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Climate Impact Comparison of Biomass Combustion and Pyrolysis with Different Applications for Biochar Based on LCA

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Abstract: Biochar can be useful to overcome several environmental challenges in different sectors of energy, industry, and agriculture. However, there are currently only a limited number of studies with the employment of biochar for various applications and their environmental impacts. This study develops an LCA framework to evaluate the climate impacts of biochar production and its applications in soil enhancement and as a substitute for coal-based fuels in steel industries and then compares it with conventional biomass usage for energy production for Sweden, Italy, and Poland. Various pyrolysis operating temperatures are also considered to determine the optimal conditions for each location. The results show that biomass pyrolysis with biochar usage in the agricultural sector has the least environmental impact with the most significant potential in Poland followed by Italy. lower temperatures (around 350 °C) are more favorable for Sweden in terms of CO_2 emissions, due to the country's renewable energy-based electrical system. Low to moderate temperatures (350–500 °C) are found to be optimal for pyrolysis temperature in Italy, while higher temperatures (around 650 °C) yield the highest GHG reduction for both biochar applications in Poland.

Keywords: LCA; biochar; soil enhancement; climate impacts; biomass; coal

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Citation: Safarian, S. Climate Impact Comparison of Biomass Combustion and Pyrolysis with Different Applications for Biochar Based on LCA. *Energies* **2023**, *16*, 5541. https://doi.org/10.3390/en16145541

Academic Editors: Timo Kikas, Abrar Inayat and Lisandra Rocha Meneses

Received: 19 June 2023
Revised: 1 July 2023
Accepted: 6 July 2023
Published: 22 July 2023

1. Introduction

Increasing worry over the dwindling supply of fossil fuels, along with concerns about energy security and environmental impact resulting from the burning of such fuels, has urged energy sector decision-makers to look to sustainable and renewable options [1–3]. Biomass has been identified as promising renewable energy sources, capable of boosting global energy sustainability and decreasing greenhouse gas emissions [4–7]. Biomass, ranked third globally as a primary energy source behind coal and oil, offers numerous advantages, including its renewable nature, simple storage, and capacity to emit CO_2 in a climate-neutral way by approximately offsetting the absorbed CO_2 during biomass lifetime through biofuel combustion [8,9].

Energy can be derived from various biomass feedstocks including agricultural crops and residues, herbal and woody materials, and organic wastes. This energy can either be produced through incineration for heat and power or refined into biogas, biodiesel, and bioethanol for use as transportation fuels or power and heat production [10–12]. Although biomass energy production has the potential for future growth due to abundance, the global share of biomass for primary energy generation is still limited and it is used mainly for heating and cooking in impoverished countries [13,14].

Modern technologies for biomass utilization could lead to significant gains. To convert biomass feedstocks to fuel and chemicals, fermentation and anaerobic digestion, gasification, pyrolysis, and liquefaction are biological and thermochemical conversion processes can be applied [15,16]. Pyrolysis has received much attention and produces a range of gas, liquid, and solid products. The solid byproduct from pyrolysis called biochar which is a product high in carbon content obtained through a controlled process of heating biomass feedstocks without an excess of oxidizing agents. Typically, the biochar contains around

70% carbon, while the residual fraction comprises hydrogen, sulphur, nitrogen, oxygen, and minerals found in the ash [17,18].

Biochar is gaining recognition as a highly promising carbon storage solution, as it improves soil nutrient retention capacity, water holding capacity, and environmental quality while reducing greenhouse gas emissions [19,20]. In addition, biochar also produces energy carriers with high energy density. Recent studies have highlighted its potential to contribute to sustainable bioenergy production when made from lignocellulosic biomass feedstocks [21,22]. Moreover, a few studies have investigated biomass application and capacity of biochar usage instead of coal and coke in the steel and iron industries [23–25]. The opportunities and obstacles of biochar performance in energy-intensive processes in steel production (e.g., coke-making, sintering, and blast furnaces) were assessed technically in their works. Biochar has been shown to have similar heating values and combustion characteristics as coal, and its use in steel production could reduce greenhouse gas emissions and dependence on fossil fuels. The production of biochar from agricultural waste products, such as rice husks or coconut shells, would also provide a sustainable and renewable source of fuel. A study by Hu et al., [26] investigated the feasibility of using biochar as a substitute for pulverized coal in a blast furnace, finding that the use of biochar resulted in lower emissions of carbon monoxide and sulfur dioxide, while maintaining the quality of the steel produced. Another study by Sefidari et al., [27] explores the potential of replacing coal with biochar in steel industries and evaluates the feasibility of this approach. The authors used a mathematical model to simulate the impact of biochar on the steelmaking process and found that the use of biochar could significantly reduce greenhouse gas emissions and enhance the overall efficiency of the process. The study demonstrates the potential application of biochar in the steel industry and highlights the need for further research in this area.

Biochar has also gained attention in agricultural applications due to its numerous environmental and soil benefits. Biochar can improve soil fertility by increasing soil carbon sequestration, reducing nutrient leaching, and improving water retention capacity. It also has the potential to mitigate climate change by reducing greenhouse gas emissions [28–30]. The study conducted by Yang et al. [31] documents the positive effects of biochar on soil fertility and plant growth in agricultural lands in Iran. The authors found that biochar enhanced soil moisture content, nutrient availability, and improved the growth of wheat and barley. The study also highlights the potential economic benefits of using biochar in agriculture, suggesting that it could be a cost-effective method to improve yields and reduce dependence on chemical fertilizers.

Despite this potential for biochar use in different applications, there is currently limited studies with the employment of biochar for various applications and their environmental impacts in practice. Therefore, the purpose of this study is development of life cycle assessment (LCA) for investigation the climate impacts of biochar production and its usage for various applications (i.e., for soil enhancement and instead of coal-based fuels in steel industries). In the following, it will be compared with the climate impacts taken via conventional biomass usage for energy production. These assessments will be carried out for three different European countries which are Sweden, Italy, and Poland with having different systems for electricity and heat production. Moreover, the considered systems are analyzed under various pyrolysis operating temperatures to find the optimal operating condition and most environmentally application for each case study.

2. Methodology and Data

By utilizing life cycle assessment (LCA), it is possible to measure the environmental effects of a product, service, or activity throughout its entire life cycle, including indirect impacts [32–34]. In this study, LCA was used to assess and compare the potential environmental impacts of biomass combustion and biomass pyrolysis in Sweden, Italy, and Poland, following the procedures recommended by ISO 14040 [35] and ISO 14044 [36]. These countries were selected since they include different systems for electricity production which leads to different carbon footprints. In Sweden, hydropower and nuclear energy are the dominant sources of electricity. In fact, around 50% of Sweden's electricity comes from hydropower plants, while over 30% is generated from nuclear power plants. The remaining electricity comes from wind farms and other renewable sources such as solar energy and bioenergy. Italy relies heavily on natural gas for electricity production, with over 40% of its electricity coming from gas-fired power plants. Poland's electricity production system is heavily reliant on coal, which accounts for over 70% of the country's electricity mix. The remaining electricity comes from natural gas and renewable sources such as wind power and hydropower. Poland has been slow to transition to renewable energy due to its reliance on coal and concerns about energy security.

The LCA process involves three main stages: defining the goals and scope, gathering life cycle inventory data, and conducting a life cycle impact assessment to interpret the results. The aim of this study is to investigate and compare the climate impacts associated with waste collection, transportation, preparation, and processing to produce energy (heat and electricity) and biochar. Figure 1 illustrates the schematic and boundaries of the systems under consideration. The study focuses on evaluating the greenhouse gas (GHG) reduction potential and climate impacts of the current operating energy system for each country, while also exploring alternate use options for pyrolysis char. Additionally, the study compares the studied system with direct combustion of biomass for heat and electricity generation.

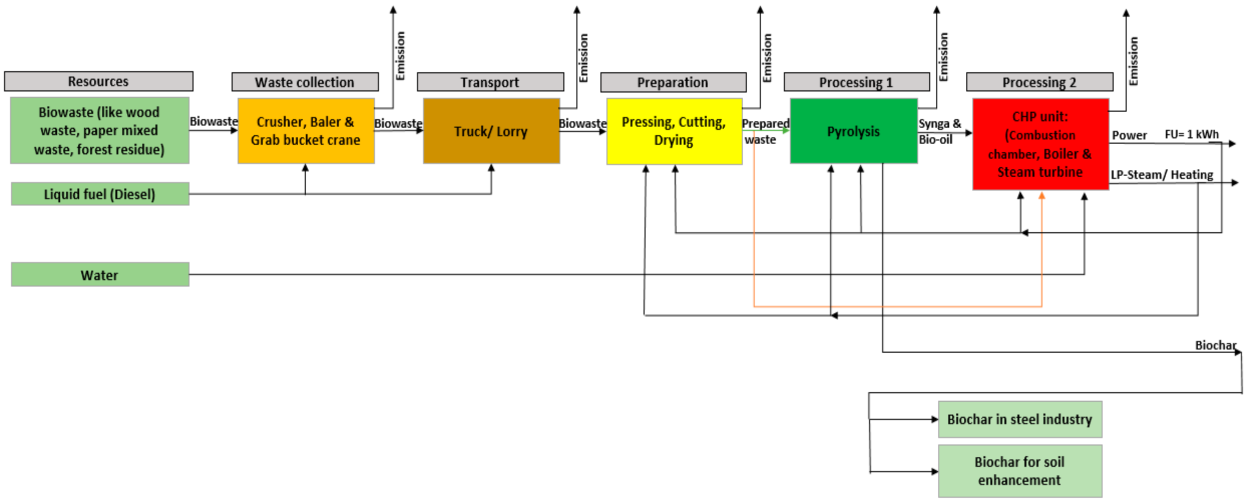

Figure 1. Block diagram of the biochar system and biomass combustion.

To facilitate comparison between different systems, a similar input-oriented functional unit (FU) is utilized in this assessment, specifically 1 kWh output electricity from each system. Apart from the current operating system, this paper evaluates three other systems: (1) biomass combustion integrated with CHP (BC+CHP), (2) biomass pyrolysis integrated with CHP that incorporates biochar into the soil (BP+CHP+S), which can reduce CO_2 while improving soil quality, and (3) biomass pyrolysis integrated with CHP that utilizes biochar as coal feedstock (BP+CHP+C), which can be used as a substitute for coal in steel industries.

The process in a biomass CHP (combined heat and power) unit involves the conversion of biomass into energy through various technologies. The following steps are involved in the process:

Biomass collection: Biomass, such as wood chips, straw, animal waste, and crop residues, is collected from agricultural or forestry sources;
Preparation: The collected biomass is cleaned, sorted, and processed to remove any impurities;
Conversion: The biomass is converted into energy through combustion chambers;
Energy production: The converted energy is used to produce electricity and heat via steam turbines.
The process in biomass pyrolysis unit typically involves the following steps:

Pre-treatment: This involves drying and grinding the biomass feedstock to the desired particle size;
Pyrolysis reactor: The biomass is then fed into a pyrolysis reactor, which is heated to the desired temperature and held at that temperature for a specific period;
Condensation: The volatile gases and liquids produced during the pyrolysis process are cooled and condensed into a liquid bio-oil;
Filtration: The bio-oil is filtered to remove any contaminants or particles;
Char production: The remaining solid char is further processed for use as fuel or biochar.

LCA CO_2 emissions calculations for these systems are performed in three different countries: Sweden, Poland, and Italy. The primary objective of this study is to identify the system with the most significant life cycle environmental benefits in each country.

The system boundaries (as displayed in Figure 1) consist of six distinct parts. To begin the process, a section is designated for resources, including varied forms of biomass feedstocks, liquid fuels, electricity, heat, and water. For this section, different kinds of biomass feedstocks can be used but, in this paper, only wood residues were considered for evaluation. Following this initial step, biowastes are gathered using a crusher, baler, and grab bucket crane, and then transported via trucks to processing plants. The preparation section is responsible for drying, cutting, and handling the input biomass feedstocks to prepare them for the following stage.

The pre-treated biomass is then either directly converted to heat and electricity (BC+CHP) via the CHP plant or subjected to the pyrolysis unit, which ultimately results in the production of biochar, bio-oil, and biogas. The output bio-oil and biogas are utilized as fuel sources for the CHP unit to generate heat and electricity, while the biochar produced has two potential applications. It can either be employed as an alternative to coal (BP+CHP+C), or used to enhance soil quality (BP+CHP+S).

The IPCC 2013 method has been applied in this study to determine the impact of climate change and CO_2 emission reduction for various systems. Ecoinvent v3.7 [37] has been used as a primary source of life cycle inventory (LCI) data, while openLCA 1.11 software [38] has been employed to conduct the Life Cycle Assessment (LCA) and calculate the environmental indexes. This software also provides valuable information on the most significant contribution parts of the system's life cycle. Moreover, the study has assumed that the pyrolysis reactor temperatures are relevant since they have a considerable influence on the product yields.

In particular, slow pyrolysis takes place when biomass undergoes decomposition in the absence of oxygen at a moderate temperature (300–700 °C) and an extended residence time. According to previous research, it has been confirmed that lower temperatures lead to higher biochar yield and lower condensable liquid product yield due to increased cracking reactions [17,39]. Therefore, the pyrolysis system's optimum operating temperature has been set at 300 °C, considering it to be the best temperature for slow pyrolysis [40].

The required data for waste collection and transport for different locations are shown in Table 1. These data were estimated based on the area of different locations and average distances operating for the collection and transport. Table 2 shows the life cycle inventory data of the entire process in function unit. Some of these data were taken from the simulation developed for the pyrolysis unit by one author in her recent paper [40].

Table 1. Life cycle inventory data for collection and transport.

		SE	**IT**	**PL**
Waste collection	ton.km	20	10	10
Waste transport	ton.km	70	50	50

Table 2. Life cycle inventory data for the systems processes.

CHP of biomass	Input biomass	kg	1.6	[40]
	Output heat Output electricity	MJ kWh	9.87 1	[40] [40]
	Flue gas	kg	CO_2: 2.56 CO: 0.00035 H_2: 0.8 × 10^{-5} NO: 0.0003	[40]
Preparation & Pyrolysis	Input biomass	kg	3.13	[40]
	Output biochar	kg	0.92	[40]
	Input electricity Input heat	kWh MJ	0.0907 0.676	[41] [41]
	Saving emissions by biochar (as avoided product)	KgCO_2eq/kg (hard coal production)	GWP: 1.04	[37]
	Avoided product added to soil	Carbon content in biochar (%) Stable carbon content in biochar (%) C-CO_2 conversion coefficient Reduction in N-fertilizer (kg) Reduction in P-fertilizer (kg) Reduction in K-fertilizer (kg) Fixed carbon from crop yield increase (kg CO_2eq) Fixed carbon from reduced SOC mineralization (kg CO_2eq)	74.5 64.8 3.67 0.00027 0.000054 0.000027 0.051 0.28	[31]
CHP for biofuel (after pyrolysis)	Output heat Output electricity	MJ kWh	11.94 1	[40] [40]
	Flue gas	kg	CO_2: 1.7 CO: 0.00012 H_2: 0.12 × 10^{-4} NO: 0.0005	[40]

3. Results

3.1. Potential Climate Impacts of Various Systems

The results obtained in this study rely heavily on the assumptions made and the data presented in the preceding section. In Figure 2, a comprehensive comparison of the climate impacts of four distinct systems has been provided. These systems include the existing electricity system, biomass combustion integrated with Combined Heat and Power (CHP), biomass pyrolysis integrated with CHP, using biochar as a product for soil enhancement and replacing coal in the steel industry, in Sweden, Italy, and Poland. The comparison made in the figure is based on total greenhouse gas (GHG) emissions that result from each system's life cycle, ranging from waste collection to energy production, heat and electricity generation, and biochar product manufacturing.

The GHG emissions, as shown in Figure 2, demonstrate that the use of biomass combustion integrated with CHP could result in about 20% lower GHG emissions than the regular electricity system. This is significant in light of the increasing carbon mitigation targets that require a reduction in GHG emissions. Moreover, when it comes to the use of biomass pyrolysis integrated with CHP, the GHG emissions are reduced even further, reaching levels as low as 70% below that of the regular electricity system. This is possible, in part, due to the beneficial uses of the biochar product that can replace coal in the steel industry and enhance soil productivity. The results presented in the figure highlight the importance of implementing low-carbon energy solutions to reduce carbon emissions and address climate change.

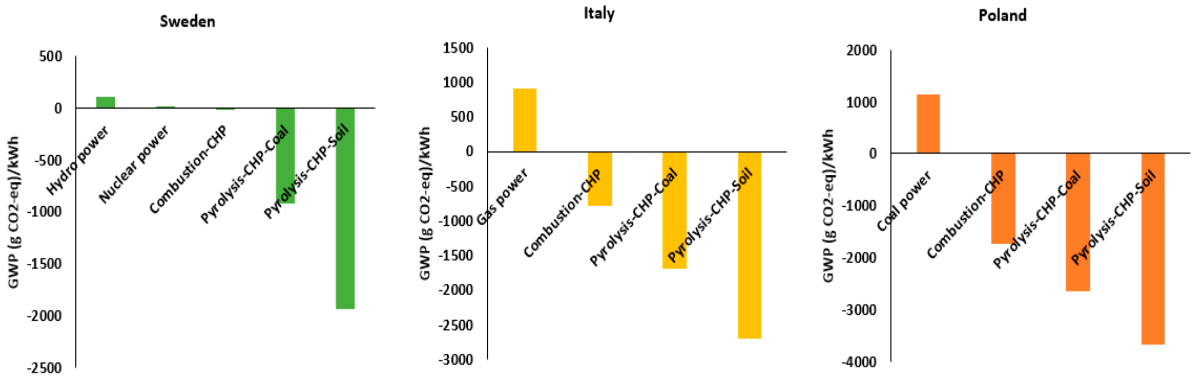

Figure 2. Climate impacts of various systems based on 1 kWh electricity production for Sweden, Italy and Poland.

In summary, the obtained results clearly indicate the significant role that biomass combustion and pyrolysis can play in reducing GHG emissions when integrated with CHP. The importance of selecting the right low-carbon energy solution cannot be overstated when addressing the urgent climate change challenges.

Moreover, the findings reveal that all three biomass-powered systems have a lower global warming potential (GWP) compared to the current electrical systems in each location. Of the three options, the BP+CHP+S system poses the least environmental impact, followed by BP+CHP and BC+CHP. These results support the conversion of biomass into heat and electricity, along with biochar production, as a promising approach for reducing atmospheric CO_2 concentrations. Biochar's high carbon content has the potential to increase soil carbon levels and capture and store atmospheric carbon dioxide in natural sinks, such as soil. Additionally, biochar's porous structure helps retain water and nutrients in the soil, promoting plant growth and reducing the need for irrigation.

The most significant potential for biochar carbon sequestration is identified in Poland followed by Italy which their electricity systems are based on the fossil fuels. In Poland, electricity is mostly produced from coal-fired power plants, which account for about 80% of the country's total electricity production. Coal-fired power plants use also coal as fuel to heat water and produce steam, which drives turbines to generate electricity. In Italy, electricity is mainly produced through thermal power plants fueled mostly with natural gas and little coal and oil. These power plants generate electricity by burning fossil fuels to produce steam, which in turn drives turbines to generate electricity.

With respect to Sweden, biomass direct combustion is almost competitive with current electricity system due to Sweden's sustainable energy system. In Sweden, the majority of electricity is produced through nuclear and hydroelectric power generation. About 40% of the country's total electricity production comes from nuclear power plants, while hydroelectric plants contribute to more than half of Sweden's electricity consumption. Wind power and other sources, such as biomass, are also becoming increasingly popular and make up a growing share of the country's electricity mix.

Figure 3 shows the proportion of different characterizations of the global warming potential of biomass-based systems. Negative values represent an environmental-benign unit, whereas positive values indicate an environmentally harmful unit. Overall, the results indicate that applying biomass pyrolysis linked with CHP unit for any application is much more beneficial compared to biomass combustion, in view of climate change and for all locations. However, biochar employment for soil enhancement could leads to a remarkably carbon capturing and storage among others.

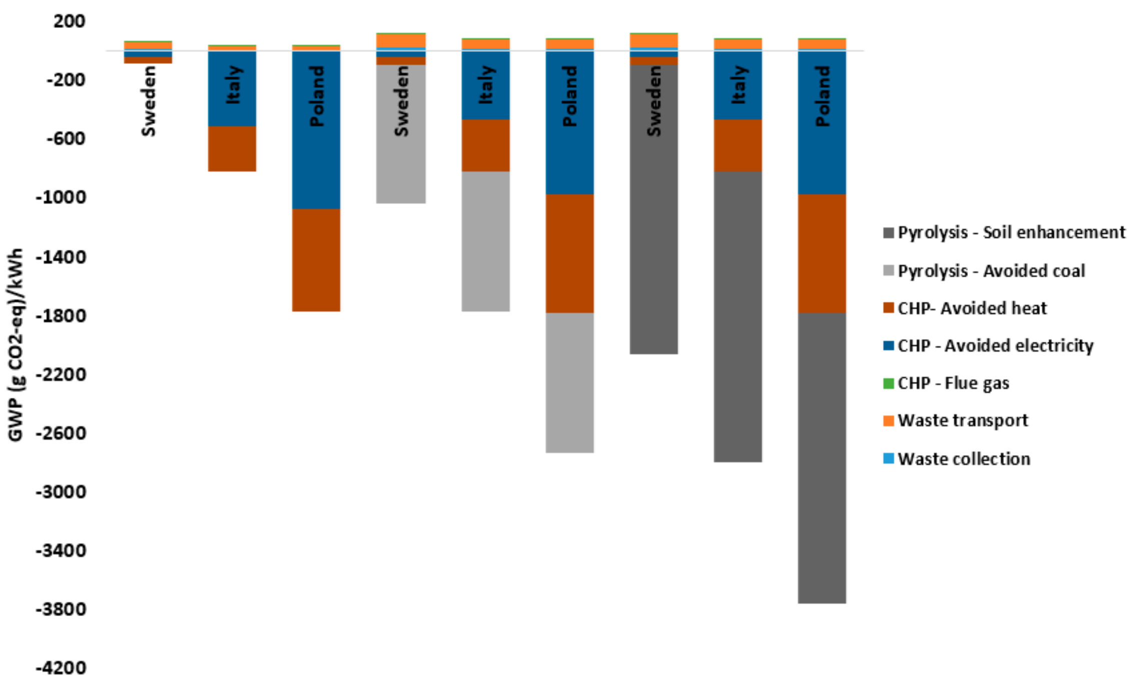

Figure 3. Contribution of the process to the potential GWP impact.

When comparing different systems for Sweden, it was found that avoiding coal and implementing carbon sequestration had a much larger impact on reducing greenhouse gas emissions than avoiding heat and electricity through a CHP unit. The potential reduction was found to be 24 and 50 times greater for avoided coal and soil enhancement applications, respectively, when compared to the reduction potential of avoiding heat or electricity. However, these findings were not the same for Italy and Poland. In Poland's case, avoiding coal had a similar impact to avoiding heat and electricity in the steel industry when using biochar. This is due to the fact that Poland's energy sector is heavily reliant on coal, which has similar physical and chemical properties to biochar. It is important to note that using biochar in soil enhancement had a much greater impact on reducing greenhouse gas emissions than avoiding coal, heat and electricity in all cases. This highlights that biochar has the potential to be an effective tool for mitigating climate change and improving soil health through carbon sequestration.

3.2. Sensitivity Analysis on the Pyrolysis Temperature

The performance of biomass pyrolysis and the yield of its products are affected by several factors, such as temperature, heating rate, residence time, and particle size. However, the biochar, bio-oil, and syngas outputs are greatly dependent on the operating temperature of the pyrolyzer [17,35,42]. Lower pyrolysis temperatures result in increased char production, while higher temperatures lead to higher yields of gases and bio-oil. This, in turn, results in an increase in heat and electricity generation through combined heat and power (CHP) plants. Therefore, the varying temperatures used during biomass pyrolysis will produce different output products and, consequently, varying reductions in greenhouse gas emissions in different locations. Thus, this will be so important to find the optimum temperate depending on the location and considered application to reach to the highest GHG reduction. To demonstrate this impact, the amounts of heat, electricity, and biochar generated between temperatures of 350–650 °C were calculated based on 1 kg biomass input to the system and presented in Table 3. As depicted, increasing the temperature in this range leads to a 53% reduction in biochar product while reciprocally growing electricity and heat by 73% and 64%, respectively.

Table 3. Impact of temperature on the systems outputs.

	T = 350 °C	T = 500 °C	T = 650 °C
Biochar (kg)	0.296	0.264	0.138
Electricity (kWh)	0.319	0.396	0.555
Heat (MJ)	3.8	4.8	6.26

Figure 4 displays the sensitivity analysis outcomes of global warming potentials (GWPs). The analysis examines biochar's benefits at various operational temperatures in two applications across three locations: Sweden, Italy, and Poland. The data reveal that lower temperatures are more advantageous for Sweden in terms of CO_2 emissions. This outcome is attributed to Sweden's renewable energy-based electrical system, which makes biochar production more favorable compared to electricity generation via biomass pyrolysis integrated with CHP. Meanwhile, low to moderate temperatures (350–500 °C) are deemed optimal for pyrolysis temperature in Italy. Conversely, the highest GHG reduction for both biochar applications in Poland is observed at higher temperatures (650 °C). The polish electrical system relies on fossil fuels, making electricity generation via BP+CHP more favorable in terms of CO_2 emissions.

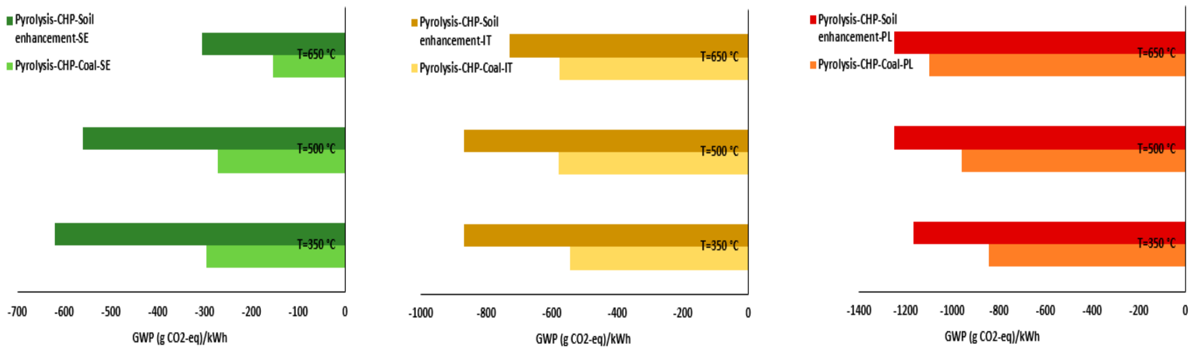

Figure 4. Impact of pyrolysis temperature on the GWP for various application and various locations.

More specific aspects can be observed in Figure 5, which displays the GWP contributions of different processes for two biochar implementations. In Sweden, as temperature rises, CO_2 uptake from both avoiding coal and soil enrichment decreases, while the impact from avoiding heat and electricity gradually increase. This indicates that utilizing BP+CHP at 350 °C for soil enrichment in Sweden will result in the greatest GHG reduction compared to other options. Conversely, the effects of avoiding heat and electricity vary significantly with increasing temperature for Italy and Poland, and are most prominent when using BP+CHP at 650 °C for soil enrichment in Poland.

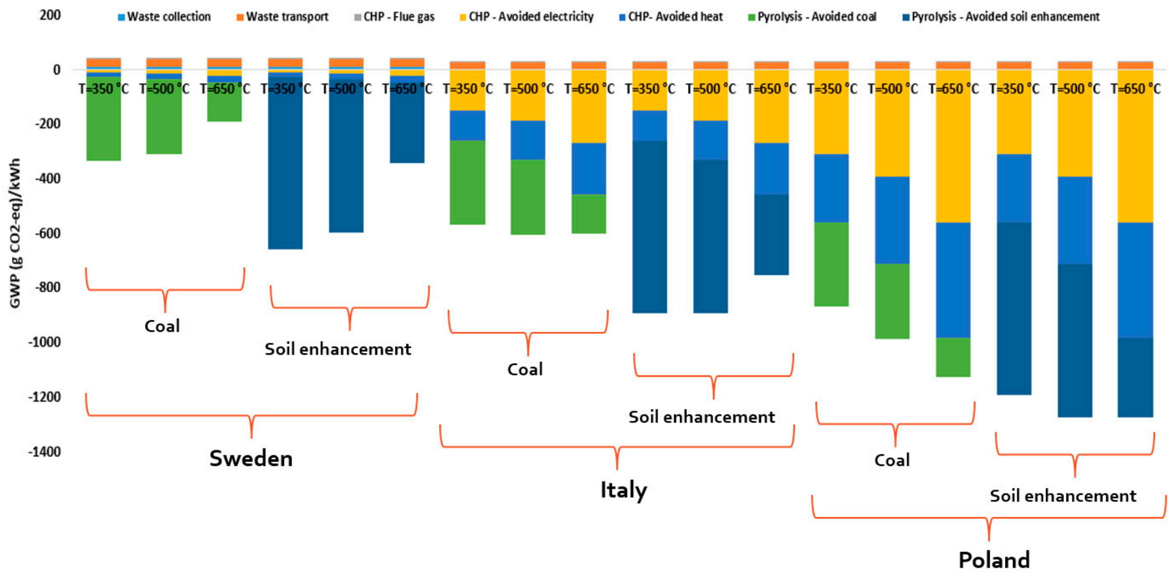

Figure 5. Contribution of the process to the potential GWP impact at different temperature.

4. Conclusions

This study utilized the life cycle assessment (LCA) method to assess the potential emissions reduction of biochar production. The aim was to develop a LCA framework to evaluate the climate impacts of biochar production and its applications in soil enhancement and as a substitute for coal-based fuels in steel industries. The study compared the emissions from conventional biomass usage for energy production across Sweden, Italy, and Poland with varying systems for electricity and heat production. Various pyrolysis operating temperatures were considered to determine the optimal conditions for each case study.

The results of the study suggest that biomass pyrolysis systems present a better option than biomass combustion and current electrical systems in terms of global warming potential (GWP) across different locations. The most climate-friendly option was found to be the BP+CHP+S system. The analysis revealed that Poland and Italy have a high potential for biochar carbon sequestration as they rely on electricity systems based on fossil fuels. The utilization of biomass combustion in these locations would be much more sustainable than using current electrical systems. On the other hand, Sweden has a sustainable energy system and biomass direct combustion can be considered almost as competitive with current electrical systems.

It is evident from the research that a shift from biomass combustion to biomass pyrolysis systems is an eco-friendly option across different locations. The BP+CHP+S system was the most viable choice since it produced negligible greenhouse gases. According to the study, Poland and Italy would benefit the most from biochar carbon sequestration through the use of biomass combustion, as they have electricity systems that are predominantly based on fossil fuels. While Sweden's sustainable energy system makes biomass direct combustion almost as competitive with the current electrical systems, the same cannot be said for other locations. Therefore, policy-makers should ensure that biomass pyrolysis systems are promoted, especially in countries where biochar carbon sequestration presents a considerable environmental benefit.

The study's findings suggest that for Sweden, adopting lower temperatures of around 350 °C is a more desirable option as it leads to reduced CO_2 emission. This is due to the country's reliance on renewable energy for its electrical system. On the other hand, in Italy, a moderate pyrolysis temperature range from 350 to 500 °C is preferable for maximum benefits. However, in Poland, higher temperatures are recommended for biochar applications as they yield the highest GHG reduction. Here, a reliance on fossil fuels for BP+CHP means that this approach is more favorable for CO_2 emissions.

In summary, there is no universal pyrolysis temperature range that can be utilized by all countries for maximum results. Each country needs to assess its energy systems before adopting the optimal pyrolysis temperature. This study's results provide guidance for policymakers in Sweden, Italy, and Poland who want to reduce the carbon footprint and maximize the benefits of pyrolysis technology.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Safarian, S.; Khodaparast, P.; Kateb, M. Modeling and Technical-Economic Optimization of Electricity Supply Network by Three Photovoltaic Systems. *J. Sol. Energy Eng.* **2014**, *136*, 024501. [CrossRef]
2. Manzano-Agugliaro, F.; Sanchez-Muros, M.J.; Barroso, F.G.; Martínez-Sánchez, A.; Rojo, S.; Pérez-Bañón, C. Insects for biodiesel production. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3744–3753. [CrossRef]
3. Manzano-Agugliaro, F.; Alcayde, A.; Montoya, F.; Zapata-Sierra, A.; Gil, C. Scientific production of renewable energies worldwide: An overview. *Renew. Sustain. Energy Rev.* **2013**, *18*, 134–143. [CrossRef]
4. Safarian, S.; Unnthorsson, R.; Richter, C. Techno-Economic Analysis of Power Production by Using Waste Biomass Gasification. *J. Power Energy Eng.* **2020**, *08*, 1. [CrossRef]
5. Safarian, S.; Unnthorsson, R.; Richter, C. *Simulation of Small-Scale Waste Biomass Gasification Integrated Power Production: A Comparative Performance Analysis for Timber and Wood Waste*; Háskóli Íslands University of Iceland: Reykjavík, Iceland, 2020.
6. Balat, H.; Kırtay, E. Hydrogen from biomass—Present scenario and future prospects. *Int. J. Hydrog. Energy* **2010**, *35*, 7416–7426. [CrossRef]
7. Puig-Arnavat, M.; Hernández-Pérez, J.A.; Bruno, J.C.; Coronas, A. Artificial neural network models for biomass gasification in fluidized bed gasifiers. *Biomass-Bioenergy* **2013**, *49*, 279–289. [CrossRef]
8. Safarian, S.; Saryazdi, S.M.E.; Unnthorsson, R.; Richter, C. Modeling of Hydrogen Production by Applying Biomass Gasification: Artificial Neural Network Modeling Approach. *Fermentation* **2021**, *7*, 71. [CrossRef]
9. Safarian, S.; Saryazdi, S.M.E.; Unnthorsson, R.; Richter, C. Gasification of Woody Biomasses and Forestry Residues: Simulation, Performance Analysis, and Environmental Impact. *Fermentation* **2021**, *7*, 61. [CrossRef]
10. Safarian, S.; Saryazdi, S.M.E.; Unnthorsson, R.; Richter, C. Artificial Neural Network Modeling of Bioethanol Production Via Syngas Fermentation. *Biophys. Econ. Sustain.* **2021**, *6*, 1. [CrossRef]
11. Safarian, S.; Sattari, S.; Hamidzadeh, Z. Sustainability Assessment of Biodiesel Supply Chain from Various Biomasses and Conversion Technologies. *Biophys. Econ. Resour. Qual.* **2018**, *3*, 6. [CrossRef]
12. Safarian, S.; Unnthorsson, R.; Richter, C. Performance analysis of power generation by wood and woody biomass gasification in a downdraft gasifier. *Int. J. Appl. Power Eng. (IJAPE)* **2021**, *10*, 80–88. [CrossRef]
13. Safarianbana, S. *Simulation of a Small Scale Biowaste Gasification System for Energy Production*; Háskóli Íslands University of Iceland: Reykjavík, Iceland, 2021.
14. Canha, N.; Lage, J.; Galinha, C.; Coentro, S.; Alves, C.; Almeida, S.M. Impact of Biomass Home Heating, Cooking Styles, and Bread Toasting on the Indoor Air Quality at Portuguese Dwellings: A Case Study. *Atmosphere* **2018**, *9*, 214. [CrossRef]
15. Safarianbana, S.; Unnthorsson, R.; Richter, C. Development of a New Stoichiometric Equilibrium-Based Model for Wood Chips and Mixed Paper Wastes Gasification by ASPEN Plus. In Proceedings of the ASME 2019 International Mechanical Engineering Congress and Exposition, Salt Lake City, UT, USA, 11–14 November 2019; American Society of Mechanical Engineers: New York City, NY, USA; Volume 59438, p. 006 06 2.
16. Safarian, S.; Unnthorsson, R.; Richter, C. Bioethanol Production via Herbaceous and Agricultural Biomass Gasification Integrated with Syngas Fermentation. *Fermentation* **2021**, *7*, 139. [CrossRef]
17. Safarian, S. Performance analysis of sustainable technologies for biochar production: A comprehensive review. *Energy Rep.* **2023**, *9*, 4574–4593. [CrossRef]
18. Tripathi, M.; Sahu, J.; Ganesan, P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 467–481. [CrossRef]
19. Duku, M.H.; Gu, S.; Ben Hagan, E. Biochar production potential in Ghana—A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3539–3551. [CrossRef]
20. Nartey, O.D.; Zhao, B. Biochar Preparation, Characterization, and Adsorptive Capacity and Its Effect on Bioavailability of Contaminants: An Overview. *Adv. Mater. Sci. Eng.* **2014**, *2014*, 715398. [CrossRef]
21. Xiang, W.; Zhang, X.; Chen, J.; Zou, W.; He, F.; Hu, X.; Tsang, D.C.W.; Ok, Y.S.; Gao, B. Biochar technology in wastewater treatment: A critical review. *Chemosphere* **2020**, *252*, 126539. [CrossRef]
22. Chi, N.T.L.; Anto, S.; Ahamed, T.S.; Kumar, S.S.; Shanmugam, S.; Samuel, M.S.; Mathimani, T.; Brindhadevi, K.; Pugazhendhi, A. A review on biochar production techniques and biochar based catalyst for biofuel production from algae. *Fuel* **2020**, *287*, 119411. [CrossRef]

23. Safarian, S. To what extent could biochar replace coal and coke in steel industries? *Fuel* **2023**, *339*, 127401. [CrossRef]
24. Mousa, E.; Babich, A.; Senk, D. Iron ore sintering process with biomass utilization. In Proceedings of the METEC and 2nd European Steel Technology and Application Days Conference (METEC and 2nd ESTAD), Düsseldorf, Germany, 15–19 June 2015.
25. Lu, L.; Adam, M.; Kilburn, M.; Hapugoda, S.; Somerville, M.; Jahanshahi, S.; Mathieson, J.G. Substitution of Charcoal for Coke Breeze in Iron Ore Sintering. *ISIJ Int.* **2013**, *53*, 1607–1616. [CrossRef]
26. Hu, Z.W.; Zhang, J.L.; Bin Zuo, H.; Tian, M.; Liu, Z.J.; Yang, T.J. Substitution of Biomass for Coal and Coke in Ironmaking Process. *Adv. Mater. Res.* **2011**, *236–238*, 77–82. [CrossRef]
27. Sefidari, H.; Lindblom, B.; Nordin, L.-O.; Wiinikka, H. The Feasibility of Replacing Coal with Biomass in Iron-Ore Pelletizing Plants with Respect to Melt-Induced Slagging. *Energies* **2020**, *13*, 5386. [CrossRef]
28. Matuštík, J.; Hnátková, T.; Kočí, V. Life cycle assessment of biochar-to-soil systems: A review. *J. Clean. Prod.* **2020**, *259*, 120998. [CrossRef]
29. Jiang, Z.; Zheng, H.; Xing, B. Environmental life cycle assessment of wheat production using chemical fertilizer, manure compost, and biochar-amended manure compost strategies. *Sci. Total. Environ.* **2020**, *760*, 143342. [CrossRef]
30. James, A.; Sánchez, A.; Prens, J.; Yuan, W. Biochar from agricultural residues for soil conditioning: Technological status and life cycle assessment. *Curr. Opin. Environ. Sci. Health* **2021**, *25*, 100314. [CrossRef]
31. Yang, Q.; Mašek, O.; Zhao, L.; Nan, H.; Yu, S.; Yin, J.; Li, Z.; Cao, X. Country-level potential of carbon sequestration and environmental benefits by utilizing crop residues for biochar implementation. *Appl. Energy* **2020**, *282*, 116275. [CrossRef]
32. Safarian, S. Environmental and energy impacts of battery electric and conventional vehicles: A study in Sweden under recycling scenarios. *Fuel Commun.* **2023**, *14*, 100083. [CrossRef]
33. Burchart-Korol, D.; Jursova, S.; Folęga, P.; Korol, J.; Pustejovska, P.; Blaut, A. Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic. *J. Clean. Prod.* **2018**, *202*, 476–487. [CrossRef]
34. Kannangara, M.; Bensebaa, F.; Vasudev, M. An adaptable life cycle greenhouse gas emissions assessment framework for electric, hybrid, fuel cell and conventional vehicles: Effect of electricity mix, mileage, battery capacity and battery chemistry in the context of Canada. *J. Clean. Prod.* **2021**, *317*, 128394. [CrossRef]
35. *ISO 14040:2006*; Standardization IOf. Environmental Management: Life Cycle Assessment; Principles and Framework. ISO: Geneva, Switzerland, 2006.
36. *ISO 14044:2006*; Environmental Management: Life Cycle Assessment; Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
37. Ecoinvent Database v3.7. Life Cycle Inventories. 2020. Available online: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7/ (accessed on 18 June 2023).
38. openLCA 1.11. Available online: https://www.openlca.org (accessed on 28 September 2022).
39. Yao, Z.; You, S.; Ge, T.; Wang, C.-H. Biomass gasification for syngas and biochar co-production: Energy application and economic evaluation. *Appl. Energy* **2018**, *209*, 43–55. [CrossRef]
40. Safarian, S.; Rydén, M.; Janssen, M. Development and Comparison of Thermodynamic Equilibrium and Kinetic Approaches for Biomass Pyrolysis Modeling. *Energies* **2022**, *15*, 3999. [CrossRef]
41. Peters, J.F.; Iribarren, D.; Dufour, J. Biomass Pyrolysis for Biochar or Energy Applications? A Life Cycle Assessment. *Environ. Sci. Technol.* **2015**, *49*, 5195–5202. [CrossRef] [PubMed]
42. Han, D.; Yang, X.; Li, R.; Wu, Y. Environmental impact comparison of typical and resource-efficient biomass fast pyrolysis systems based on LCA and Aspen Plus simulation. *J. Clean. Prod.* **2019**, *231*, 254–267. [CrossRef]