



Article

Agro-Industrial Symbiosis and Alternative Heating Systems for Decreasing the Global Warming Potential of Greenhouse Production

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Abstract: Greenhouses require large amounts of energy, which is the dominant factor making greenhouses more emission intensive than open-field cultivation. Alternative heating systems, such as combined heat and power (CHP), biogas, and industrial waste heat, are continuously being researched for reducing the environmental impacts of greenhouses. This paper assesses utilizing industrial waste heat and CO₂ enrichment in greenhouses as an example to propose “agro-industrial symbiosis” (AIS), to refer to a symbiotic co-operation between agricultural and industrial partners. The global warming potentials (GWPs) of greenhouse production using different heating systems are inadequately compared in the literature, which is the research gap addressed herein. Additionally, potential emission reductions of greenhouse production with industrial waste heat are yet to be assessed via lifecycle assessment (LCA). A comparative LCA of Finnish greenhouse tomato and cucumber production using various heating systems was conducted. Naturally, replacing fossil fuels with bioenergy and renewables significantly decreases the GWP. CHP systems result in decreased GWP only when using biogas as the energy source. Additionally, utilizing industrial waste heat and CO₂ resulted in a low GWP. These results are applicable worldwide to guide political decision-making and clean energy production in the horticultural sector.

Keywords: greenhouse production; heating systems; lifecycle assessment; global warming potential; agro-industrial symbiosis



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1. Introduction

Human interference with nature and its operating systems, such as the climate, has continuously increased over the Anthropocene. Recently, the 2019 Special Report on Climate Change and Land published by the Intergovernmental Panel on Climate Change (IPCC) [1] estimated that around 70% of the Earth's ice-free land is occupied by humans, and almost 60% of this area is used for agriculture [2]. Compared with open-field cultivation, the development of greenhouses reduces arable land requirement for food production. Greenhouses protect plants from atmospheric impacts and modify the microclimate for the crops, leading to improved quality and higher yields of production, while lengthening the market availability of domestic crops. Due to their high economic efficiency, greenhouses are an attractive business for agricultural entrepreneurs, which explains the continuous growth of greenhouse production in Finland over the past few years [3]. As a downside, greenhouse production consumes high quantities of energy, requires multiple production inputs, and generates large amounts of waste, which can lead to environmental concerns. Organic farming is presented as a solution to secure sustainable food production. However, the low yields of organic farming have in some cases increased the environmental impact of greenhouses due to higher energy demand [4,5]. Bosona and Gebresenbet [6] have also

recognized the need to examine sustainable greenhouse practices with solutions other than solely organic farming.

The global warming potential (GWP), also described as the carbon footprint, of greenhouse produce arises from the inputs required for the production. Commercial greenhouses in Finland often demand heating and artificial lighting, especially when producing crops year-round. Moreover, electricity is needed to control pumps, machinery, and sometimes ventilation. In greenhouses, photosynthesis is boosted by injecting excess carbon dioxide (CO₂) into the greenhouse, which is called CO₂ enrichment. Other inputs that are used for the optimization of growth conditions in greenhouses are fertilizers and irrigation water, substrate material, and occasionally herbicides. Use of packaging materials (usually plastic or cardboard), waste management, and transportation are additional aspects that contribute to the environmental impact of the produce. Energy usage, especially for heating, primarily contributes to the environmental impact of the greenhouse produce. In the early 2000s, a lifecycle assessment (LCA) by van Woerden [7] estimated that energy usage contributed to 75% of the total environmental impact of the Dutch glasshouse horticulture. Other studies in various geographical locations have likewise confirmed that in greenhouse production heating is the main cause of acidification, greenhouse gas (GHG) emissions, and the formation of compounds that cause eutrophication [8–10].

The energy demands of greenhouses are greatly affected by the surrounding climate. Mariani et al. [11] discovered that for greenhouse tomato production, the energy requirement in colder regions can be 20-fold higher compared to that in warmer regions. The same study presented that during winter, the energy consumption in northern greenhouses can progressively increase to up to 1000 MJ m⁻² higher than during summer. Therefore, reducing the energy consumption would be the most effective solution for cutting down the emissions of greenhouse production, especially in colder regions. After adequate insulation, the methods of energy production play the most significant role in the reduction of GHG emissions related to energy consumption. A common heating method used worldwide for greenhouses is a natural gas boiler [12]. In Finland, greenhouses are heated using various methods, such as by burning wood chips, peat, or fossil fuels, or via local district heating. In 2013, Yrjänäinen et al. [13] reported that in Finnish greenhouses, the replacement of grid electricity and oil boilers with green electricity and wood chip boilers could result up to an 84% reduction in GHG emissions. These study results were truly embraced by entrepreneurs, as evidenced by the fact that from 2004 to 2017, the Finnish greenhouse sector reduced its carbon footprint by 56%, primarily by replacing oil with green energy [14]. With increased curiosity toward clean energy sources, greenhouse horticulture has also experienced a rising trend in the utilization of heating solutions such as combined heat and power (CHP) systems [11]. Studies conducted in the Netherlands [5,15] have shown promising environmental and financial benefits associated with the use of CHP boilers compared with conventional natural gas boilers. Industrial waste heat can also be used for heating greenhouses because they can easily utilize such a steady source of low-temperature heat. In earlier research, such partnerships were also found to cut down emissions and improve the economic efficiency of both industries and greenhouses in many geographic locations, such as Canada, Denmark, Sweden, Germany, Greece, and Italy [16–21]. Suitable waste heat can be obtained from various types of industrial processes. In such a partnership, the greenhouse utilizes the industrial waste heat as its primary or secondary heat source, decreasing or completely covering its additional heating needs. In many cases, the CO₂-rich exhaust streams from industrial processes can also be injected into greenhouses to replace out-sourced CO₂ enrichment [22]. In this paper, the concept of “agro-industrial symbiosis” (AIS) is tested to analyze this type of symbiotic operational model between agricultural and industrial partners.

The increased awareness of sustainable food production has impacted the horticultural sector by the numerous resulting environmental assessments of greenhouse production. Even though several studies cover different climates and continents, such as Europe [6,10,23], North America [16,24], and Asia [25], their case-specific approaches limit

the comparability among studies. Studies in the field often quantify the environmental impacts of individual production systems with empirical data collected within them. Some studies also focus on comparing the environmental impacts resulting from production variances. Regardless of the major role of heating on the environmental impacts of greenhouse production, examined production variances are often chosen from outside of the heating method. For instance, Bosona and Gebresenbet [6] compared the environmental burdens of fresh organic tomato and dried tomato value chains. In Asia, Pineda et al. [25] determined the environmental impacts of conventional greenhouse tomato production versus a rooftop greenhouse. Only a few scientific publications have evaluated multiple heating fuels and systems in greenhouse production [16,24], but have been limited to comparing only a small number of heating methods within the same study. The scientific scheme lacks information on how the different heating methods for greenhouses perform against one another from the environmental standpoint. This research fills the identified research gap by performing a comparative LCA from the GWP perspective for greenhouse tomato and cucumber produced with various heating methods. Moreover, this research quantifies the possible GHG emission reductions using the CHP system and industrial waste heat in greenhouses. This study aims to answer how the change in the greenhouse heating method impacts the GHG emissions of greenhouse production, and whether and how effectively the implementation of CHP systems and the utilization of industrial waste heat reduce the GHG emissions of greenhouses.

2. Conceptual Framework for the Utilization of Industrial Heat in Greenhouses

In an earlier study, the practice of heating greenhouses using industrial waste heat was described as “industrial symbiosis” (IS) [21]; however, the author argues that the term IS describes this process inadequately because the term narrows the system scope only to the industrial landscape, in which greenhouses are not included. As Gibbs [26] puts it, “industrial symbiosis uses metaphors drawn from natural ecosystems to suggest that industrial production can be reconfigured into an ‘industrial ecosystem’”. This suggests that IS refers to industrial processes imitating practices found in ecosystems, which is called biomimicry. The concept of IS originates from industrial ecology, which seeks to optimize the use of virgin and reusable materials by circulating natural resources, energy, and capital [27]. By recognizing the symbiotic possibilities of circulating such goods through collaborations, companies and entrepreneurs are able to establish beneficial symbioses. As the circulation of goods demands spatial proximity, symbiosis opportunities must be realized in closely compact areas. These areas are referred to as eco-industrial parks [28]. Based on what Gibbs [26] says, in this term, eco refers to ecosystemlike and not ecological processes. The first model of IS was the Kalundborg Eco-Industrial Park, Denmark, where the partners in the symbiotic network were mostly industrial actors, such as an oil refinery, a power station, a gypsum board facility, and the municipality of Kalundborg. In Kalundborg symbiosis, the agricultural operators acted solely as receivers of waste rather than as partners circulating goods. Moreover, studies on other such eco-industrial parks have identified symbioses between agricultural actors and food processors, such as the Montfort Boys Town integrated biosystem in Suva, Fiji, which was described as an integrated biosystem instead of eco-industrial park [28].

Koppelmäki et al. [29] presented a concept “agroecological symbiosis” (AES) that describes the symbioses between agricultural actors and food processing, such as the one above in Fiji. The concept of AES was first introduced in 2016 in a pilot case study on the Palopuro AES, which is located in a rural community in the vicinity of Hyvinkää, Finland [29]. The Palopuro AES consists of an organic cereal farm, a local hennery, horse stables, and an aerobic digester. It circulates agricultural material flows, such as grain, milling waste, eggs, and fallow biomass to produce food, green manure, biogas, and biochar in close collaboration. Based on the operations in Palopuro AES, Koppelmäki et al. [29,30] recognized the main operational functions of AES as closed nutrient loops, biogas production, and renewable energy sufficiency derived from domestic feedstocks. AES also

consists of integrated supporting processes, such as an anaerobic digester [31]. As its scope excludes symbiotic opportunities with an industrial partner operating outside of the food production processes, AES is considered an inappropriate concept to describe symbiotic processes between agricultural and industrial partners, such as the utilization of industrial waste heat in greenhouses.

Even though AES is described as “a food system application” of IS [30], the two concepts vary in their aims and ideologies. IS aims to minimize waste of materials and energy to maximize ecological and financial benefits (green growth). These principles are in common with those of environmental economics and the circular economy. Unlike in establishing IS, green growth is not a particular aim when forming collaborations based on the AES principles. In AES, the ecosystem services of the agroecological environment are not to be compromised when managing agroecosystems for production, even if symbiotic loops were found. AES maintains the operations of the ecosystem services not only in human-centric terms (continuous productivity) but also from the perspective of holistic ecological sustainability (maintenance of ecological integrity) [31]. The principles of AES are more aligned with ecological economics. As the ideologies of IS and AES are not in line, and symbiotic processes between agricultural and industrial partners is difficult to place only under the other, the authors have recognized a need for a unitive concept.

The terms IS and AES describe the symbiosis network based on the operational environment and context. IS occurs in an industrial context, where companies and factories share and circulate waste products, resources, and energy between industrial processes. AES occurs in an agroecological context, where the goods derived from the ecosystem services are exploited and circulated among agricultural processes. Symbioses between agricultural and industrial partners occur between the operational environments of AES and IS, which this paper refers to as the agro-industrial context, creating a demand for a new term, AIS, to describe symbioses between industrial and agroecological partners, as shown in Figure 1. This research tests the representation of industrial waste heat utilization in greenhouses based on the concept of AIS.

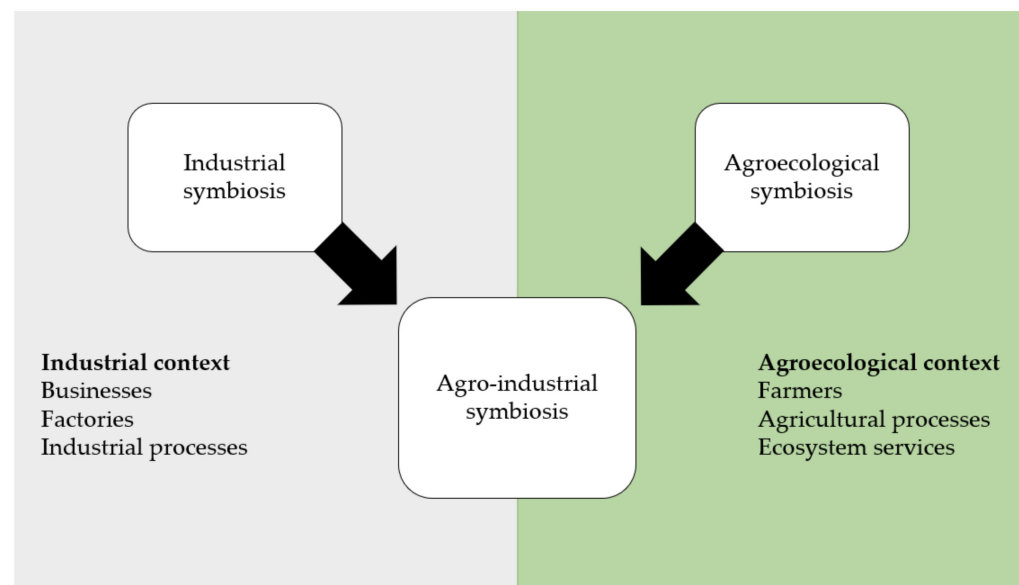


Figure 1. The conceptual framework of an agro-industrial symbiosis (AIS).

3. Materials and Methods

LCA enables the assessment of a product or system over its entire life span. LCA evaluates the use of process inputs, such as energy, water, fertilizers, metals, wood, or chemicals, as well as outputs, such as emissions or waste, of the product or system being analyzed. LCA considers all steps in a product’s or system’s life cycle, including raw material extraction, its conversion into the product, transportation, product use, and

disposal. This methodology can be used to assess the impacts of the product or system on different scales, such as cradle-to-grave (from raw material extraction to waste disposal) or cradle-to-gate (from raw material extraction to the finished product). LCA is usually used to define the solutions and designed systems that come with the highest or lowest burdens for the environment. LCA has been used in numerous studies for assessing the environmental impacts of the European greenhouse production [5,7,10,23,32,33].

3.1. Goal, Scope, and System Boundary Definition

The objective of the study is to assess the GWP of different heating methods for greenhouse tomato and cucumber production. The results are addressed in terms of a 100-year GWP (GWP100). The GWP is calculated according to the ISO standards 14040, 14044, and 14067, using the GaBi ts 9.5 software according to characterization factor CML2001—April 2013, Global Warming Potential (GWP100). As the majority of the Finnish greenhouse cultivation area is used to produce primarily tomato and cucumber [3] the functional unit (FU) is set as 1 ton for both. The study area is in the boreal climate zone, more specifically in Finland. The required data for the LCA were collected from the GaBi LCI database and via a literature review on greenhouse horticulture, more specifically the LCAs carried out in this field. The empirical data gathered for the LCA of the Finnish greenhouse production by Yrjänäinen et al. [13] and later updated by Silvenius et al. [34] were used as set points for this study.

The system boundary of the studied greenhouse operation system is cradle-to-gate, as illustrated in Figure 2. The system boundary includes impacts from the construction of the greenhouse, agricultural operations, and inputs of the greenhouse, such as energy, carbon dioxide for CO₂ enrichment, fertilizers, and substrate materials, as well as the transportation, packaging of the products, and waste management. As seeds and seedlings used in Finnish greenhouses are outsourced by the greenhouse and their production has a minimal contribution to the total GWP of the produce [13], their impacts on the GWP have been ignored.

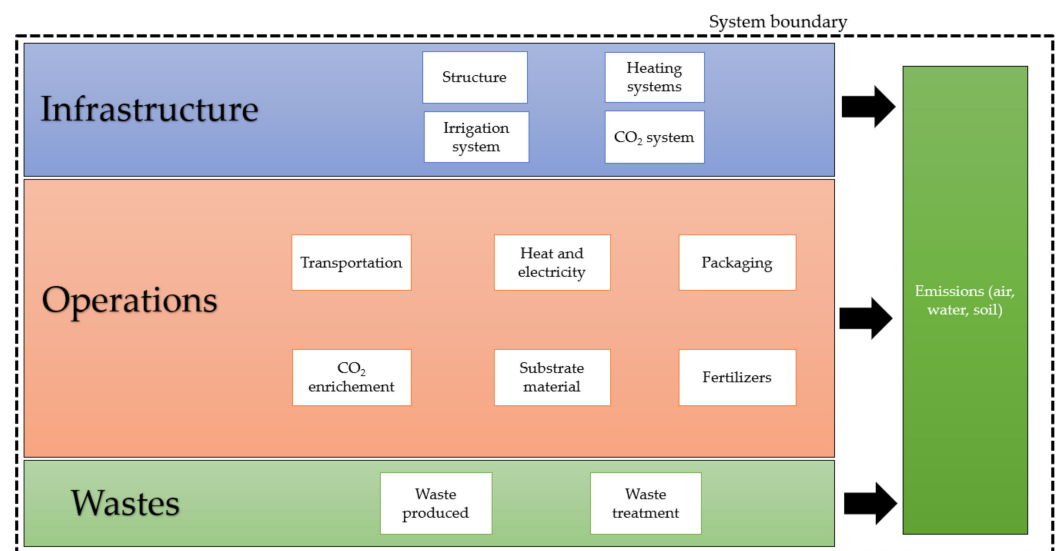


Figure 2. The system boundary of the study includes all relevant input and output flows of the greenhouse (excluding the minimal contribution of seeds and seedlings).

3.2. Scenario Description

Herein, the GWP of different heating methods are examined via LCA by comparing them based on eight heating scenarios, which are detailed in Table 1. Scenarios 1–4 represent the most popular greenhouse heating methods in Finland, which are via oil, peat, and wood chip boilers, and district heating. In these scenarios, electricity is taken from the national grid and the additional CO₂ is obtained from an external CO₂-provider. Scenarios

5 and 6 use natural gas boilers and biogas boilers for heating, respectively, and the boiler exhaust gas is utilized for CO₂ enrichment. In scenario 7, a CHP boiler is used as the source of heat, electricity, and CO₂ for the greenhouse. The greenhouse is supplemented with additional grid electricity when there is a deficit, and sells electricity to the grid when electricity production is in excess. Sensitivity analysis examines the GWP resulting from the use of a CHP boiler incorporating natural gas and biogas under different heat demands and electricity emission factors. Scenario 8 represents a case wherein AIS has been established between a greenhouse and an industrial partner. In this scenario, the industrial waste heat is utilized for greenhouse heating via using a heat pump. Additionally, the exhaust gases of the industrial process are utilized for CO₂ enrichment, which is considered carbon neutral. The GWPs resulting from AIS are examined in the sensitivity analysis based on different heat pumps' coefficients of performance (COPs) and various electricity emission factors.

Table 1. The scenarios to analyze different heating methods.

Scenario	Heat Source	Electricity Source	CO ₂ Source
Scenario 1	Oil boiler	National grid	External input
Scenario 2	Peat boiler	National grid	External input
Scenario 3	Wood chip boiler	National grid	External input
Scenario 4	District heating	National grid	External input
Scenario 5	Natural gas boiler	National grid	Boiler exhaust gas
Scenario 6	Biogas boiler	National grid	Boiler exhaust gas
Scenario 7	Natural gas CHP boiler	CHP + National grid	Boiler exhaust gas
Scenario 8	Industrial waste heat	National grid	Industry exhaust gas

3.3. Life Cycle Inventory (LCI)

The main inputs of a greenhouse are heat, electricity, fertilizers, CO₂, substrate material, water, and packaging material. The outputs of a greenhouse include the products and waste. The LCI of these inputs and outputs is presented in Table 2. In Finland, the yields of greenhouse tomatoes and cucumber were 41 kg m⁻² and 87 kg m⁻², respectively, in 2017 [3], implying that the required greenhouse area FU⁻¹ is 24.4 m² for tomatoes and 11.5 m² for cucumber. The GWP of the infrastructural operations for greenhouse production varies greatly depending on the type and construction material of the greenhouse. The GWPs of infrastructural operations of greenhouses were researched in detail by Boulard et al. [10], who determined the GWP to be around 140 kg CO₂-eq. per 1000 kg of tomatoes in France. As the yields of greenhouse tomato and cucumber vary greatly, even in the same geographic location [13,35], the share of infrastructural operations in the total GWP is in this research assumed to be 140 kg CO₂-eq. per 1000 kg of produce for both tomato and cucumber.

Energy: The heat and electricity demand of a greenhouse is highly case specific. This research applies the estimations of Silvenius et al. [34], who defined that in Finland, the heat and electricity requirement for tomato production are 9.84 and 3.32 MWh FU⁻¹, and those for cucumber production are 2.73 and 7.64 MWh FU⁻¹, respectively. The emission factors for the heating systems, excluding district heating, are obtained from the GaBi LCI database and are used in the LCI analysis (LCIA). For district heating, the emission factor is considered to be 196 kg CO₂-eq MWh⁻¹, which is obtained from Statistics Finland [36]. It is expected that a greenhouse uses electricity from the Finnish national grid, which has a yearly average emission factor of 140 kg CO₂-eq MWh⁻¹ [37].

Fertilizers: According to a questionnaire by Grönroos and Nikander [38], Finnish greenhouses consume around 0.9 m³ m⁻² annum⁻¹ of irrigation water, which is usually enhanced with nutrients, such as nitrogen (N), phosphorus (P), and potassium (K). The NPK-fertilizer doses for tomato and cucumber production, defined by the Finnish Horticultural Trades Association [34], are presented in Table 2. An adjusted NPK-fertilizer

production process, GLO: NPK fertilizer mixer ts, is taken for the LCIA from the GaBi LCI database. This study follows the IPCC [39] methodology, wherein 1% of the added N in the soil is emitted as nitrous oxide (N₂O).

CO₂ enrichment: Most greenhouse crops experience increased growth and improved quality with increased CO₂ levels up to 1000–1500 ppm [40]. Greenhouse tomatoes for example have recorded a 90% increase in yield with CO₂ concentration of 1000 ppm [41]. The average annual consumption of CO₂ in a greenhouse varies usually between 1.0 and 6.7 kg CO₂ m⁻² based on the enrichment control strategy of the greenhouse [42]. In this research, CO₂-enrichment is carried out according to a quasi-optimal economic yield strategy defined by Chalabi et al. [42] (Table 2). CO₂ enrichment is usually performed by either guiding exhaust gases from the boilers into the greenhouse or by gasifying pure liquid CO₂ and injecting it into the greenhouse. In Finland, greenhouses often utilize CO₂ that is created as a byproduct from different processes, such as fertilizer production, after which it is pressurized and brought to the greenhouse [43]. In scenarios 1–4, wherein CO₂ is outsourced, the obtained CO₂ is expected to be a byproduct of ammonia synthesis, the emissions for which are obtained from the GaBi LCI database.

Substrate material: According to the questionnaire of Grönroos and Nikander [38], rock wool is a popular substrate material used in Finnish greenhouses. Based on the statistics of Natural Resources Institute Finland [3] and expert evaluations [34], the required amount of rock wool is approximately 3900 kg ha⁻¹. For the quantification of the GHG emissions of rock wool production, the process of EU-28 Stone wool ts was used from the GaBi LCI database.

Waste management: It is estimated that greenhouse tomato and cucumber production generates around 400 kg and 700 kg of green waste FU⁻¹, respectively [3,44]. Rock wool waste is assumed to be composted with green waste [10]. Moreover, wood chips are added to this waste mix. After mixing, wood chips represent 15% of the total weight of the final waste mix. Half of the N in the composting material is assumed to be released, with 5% of it being released in form of N₂O [13]. Additionally, 65% of the biogenic carbon present in the mix is released, of which 3% in form of methane [13].

Packaging: In Finland, cucumbers are packed in a plastic film, and tomatoes are often transported in cardboard boxes [14]. Finnish cucumbers are wrapped in plastic sheets made from fossil-fuel-based polyethylene (PE) plastic, and the amount of plastic required is around 6.25 kg per ton of cucumber [45]. By estimating a 10% loss of the wrapping plastic during the packaging process, the total estimation of plastic use comes close to 7 kg of PE plastic FU⁻¹ for cucumber. Dias et al. [24] estimated that the amount of cardboard packaging is 105 kg per ton of tomato. The same estimation is used in this study. The emissions that originate from the production of plastic film and cardboard are taken from the GaBi LCI database.

Transportation: Transportation of the needed goods is conducted by truck, Euro 0–6 mix, 12–14 t gross weight/9.3 t payload capacity model used from the GaBi LCI database. The expected distance of the greenhouse from the fertilizer, CO₂, and stone wool producers is assumed to be 50 km, and the transport segment greenhouse-to-wholesale-to-retail is expected to be 100 km.

Table 2. Inventory data per functional unit.

Inventory	Unit	Tomato	Cucumber
Needed cultivation area ^a	m ²	24.4	11.5
Infrastructural impact ^b	kg CO ₂ -eq.	140	140
Primary heat demand ^c	MWh	9.84	2.73
Primary electricity demand ^c	MWh	3.32	7.64
Fertilizer application ^c :			
NH ₃	kg	9.9	5.7
K ₂ O	kg	20.4	10.1

Table 2. Cont.

Inventory	Unit	Tomato	Cucumber
P ₂ O ₅	kg	5.0	2.7
Irrigation water ^d	m ³	34	16
Stone wool ^{a,c}	kg	9.5	4.5
CO ₂ ^e	kg	146	69
Packaging			
Cardboard ^f	kg	150	-
Plastic film ^g	kg	-	7
Green waste ^{a,h}	kg	400	700
Transportation:			
From input production to greenhouse	km	50	50
From greenhouse to retailer	km	100	100

^a National Resources Institute Finland [3]. ^b Boulard et al. [10]. ^c Silvenius et al. [34]. ^d Grönroos and Nikander [38]. ^e Chalabi et al. [42]. ^f Dias et al. [24]. ^g Katajajuuri [45]. ^h Keitaanpää [44].

4. Results

4.1. LCIA of Greenhouse Tomato Production

Due to the colder climate, the production of greenhouse tomatoes in the Northern Hemisphere requires high amounts of heat energy. With higher heat demands, the significance of heating methods for the environmental impacts of greenhouse production increases. The results of this study show that the GWP of greenhouse tomato production is the lowest when using biofuels or industrial waste heat as a heat source for the greenhouse, as shown in Figure 3. The results show quite a significant difference between the two biofuels, wood chips and biogas. The usage of biogas creates larger emissions, with most of its emissions occurring during its more complex production and upgrading processes compared to wood chips. The GWP of the Finnish greenhouse tomato production varied between 857 and 6523 kg CO₂-eq. FU⁻¹ in this study. The largest GWP, 6523 kg CO₂-eq. FU⁻¹, was obtained when using peat, followed by oil and natural gas boilers, with the GWPs of 4259 and 3523 kg CO₂-eq. FU⁻¹, respectively. The lowest GWP, 857 kg CO₂-eq. FU⁻¹, resulted from the use of a wood chip boiler, followed by industrial waste heat and biogas boiler, with the GWPs of 1187 and 1807 kg CO₂-eq. FU⁻¹, respectively. The usage of local district heating resulted in a fairly average GWP of 3020 kg CO₂-eq. FU⁻¹. Applying a CHP boiler to cover the heat demand of a greenhouse tomato production resulted in a GWP of 4394 kg CO₂-eq. FU⁻¹, which is considerably higher than that obtained using a conventional natural gas boiler.

Majority of the generated GWP of the tomato production results from heat consumption in most of the scenarios, as shown in Figure 3. Overall, heating was found to contribute to 12–88% of the total GWP in all scenarios, excluding the CHP boiler scenario, wherein emissions from both heat and electricity consumption were allocated under heating. Using a CHP boiler for heat production produces excess electricity, which is expected to be sold to the grid to replace production of national grid electricity, resulting in avoided emissions. The avoided emissions are allocated as emission reductions for the greenhouse production, presented under “electricity” in the CHP scenario in Figure 3. Electricity consumption had the second largest contribution to the GWP in all scenarios, except for the wood chip boiler and industrial waste heat scenarios, wherein electricity consumption was the primary contributor to the GWP. On average, heating contributed to 63% and electricity to 24% of the total GWP in all scenarios. Production inputs other than energy have an insignificant combined contribution to the GWP of greenhouse tomato production in Finland. The GWPs resulting from infrastructure, fertilizer production and application, waste treatment, CO₂ enrichment, transportation, packaging, substrate material, and water have a GWP impact of 240–286 kg CO₂-eq. FU⁻¹ depending on the source of CO₂ enrichment.

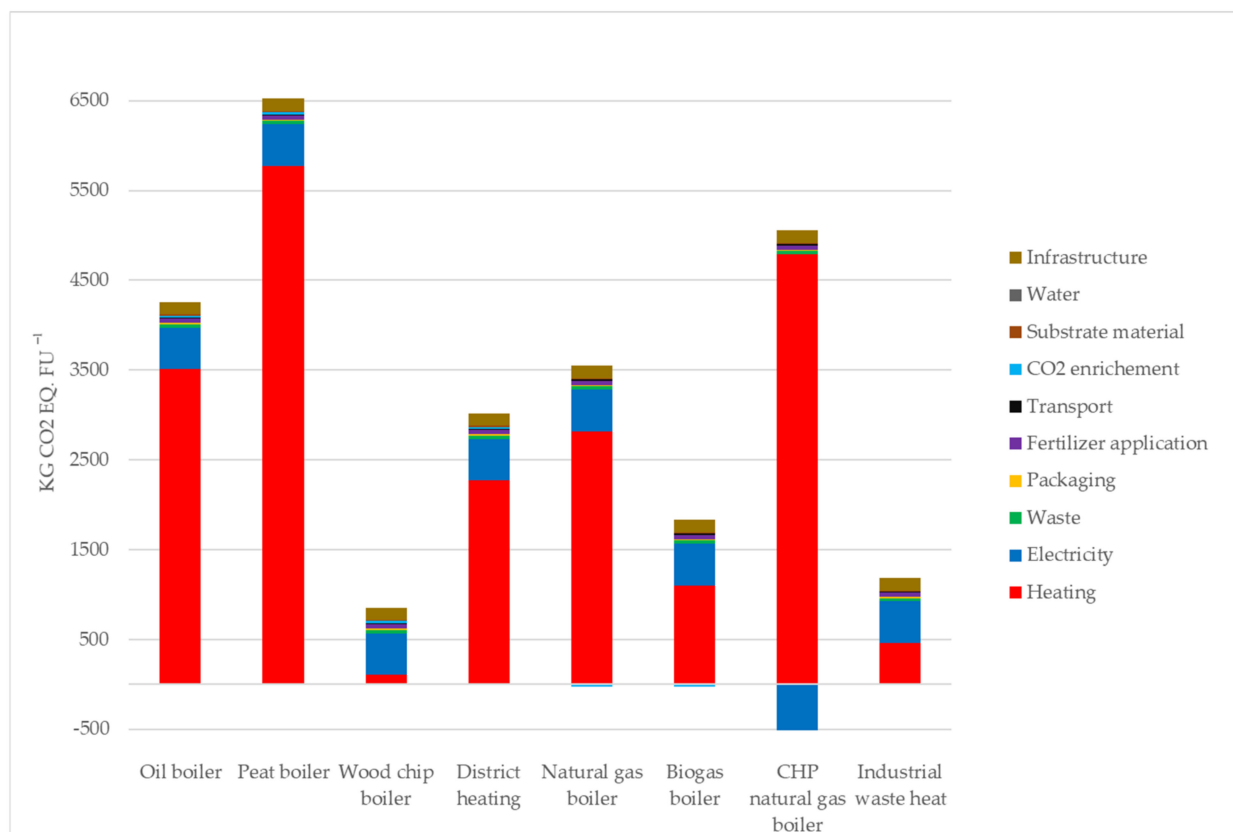


Figure 3. Global warming potential (GWP100) comparison of the Finnish greenhouse tomato production when using different heating methods.

4.2. LCIA of Greenhouse Cucumber Production

Similar to greenhouse tomato production, the GWP of greenhouse cucumber production is the lowest when using biofuels or industrial waste heat as the heating method, as shown in Figure 4. Due to higher lighting demand, the production of cucumbers requires more electric than heat energy. Due to the lower heat demand, differences in GWP among the different heating scenarios are not as remarkable as those for tomato production. Even though greenhouse cucumber production requires almost as much total energy as that for greenhouse tomato production, its production is less emission intensive than tomato production. This is due to the lower emissions of the Finnish grid electricity compared to the emissions of most heating methods. In total, the GWP of the Finnish greenhouse cucumber production varied between 1379 and 2951 kg CO₂-eq. FU⁻¹. Similar to tomato production, the largest GWP, 2951 kg CO₂-eq. FU⁻¹, was obtained when using a peat boiler, which was followed by the oil and natural gas boilers, with GWPs of 2323 and 2110 kg CO₂-eq. FU⁻¹, respectively. The lowest GWP, 1379 kg CO₂-eq. FU⁻¹, resulted from the use of a wood chip boiler, followed by industrial waste heat and the biogas boiler, with GWPs of 1466 and 1634 kg CO₂-eq. FU⁻¹, respectively. The use of the Finnish district heating resulted in a fairly average GWP of 1979 kg CO₂-eq. FU⁻¹. Applying the CHP boiler to cover the energy needs of the greenhouse cucumber production resulted in a GWP of 2351 kg CO₂-eq. FU⁻¹.

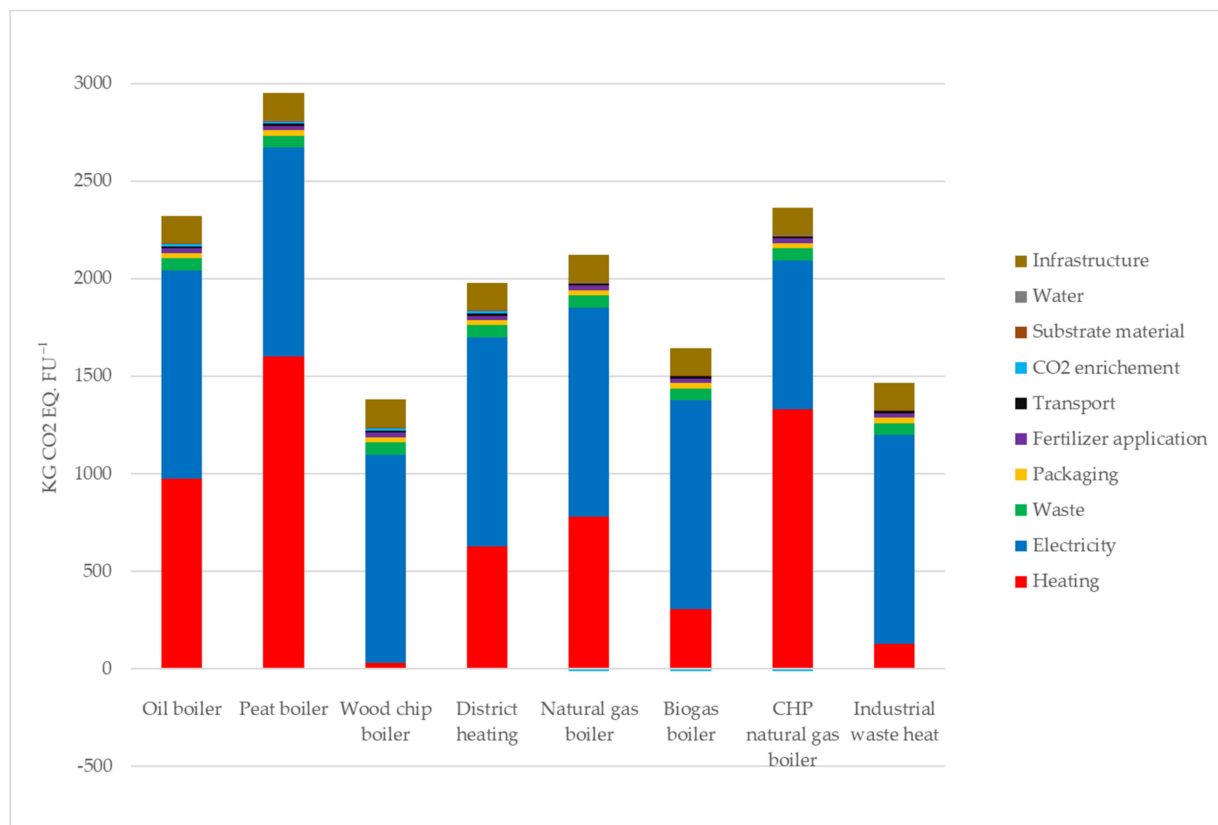


Figure 4. Global warming potential (GWP100) comparison of the Finnish greenhouse cucumber production when using different heating methods.

For greenhouse cucumber production, electricity consumption contributed to 36–77% of the GWP. On average, heating contributed to 28% and electricity to 58% of the total GWP for all scenarios. For greenhouse cucumbers, heating was the main contributor to the GWP when using peat or a natural gas CHP boiler for heat production. For other heating methods the main contributor to the GWP was electricity consumption. As cucumber production demands more electricity than heat, using a CHP boiler for heat production covers only a part of the electricity demand, unlike that in greenhouse tomato production. Therefore, part of the emissions of electricity consumption are allocated to heat production, but no emission reductions occur. The GWPs resulting from infrastructure, fertilizer production and application, waste treatment, CO₂ enrichment, transportation, packaging, substrate material, and water have a combined GWP of 257–280 kg CO₂-eq. FU⁻¹.

4.3. Sensitivity Analysis

As defined in the earlier results, the GWP of greenhouse production is significantly affected by the energy demand and the source of energy. The GWP of the produce of an individual greenhouse when using a certain heat source varies greatly, as the conditions, such as the primary energy demand and emission factors, change based on the location of the greenhouse. This sensitivity study is conducted to highlight under which conditions the CHP boilers and AIS lead to the reduction in the GWP of greenhouse production. The natural gas boiler is used as the reference scenario to help in understanding the results.

4.3.1. CHP System

The CHP system is analyzed to examine the effects of changing the electricity emission factor and the heat demand of tomato production when using natural gas and biogas CHP boilers. Herein, the GWPs resulting from the use of natural gas CHP (blue, Figures 5 and 6) and conventional (brown, Figures 5 and 6) natural gas boilers are examined under electricity

emission factors of 50–350 kg CO₂-eq. MWh⁻¹ and under primary heat demands between 2 and 10 MWh. Figure 5 presents the results for natural gas boilers and Figure 6 for biogas boilers. As mentioned earlier, the excess electricity produced by the CHP boiler is assumed to be sold to the national grid, which is expected to reduce the demand of grid electricity production and cut down emissions.

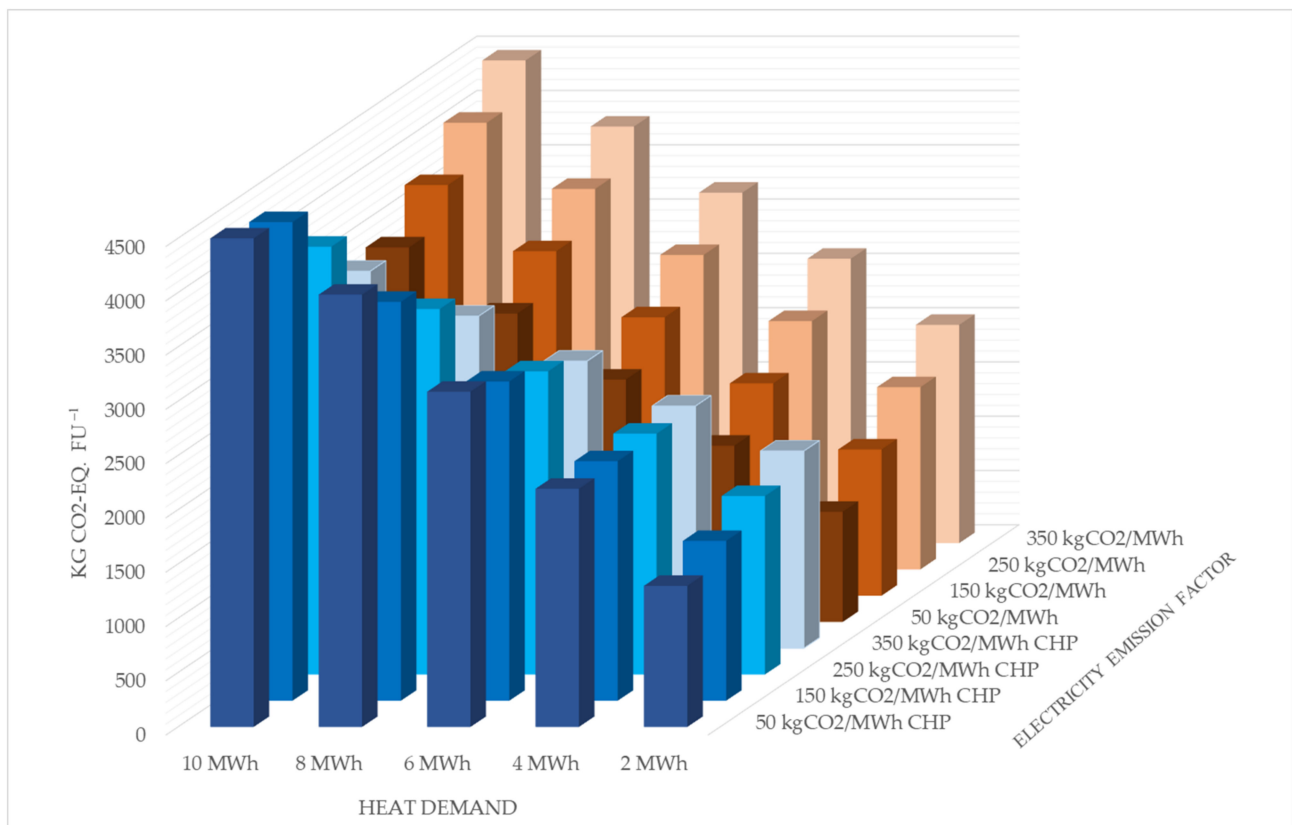


Figure 5. Effects of electricity emission factor and heat demand on the GWP of the Finnish greenhouse tomato production when using a natural gas CHP (blue) and conventional (brown) natural gas boiler.

The results show that using a natural gas CHP boiler instead of a conventional natural gas boiler maintains the GWP of greenhouse tomato production fairly similar. When using a conventional natural gas boiler, the lowest GWP is achieved with a low heat demand and a low electricity emission factor, as expected. A natural gas CHP boiler shows the same result for low heat demands, 2–4 MWh, which represent situations wherein no excess electricity is produced by the natural gas CHP boiler. In contrast, for high heat demands, 6–10 MWh, the GWPs decrease with increasing the electricity emission factor. This occurs because with higher heat demands, excess electricity is produced by the natural gas CHP boiler, which decreases the demand of grid electricity production. The more emission intensive the grid electricity, the more emission reductions there will be. Even though these emission reductions occur in the grid, they are assigned to the greenhouse in these calculations.

The results indicate that for electricity emission factors of 50 and 150 kg CO₂-eq. MWh⁻¹, the use of the conventional natural gas boiler resulted in lower GWP than that of the natural gas CHP boiler. For electricity emission factors of 250 and 350 kg CO₂-eq. MWh⁻¹, the use of the natural gas CHP boiler resulted in lower GWP compared to that of the conventional natural gas boiler, even though no remarkable benefits were recorded. An analysis of the results suggests that regardless of the heat demand, using the conventional natural gas boiler results in lower total GWP than using the natural gas CHP boiler when the electricity emission factor of the local grid electricity is under 228.3 kg CO₂-eq. MWh⁻¹. Conversely,

the natural gas CHP boiler results in a lower GWP when the grid's electricity emission factor is above this threshold value.

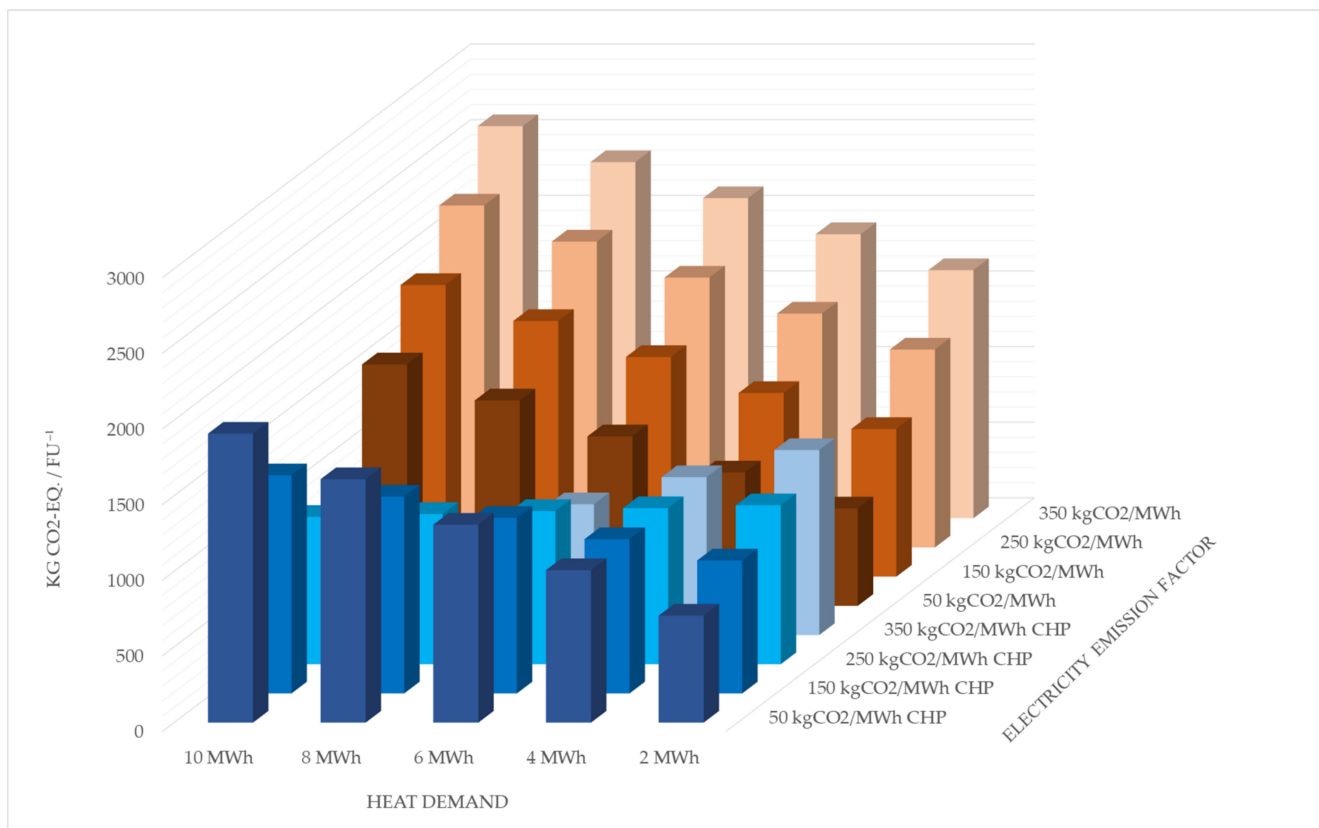


Figure 6. Effects of electricity emission factor and heat demand on the GWP of the Finnish greenhouse tomato production when using a biogas CHP (blue) and conventional (brown) biogas boiler.

The results suggest that using a biogas CHP boiler instead of a conventional biogas boiler results in lower GWP for several electricity emission factors, as shown in Figure 6. Similar to a natural gas CHP boiler, a biogas CHP boiler leads to a decrease in the GWP for higher heat demands, and in an increase in the GWP for low heat demands when increasing the electricity emission factor.

For an electricity emission factor of $50 \text{ kg CO}_2\text{-eq. MWh}^{-1}$, the use of the conventional biogas boiler results in a lower GWP than that of the biogas CHP boiler. For electricity emission factors of 150, 250, and $350 \text{ kg CO}_2\text{-eq. MWh}^{-1}$, the use of the biogas CHP boiler results in lower GWP than that of the conventional biogas boiler. The results show that the higher the electricity emission factor and the higher the heat demand, the higher the benefits of using the biogas CHP boiler will be. An analysis of the results suggests that when the electricity emission factor of the grid is under $89 \text{ kg CO}_2\text{-eq. MWh}^{-1}$, the conventional biogas boiler leads to a lower GWP than that of a biogas CHP boiler. The use of a biogas CHP boiler results in a lower GWP than that of a conventional biogas boiler when the grid electricity emission factor is above this threshold value.

4.3.2. Agro-Industrial Symbiosis

The AIS analysis examines how the GWP of the greenhouse production utilizing industrial waste heat is affected by the changes in the COP of the heat pump and the electricity emission factor. The waste heat pump usually has a COP of 2–4, which implies that for each unit of electricity consumed by the heat pump, 2–4 units of thermal energy is produced. The COPs from 1 to 4 are examined for electricity emission factors of 15–250 $\text{kg CO}_2\text{-eq. MWh}^{-1}$ for both greenhouse tomato and cucumber production.

According to the results shown in Figure 7, the GWP of greenhouse tomato production under AIS (scenario 8) results in lower GWPs than that when using a natural gas boiler for all studied electricity emission factors. The results indicate that the AIS effectively lowers the GWP of the greenhouse tomato production even when utilizing non-renewable electricity. Under AIS, the highest emission reductions are obtained under low electricity emission factors. Even the worst-case scenario, represented by a COP of 1, resulted in GWP of just above 2000 kg CO₂-eq. FU⁻¹ for the electricity emission factor of 150 kg CO₂-eq. MWh⁻¹, which is still less than the GWPs recorded when using the Finnish district heating and fossil fuels, shown in Figure 3. The minor variations among the GWPs of the COPs 2–4 suggests that low GWPs of the greenhouse production can be expected even without fully optimizing the efficiency of the heat pump.

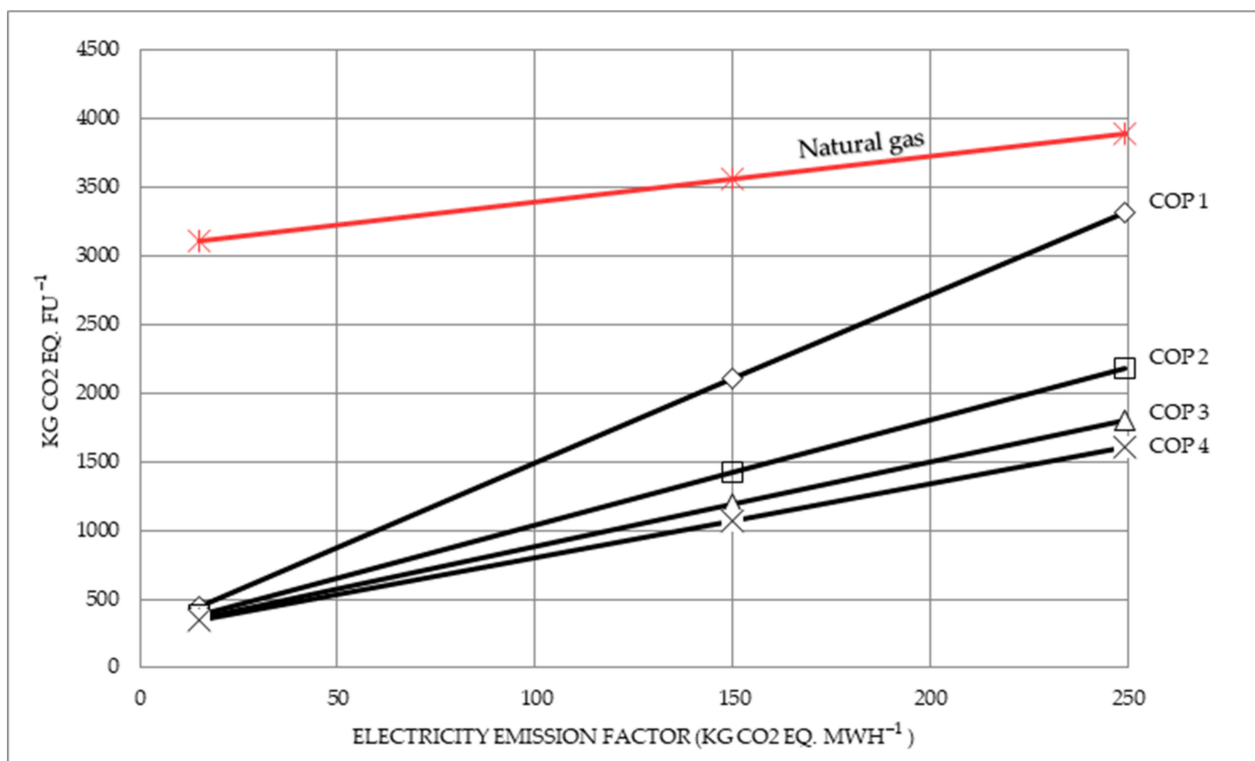


Figure 7. Effects of electricity emission factor and coefficient performance (COP) on the GWP of the Finnish greenhouse tomato production using a waste heat pump.

The greenhouse cucumber production under AIS also presents a lower GWP compared to that when using a natural gas boiler for all studied electricity emission factors (15–250 kg CO₂-eq. MWh⁻¹). The results show that the GWP remains relatively on the same level for all studied heat pump COPs, as shown in Figure 8. Due to the low heat demand and high electricity demand, the results do not present emission reductions as remarkable as those seen in the case of the greenhouse tomato production. The results from these sensitivity analyses suggest that the GWP benefits of waste heat pumps are the greatest for low electricity emission factors and high heat demand. It is also noted that optimization of the COP of the waste heat pump is not particularly important from the GWP perspective as even with a COP of 2, the utilization of industrial waste heat pumps results in a lower GWP than that when using several other heating methods.

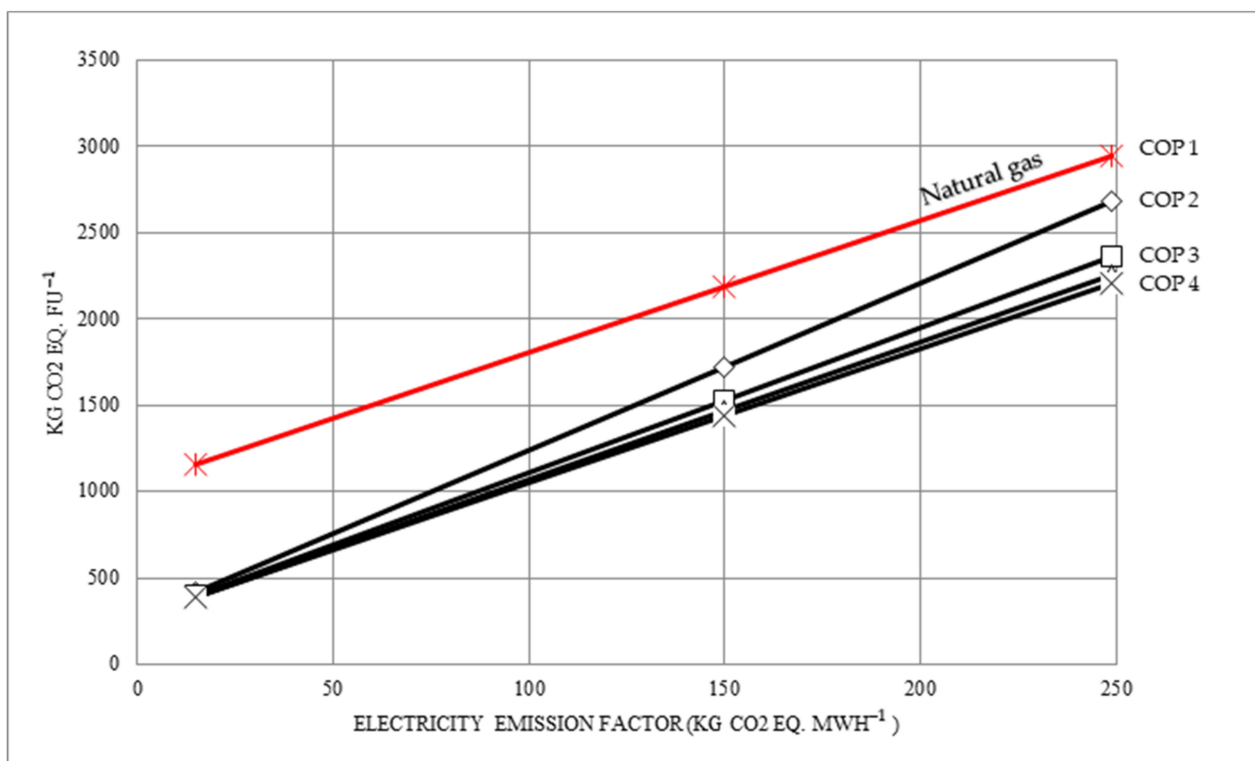


Figure 8. Effects of electricity emission factor and COP on the GWP of the Finnish greenhouse cucumber production using a waste heat pump.

5. Discussion

The GWP of greenhouse production has been widely researched via LCA in multiple geographical locations, especially the GWP of greenhouse tomato production. The majority of the calculations from earlier research were case specific, and their usability was limited because each greenhouse is a unique production system. For example, the most significant factor impacting the GWP of greenhouse production is the cumulative energy consumption (CED), which has been found to vary tremendously even between greenhouses that are located in the same geographic region [13] (Table 3). Outside of surrounding climate, production decisions, such as the species of crops grown and production intermittency, as well as constructional variances affect the CED of greenhouses. It has also been observed that tomato and cucumber greenhouses use heat and electricity to varying extents, despite the fact that the CEDs for their production are in close range [34] (Table 2). To overcome the challenge of case-specificity, this research employed empirical data gathered by other researchers in the field of greenhouse horticulture and modeled an “average” greenhouse in Finland and examined various greenhouse heating methods within it.

Table 3. The GWP and CED of the production of 1000 kg of greenhouse tomatoes calculated from studies carried out at different geographic locations.

Production Country	CED (MWh)	Heat Source	GWP ₁₀₀ (kg CO ₂ -eq.)	Reference
Italy	1.1	No heating	740	Cellura et al. [45]
South Korea	1.1	Natural gas	1700	Pineda et al. [25]
the Netherlands	6.2	Natural gas	1760	Vermeulen and van der Lans [5]
France	8.8	Natural gas	2070 ^a	Boulard et al. [9]
Ontario, Canada	16.7	Bunker fuel, natural gas	3200	Dias et al. [24]
Sweden	12.8	Wood chips, natural gas	547	Bosona and Gebresenbet [6]
Finland	13.2	Natural gas/wood chips	3523/857	This study

^a GWP 20 years greenhouse warming potential.

The uniqueness of individual greenhouses exemplifies the major challenge regarding the validity and reliability of this research as well. The greatest uncertainty in the inventory data is the CED of a greenhouse due to its great variation among greenhouses and dominant impact on the GWP. Even though this research utilized the averages of the CED and consumption of other inputs, the applied inventory data do not precisely represent every individual greenhouse. Therefore, individual greenhouse entrepreneurs need to analyze, for example, their energy consumption prior to the application of the study results. Another uncertainty of the study is that instead of the electricity emission factor in GaBi's LCI database, this research applies the electricity emission factor defined by Motiva Oy [37], which is a Finnish government-owned company that promotes sustainable development. Their calculation scope could diverge from the one in GaBi, for example, regarding indirect emissions. The difference between the two electricity emission factors may limit the comparison of the results in this study with those of other studies. The last uncertainty is related to the calculations of this study regarding CHP boilers. In this research, the excess electricity produced by a CHP boiler was assumed to be sold to the grid as a whole, which might be problematic in times of electricity surplus.

In earlier research, higher CED led to higher GWP of the greenhouse crops [24,45]. A low mean annual temperature and long dark winters increase the CED of year-round greenhouse production, especially in the boreal climate zone. The scientific consensus of energy consumption being the prime factor impacting the GWP of greenhouse production was confirmed by this research as well. Table 3 shows that the GWPs of tomatoes produced in fossil-fuel-based greenhouses are relatively lower in southern and higher in northern geographical locations. These data show a positive correlation between the CED and GWP of a greenhouse. However, the conclusions drawn via LCA carried out in different locations and by different researchers should be assessed with caution. The differences in, for instance, the calculation methods, system boundaries, and primary data can cause fluctuations in the results. An example of this is an LCA carried out in South Korea [25], of which ratio between the CED and GWP significantly varies from those of others (Table 3). Moreover, this paper presented that the GWP of greenhouse production can be tremendously altered by changing the greenhouse heating method.

This work expanded on the Finnish greenhouse GWP calculations performed by Yrjänäinen et al. [13] and later updated by Silvenius et al. [34] for a more detailed understanding of the effect of greenhouse heating systems. Yrjänäinen et al. [13] calculated the GWP of Finnish greenhouse production to vary between 1360 and 3680 kg CO₂-eq. FU⁻¹ for tomatoes and between 335 and 3060 kg CO₂-eq. FU⁻¹ for cucumber. Their calculations were carried out for four individual greenhouses that were heated using fossil fuels, complimented with some biomass. Thus, the results of this paper are relatively consistent with those of Yrjänäinen et al. (2013), even though some of the greenhouses utilized green electricity, unlike in this study. The results of this paper suggest that based on the selected heating method, the GWP of greenhouse production in Finland can vary between 857 and 6523 kg CO₂-eq. FU⁻¹ for tomatoes and between 1379 and 2951 kg CO₂-eq. FU⁻¹ for cucumber. The results presented herein are also consistent with those of studies carried out at other geographical locations across the globe (Table 3). In southern countries, where little to no heating is required, fossil-fuel-based greenhouse tomato production have afforded very low GWP₁₀₀. In Central Europe, the GWP of greenhouse tomato production using natural gas was 1760 kg CO₂-eq. FU⁻¹ in the Netherlands [5] and 2070 kg CO₂-eq. FU⁻¹ in France [9]. In Ontario, Canada, Dias et al. [24] calculated a GWP of 3200 kg CO₂-eq. FU⁻¹ for fossil-fuel-based greenhouse tomato production. In this study, the Finnish greenhouse tomato production using a natural gas boiler led to a same scale GWP as that in Canada.

The lowest GWP was obtained when using a wood chip boiler for both greenhouse tomato and cucumber production (Figures 3 and 4). Using biogas boilers resulted in lower GWP of greenhouse production in other studies as well. In Canada, Dias et al. [24] found that replacing natural gas and bunker fuel with willow pellets as a heat source decreases the GWP of greenhouse tomato production by 72%. Bosona and Gebresenbet [6] found that

in Sweden, the production of organic greenhouse tomatoes using a biogas boiler afforded a GWP of 547 kg CO₂-eq. FU⁻¹. The GWPs obtained in northern countries when using a wood chip boiler are on the same level as those obtained in Italy when using natural gas [45] (Table 3). This suggests that greenhouse tomato production in Northern Europe can accomplish considerable GHG reductions and achieve GWPs as low as those in Southern Europe by employing low-carbon energy sources.

Low emission intensity of biofuels is based on a traditional view, wherein the regrowth of forest biomass is assumed to compensate for the CO₂ emissions from the burning of biomass. This assumption disregards the forests' carbon stock and balance and the fact that some of the emissions of biofuels result from indirect impacts such as a decrease in the amount of carbon stored in forests [46]. To include the GWP of such impacts of biofuels, a metric indicator of GWP_{bio} has been introduced. Cherubini et al. [47] have estimated that GWP_{bio} for biofuels originating from forests, with a rotation period of 100 years, would be 0.43. This means that every kilogram of discharged biogenic CO₂ would still lead into an indirect global warming impact of 0.43 kg CO₂-eq. Even using agricultural, forestry, or other type of residues and biowastes that would otherwise decompose and emit CO₂, might not always be carbon neutral. The decomposition of biomass does not mean that all of the carbon present in leaves and crops is emitted into the atmosphere. For example, Helmisaari et al. [48] found that the collection of harvesting residues in forests negatively affects the soil carbon content and tree growth, having indirect impacts that can affect the atmospheric carbon balance.

Natural gas CHP boiler was determined to be an undesirable solution for greenhouses in Finland (Figures 3 and 4). This is due to the CHP boiler's large demand for natural gas, which is more emission intensive than the Finnish grid electricity. Studies in the Netherlands [5,15] obtained contrasting results, stating that the GWP of greenhouse tomato production decreases when switching from a conventional natural gas boiler to a natural gas CHP boiler. The reductions in the GWP were obtained in the Netherlands because at the time of the research, the Dutch grid electricity was produced primarily using natural gas and coal, making the grid electricity more emission intensive than natural gas. A sensitivity analysis in this paper suggests that using a biogas CHP boiler in Finland leads to a lower GWP₁₀₀ than that of a conventional biogas boiler because biogas is less emission intensive than the Finnish grid electricity. The analysis defined the tipping points for the electricity emission factor as 228.3 kg CO₂-eq. MWh⁻¹ for natural gas and 89.3 kg CO₂-eq. MWh⁻¹ for biogas. When the electricity emission factor is under these limits, the usage of CHP leads to a higher GWP compared to that obtained using a conventional gas boiler and vice versa. The sensitivity analysis showed that the changes in heat demand do not affect the tipping point.

This research presented a conceptual framework and tested the concept of AIS for defining a cooperation between greenhouses and industrial partners. As the term AIS includes the industrial and agroecological environment into its context, it is argued that AIS describes the symbiosis more adequately than the term IS. Thus, describing all symbioses between industrial and agricultural partners as AIS was found to be more adequate than the term IS. The LCA suggests that an AIS can lead to a relatively low GWP for greenhouse production (Figures 3 and 4). Other studies have also estimated reduced emissions when utilizing industrial waste heat for greenhouse heating compared with fossil-fuel heating [16,21]. To the best of the authors' knowledge, this is the first attempt to calculate the GWP of such a system. The low GWP resulting from such an AIS is due to two main reasons: (1) Heat pumps utilizing industrial waste heat have a high efficiency that can even reach COP4.5 [49], meaning that the consumed primary energy is only a fraction of the final energy provided; (2) Heat pumps work on electricity, and Finnish grid electricity has a significantly lower emission factor than many heating fuels. The usage of electricity also allows the opportunity to choose renewables as the energy source, and as countries continuously increase their investments in renewable energy, lower electricity emission factors can be expected in many regions. As seen in Figures 7 and 8, the industrial

waste heat pump technology will continue to show better results with lower electricity emission factors than those of conventional boilers from the GWP perspective, which must be considered when designing sustainable greenhouse production.

The symbiosis can decrease the amount of energy losses and emissions for the industrial partner while creating additional revenue from the waste heat. For greenhouses, the symbiosis can provide a cheap, low-emission energy source. Marchi et al. [21] estimated that compared to natural gas heating, AIS could lead to financial benefits of between EUR 7.2 and 9.0/m² in greenhouse production. Andrews and Pearce [16] have also performed a financial analysis for such a symbiosis in Canada. They calculated that despite the high capital costs, the low operational costs of an industrial waste heat system would lead to a lower net present value than using a regular gas boiler. In 2016, a payback period of such a system was calculated in three locations in China by Yu and Nam [50] who determined that the annual operating costs of the waste heat system are 83% lower compared to a conventional fossil-fuel system. In their feasibility assessment, the higher capital costs of waste heat system can be recovered in 2–3 years from the reduced annual operating costs in a subsidized scenario. However, in a non-subsidized scenario the payback period was 10 to 12 years. Moreover, utilizing CO₂-rich exhaust gases gives companies indirect and intangible financial benefits. As the exhaust gases are used as valuable products, the emissions of the process are decreased, which can lead to the reduction in emission control technologies and a better environmental image for the company. Andrews and Pearce [16] estimated that capturing exhaust gases from a float glass plant for CO₂ enrichment of greenhouses would prevent additional emission reduction retrofits worth approximately USD 2.1 million.

In addition to financial feasibility, a successful symbiosis depends on the distance between symbiosis partners (a maximum of 10 km for CO₂ and 5 km for heat) and on the purity and suitable production intermittency of CO₂ [22]. Additionally, an industrial waste heat source can be available intermittently or can even be cut off due to reduced or terminated production. Further, it is important that industrial exhaust gases are examined and purified when necessary prior to using them for CO₂ enrichment. As these gases stem from industrial processes, any malfunctions in the emission reduction equipment would need to be handled with extreme caution as they come with a risk of heavy metal contamination that could affect the health of the produce and eventually of humans [16]. For the crops, exposure to high concentrations of nitrogen oxides (NO_x), ethylene (C₂H₄), and sulfur dioxide (SO₂) can also lead to yield reduction and plant damage, such as epinastic growth, abscission of flower buds, petals or leaves and interveinal leaf necrosis [51]. Even though the purity of the gas should always be examined beforehand, using horticulture as a carbon capture and utilization (CCU) method is a mature technology (TRL 9) [52]. Dijk et al. [53] have defined permitted concentrations for harmful gases inside a greenhouse for safe working time periods: 40 ppb 24-h⁻¹ for NO_x, 11 ppb 8-h⁻¹ for C₂H₄, and 100 ppb 24-h⁻¹ for SO₂.

Herein, a preliminary case analysis for CO₂ enrichment suitability of a specific gaseous sidestream has been carried out. The gaseous sidestream that originates from the biogas production plant in Central Finland contains 10.04% CO₂. The only recognized limiting factor for using this sidestream for CO₂ enrichment is the presence of 2-ppm of hydrogen sulfide. Assuming that all sulfur reacts to form SO₂, for every kilogram of CO₂ injected, 0.038 g of SO₂ is created in the greenhouse. Further, assuming that the maximum CO₂ concentration allowed inside the greenhouse is 1200 ppm, the maximum SO₂ concentration would be 45.6 ppb, which is under the 24-h-round risk concentration. The need for artificial CO₂ enrichment for the entire 1200 ppm is rarely needed considering that the outside air contains 350–400 ppm of CO₂. Thus, the additional CO₂ requirement would be 650 ppm, which results in a SO₂ concentration of 15.2 ppb, which is clearly under the threshold limit. Hence, this analysis suggests that the exhaust gas is expected to be suitable for CO₂ enrichment, but concentration measurements within the greenhouses are necessary to verify the safety regarding the use of this gas.

As mentioned earlier, the heat demand of the Finnish greenhouse cucumber production is often lower than that of the tomato production [34]. In greenhouses, a large part of the electricity is used for artificial lighting, and due to the low efficiency of light bulbs, the excess heat of artificial lighting often covers part of the heat demand [43]. As greenhouse cucumber production demands a lot of lighting, the low efficiency of light bulbs explains cucumber's low heat demand (Table 2). In Finland, some greenhouses have realized the inefficiency of light bulbs as an opportunity to decrease their heat demand. Agrifutura Oy for instance, uses specific fans to push the excess heat that is created by the artificial lighting on the ceiling, to the ground where tomatoes are grown [54]. In greenhouses of southern countries that have a low heat demand, and where heating is mostly needed during the night, the utilization of this excess heat could present a beneficial opportunity. It could be noteworthy to examine whether greenhouses located in southern regions could cover their heat demand by increasing the amount of artificial lighting and utilizing the waste heat efficiently. Exploiting artificial lighting to cover the heat demand of a greenhouse could be a financially favorable solution, as it eliminates the need for an external heating system, while extending the hours of photosynthesis in the greenhouse, making it an interesting topic for future research.

6. Conclusions

This paper signifies the impacts of heat demand and the heating method on the GWP of greenhouse production. The GWP of Finnish greenhouse production can be minimized by switching to biomass and biogas boilers as heat sources or by establishing AIS with nearby industrial partners. CHP boilers can decrease the GWP of greenhouse production only if the boiler fuel is considerably less emission intensive than the grid electricity, which in Finland, would mean using biogas. As the GWP was examined specifically from the heating system perspective, the results of this study can be generalized for application outside the horticultural sector after careful interpretation. The concept of AIS appropriately describes the collaboration between an industrial partner and a greenhouse. AIS is also considered suitable to describe all symbiotic business models between agricultural and industrial partners. Establishing an AIS between a greenhouse and an industrial process is seen as a feasible step toward sustainable food production, as it reduces the emissions of both partners while bringing financial benefits to both. This paper recognizes that increasing the policy-level support in establishing AIS business models is essential to push toward the transition to more sustainable food production. For agricultural entrepreneurs and greenhouse businesses, this paper recommends the increase in biofuel usage and the establishment of AIS to achieve lower environmental impacts of greenhouse production. Although this study detailed an LCA that focused on the aspects affecting the GWP of greenhouse production, a more detailed analysis regarding the implementation and feasibility of heating system selections, especially industrial waste heat utilization, is an important research topic for the future. Finally, the quantification of other environmental indicators via an LCA is necessary to obtain a holistic view of sustainable greenhouse heating.

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