the Supplementary Materials.

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