Environmental Impact Assessment of Dutch Tomato Crop Production in a Venlo Glasshouse

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Abstract

This environmental impact assessment of the current situation of Dutch tomato production in a Venlo greenhouse in a temperate climate was developed as part of the EUPHOROS project. The project aims to develop a more sustainable greenhouse system with a reduction of external inputs yet with high productivity and an efficient use of resources. The environmental impact analysis was based on using the Life Cycle Assessment (LCA) methodology as defined by the ISO 14040. The crop production system was structured in several stages and processes to facilitate the study and interpretation of results. The stages considered were structure, auxiliary equipment, climate control system, fertilizers, pesticides and waste. The main results and issues to be improved are described and presented in this paper. The use of a cogeneration system (CHP) and the consequent production of electricity create a methodological question on how to handle allocation between products. This paper shows two different methods for dealing with co-production: considering electricity as an avoided product and energy allocation at CHP. Depending on the approach considered values can range between 12 to 31 MJ/kg of tomato or 0.78 to 2.0 kg CO_2 eq/kg of tomato for instance. Climate control system had a high energy demand with major contributions to all the impact categories (81.1 to 96.1% of the total) and the rockwool substrate accounted for 57.0 to 81.7% of the auxiliary equipment contribution. More effort should be made to recycle rockwool and reduce the high energy demand associated with the expansion of the mineral in the manufacturing processes. The structure was a major burden due to the high amount of steel and glass. Energy environmental impacts could be reduced, because of the avoided electricity production by the power plant, by using a combined heat and power plant to meet greenhouse electricity demands, resulting in a surplus which could be delivered to the public grid. Further research should also be oriented to developing efficient technologies to improve the intensive use of materials and energy.

INTRODUCTION

Greenhouse horticulture production in the Netherlands is an efficient process in which most inputs are carefully considered, obtaining notably high yields. However, greenhouses in northern countries have high energy requirements for heating and lighting. A review of the literature shows that this value has decreased over time due to the constant concern for improvement.

Jolliet (1993) demonstrated that the use of heating and/or artificial lighting in greenhouses are the worst environmental options. The extensively cited paper of Stanhill (1980) had previously reported a value of 137 MJ/kg of tomato for a heated glasshouse in the south of England with a tomato yield of 21.3 kg/m^2, which could be considered a very low production.

Van Woerden (2001), applying LCA to Dutch glasshouse horticulture, showed that energy use was responsible for about 75% of the total environmental impact of a tomato crop, with the glasshouse structure contributing over 10%.

In an LCA study for greenhouse tomato crop in Germany, Mempel and Meyer (2004) obtained a value of 25,000 GJ/ha. These authors estimated that the cumulative primary energy demand for heating was more than fifty times higher than for all other processes. Assuming a yield of 50 kg/m^2, this is an energy demand of 50 MJ/kg. Later, Williams et al. (2008) gave a value of 36 MJ/kg energy consumption for tomato production, taking into account a yield of 52.6 kg/m^2, in the United Kingdom.

These values of energy (and also of yield) are quite high compared to those in mild winter climates. In an assessment of Mediterranean greenhouses, Antón et al. (2005) identified fertilizers and substrate use as the major environmental burdens, and not direct energy consumption. In southern European unheated greenhouse tomato production, 1 MJ/kg (Muñoz et al., 2008) and 7 MJ/kg (Antón et al., 2009) have been reported for crops grown in soil and hydroponics, with yields of 12 and 20 kg/m^2, respectively. The aforementioned paper of Stanhill (1980) gives 7 MJ/kg for an unheated glasshouse in Israel, with a yield of 20 kg/m^2.

Most of the studies cited are focused on the energy demand, however, other aspects with environmental interest, such as eutrophication, air acidification and global warming, need also be included.

This study is within the context of the European EUPHOROS project, which aims to develop a more sustainable greenhouse with a reduction of external inputs yet with high productivity and an efficient use of resources. New technological developments will be designed in the course of the project and subsequently applied to the greenhouse in order to decrease the main burdens of the protected tomato crop.

A first and important step was a detailed environmental impact assessment of several European scenarios as reference situation of current greenhouse production systems. The aim of this paper is to show the results for the reference situation identifying the main environmental bottlenecks for five impact categories relevant for agricultural production systems and an energy flow indicator cumulative energy demand (MJ) in tomato production in glasshouse in temperate climate.

MATERIALS AND METHODS

The environmental assessment was carried out using Life Cycle Assessment (LCA) methodology. As defined by the ISO 14040 standard (ISO-14040, 2006) LCA is a “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”. The environmental impacts of the complete production system should be considered in an LCA study, from raw materials extraction to final waste disposal.

The study location was in Westland-Oostland, the Netherlands (4°29’E longitude, 52°01’N latitude). In northern Europe, Venlo type glasshouses are usually used to produce vegetables in temperate climate conditions, and the life-span of the greenhouse in this study was estimated at 15 years (CEN, 2001).

The functional unit (FU) reflects the main function of the analysed production system and is the reference unit to express environmental interventions. The functional unit for this study was 1000 kg tomatoes (1 t).

The production system was modelled to represent tomato production in a glass-house, using the SimaPro program version 7.2 (PRéConsultants, 2010) for the assessment. The processes included were: raw materials; inputs and outputs in the manufacture of greenhouse components; transport of materials; waste management processes; and water, fertilizers and pesticides consumption. Marketing activities past the farm gate, such as packaging and commercialisation, were not included.

One energy flow indicator (cumulative energy demand) and five impact categories, defined by the CML2001 method v. 2.05 (Guinée, 2002), were selected for the environmental assessment. The five impact categories were: abiotic depletion, AD, (kg Sb eq), acidification, AA, (kg SO_2 eq), eutrophication, EU, (kg PO_4^{-3}eq) global warming, GW, (kg CO_2 eq) and photochemical oxidation, PO (kg C_2H_4 eq).

Inventory analysis involves data collection and quantification of relevant inputs and outputs of a product system. The Ecoinvent database (Ecoinvent, 2010) was used to obtain information for manufacturing processes of the greenhouse components, substrate, and pesticides following integrated pest management practice; the energy production mix; emissions related to transport including construction of roads and maintenance, and disposal processes. For fertilizers manufacture, data from the LCA Food database (Nielsen et al., 2003) were applied.

The inventory analysis was prepared following (Antón, 2004; Antón et al., 2004; Audsley, 1997), and ISO standards (ISO 14040-14044, 2006). It was assumed that steel and aluminium should be produced from recycled metal. A coating treatment for metal was also taken into account.

In order to facilitate the inventory analysis and interpretation of results, the cultivation system was structured in the following stages: glasshouse structure, auxiliary equipment, climate control system, fertilizers, pesticides and waste (Fig. 1).

Structure: The greenhouse was a Venlo type of 25 spans, with modules of two bays 8 m wide x 5 m long. The main materials and quantities applied are shown in Table 1.

Auxiliary equipment: This included the distribution system for watering the crop and the substrate (see Table 1). The watering installation was a closed-system with recirculation of drainage water. Crop density was 1.25 plants/m^2. The substrate used was rockwool in plastic bags, with three plants of two stems each per bag. The crop period was 49 weeks from December 2008 to December 2009, with a commercial yield of 56.50 kg/m^2. Water consumption was considered as the main transpiration value for the crop, which was 7,944 m^3/ha (Hortimed, 2001-2003), giving a water use of 14.06 L/kg tomato produced.

Climate control system: This included the distribution equipment and heating, a combined heat and power (CHP) plant, heat storage, CO_2 systems (Table 1) and greenhouse climate management. Total electricity consumption for the greenhouse was also included. Demands for heating was provided by Wageningen UR (Montero et al., 2011).

The CHP plant, with natural gas as the energy source, produces electricity and thermal energy for the greenhouse. Total consumption of natural gas and electricity produced by the CHP system considered is shown in Table 2. The production of electricity was 178 kWh/m^2 and exceeded the electricity needs for greenhouse operations. All the surplus electricity generated is transferred to the public grid. Electricity consumption for pumps, equipment and greenhouse operations is obtained from the power station. According to the ISO 14044 (ISO-14044, 2006) there are different approaches to deal with allocation procedure, in this study two approaches were considered to analyse the energy consumption of CHP:

a) Wherever possible, allocation should be avoided by including the additional functions related to the co-products, in this case electricity. Therefore, a first approach was considered where exported electricity was credited against production burdens and consequently equivalent emissions of electricity produced are subtracted from the tomato production. Nevertheless, the correct assumption of which electricity production is being displaced depends on multicriteria. Some studies distinguish between electricity peak hours or not (Blonk et al., 2010), to use average or marginal electricity production. The later is based on the concept of installing new electricity generating equipment; therefore assumption of which marginal electricity is displaced is a consequential approach out of the scope of this study. In this study we used the electricity production mix in The Netherlands.
b) Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them. Therefore, allocation of the CHP was carried out following energy criteria, this means to calculate the correspondent amount of natural gas to produce heat and electricity. A CHP engine of 40% electrical efficiency was considered. To produce 1 kWh electricity 0.129 m^3/kWh of natural gas

was needed (Blonk et al., 2010), so 23.01 m^3/m^2 were consumed to produce 178 kWh electricity, or 728.2 MJ/m^2 considering a calorific value for natural gas of 31.65 MJ/m^3, with a heat efficiency of 90%. To heat the glasshouse, 41.74 m^3 of natural gas or 1,319.6 MJ/m^2 were used. As CO_2 produced by the CHP is usually incorporated to greenhouse, allocation between heat and CO_2 was not considered. Therefore, the energy consumption considered for the heating system was 23.36 MJ/kg tomato. General electricity consumption for the greenhouse was 10 kWh/m^2.

Fertilizers: The total quantities of N, P and K applied to the crop were: N, 1,688 kg/ha, 2.99 kg/t tomato; P_2O_5, 406 kg/ha, 0.72 kg/t tomato; K_2O, 1,855 kg/ha, 3.28 kg/t tomato. The emissions of NH_3-N, N_2O-N and NO_x-N to air were taken into account (Audsley, 1997; Brentrup et al., 2000). Emissions during the manufacturing process were also included.

Pesticides: The total amount of active ingredient was considered for insecticides (3 kg/ha) and fungicides (7 kg/ha). The manufacture of pesticides and the use of machinery for their application were also included. Pesticide toxicity was excluded since there is no general consensus on its evaluation.

Waste management: Several waste material treatments could be considered. As a reference situation we considered that metal and glass were 100% recycled, concrete and substrate in plastic bags 50% recycled and 50% transported to landfill, and plastics 50% recycled and 50% incinerated. Green biomass was partially dried and, therefore, 40% of the total fresh weight was treated at the composting plant. Emissions included in the study were those of transports to landfill, incinerating and composting plants, and emissions due to landfill and incineration. Transports to the recycling plants and recycling processes were considered as part of the recycled process and therefore to be included in the correspondent process which will use the recycled material The estimated life spans depended on the material: 15 years was applied for metals, glass and concrete, 3 to 5 years for plastics, and 1 year for rockwool.

Transport by lorry was included for all elements delivered to the greenhouse, considering manufacture of vehicle and road, maintenance and diesel consumption. Transports of fertilizers and pesticides were not incorporated in the system since it was considered that these products were delivered from a local supplier.

RESULTS AND DISCUSSION

Two approaches for the cogeneration were considered to analyse the environmental impacts of the tomato production system:

Table 3 shows the absolute values for the total production system, and the different stages and impact categories selected. Values when energy allocation was considered are given in Table 4.

LCIA Considering Electricity Produced by CHP as an Avoided Product

The CHP plant produced a high amount of electricity that exceeded the electricity greenhouse consumption. All surplus electricity produced was transferred to the public grid. The electricity produced by CHP was entered as an avoided product.

The climate system was the major contributor to all impact categories except for EU, with percentages of between 57.0 and 89.5% (Table 3).

The negative values for EU were due to the avoided electricity burden, with electricity obtained from gas in the CHP producing less eutrophicant emissions than that of the electricity production mix in the Netherlands, where 25% of electricity is produced by hard coal. The disposal of waste from coal mining produces phosphates emission to water that contributes to eutrophication (Table 3).

LCIA Considering Energy Allocation of Natural Gas to Heat the Greenhouse in CHP

The LCIA results for tomato production in the Netherlands considering energy allocation of natural gas to heat the greenhouse are shown in Figures 2 to 6. The climate control system was the main contributor to all the impact categories selected, with percentages of between 81.1 and 96.1% of the total (Fig. 2). The high amount of natural gas for heating the greenhouse was mainly responsible for these high environmental impacts. The contribution of natural gas in the climate control system was between 74.4 and 94.1% (Fig. 3).

Depending on the approach considered (avoided electricity or energy allocation) values can range between 12 to 31 MJ/kg of tomato or 0,78 to 2,0 kg CO_2 eq/kg of tomato for instance. Values are similar to those in other studies (William et al., 2008; Blonk et al., 2010; Vermeulen, 2010) and point out the importance of the criteria selected to do assessment.

Results for the Venlo greenhouse structure are shown in Figure 4. The high amount of metal in the frame, mainly made of steel and aluminium, was reflected in the results which were the highest burden for all the impact categories, with percentages of between 50.7 and 78.2%. The highest contribution (0,076 g PO_4^{-3} eq/kg of tomato) was to EU because of emissions of phosphates to water and nitrogen oxides to air. The second major contributor to the impact categories was glass, with contributions of between 18.1 and 45.8%. The highest contribution was to acidification (0.3 g SO_2 eq/kg of tomato) because of emissions of sulphur dioxide and nitrogen oxides in the production of glass. Plastic contribution to impact categories was much lower, between 2.0 and 5.6%.

Figure 5 shows the contribution of the processes included in auxiliary equipment. These results show the importance of substrate contribution to impact categories, and reduction of its impact is also one of the objectives of the EUPHOROS project. Substrate presented the highest contribution to all impact categories, with percentages of between 57.0 and 81.7%. Substrate processes included rockwool manufacture; plastic bag manufacture and transport to greenhouse. Rockwool manufacture was the most significant due to emissions from energy consumption during its production. The plastics used in pipes, benches, etc., were also major contributors to the impact categories (13.0 to 38.8%). Metal environmental impacts accounted for between 4.0 and 12.1%, while transport contribution was not significant, less than 0.5%.

Fertilizer use involved environmental impacts both from manufacturing processes and emissions in application (Fig. 6). The highest scores were for N fertilizers production for all impact categories, with high percentages, between 57.2 and 82.3%. Emissions from application were also a major burden in the GW impact category, with a contribution of 36.5%, mainly because of dinitrogen monoxide emissions.

The pesticides contribution was negligible with regard to the total contributions of the tomato production. Pesticides toxicity was not evaluated.

Waste management assessment showed that biomass transport to the compost plant was the main burden in the AD, AA, PO and CED impact categories, with contributions of between 57.8 and 60.3%. These high contributions were due to the fact that transport was carried out every year, at the end of the crop season, while transport of other materials depends on their useful life. Plastics incineration gave the highest scores in EU and GW (41.6 and 81.5%). Emissions due to concrete disposal at landfill made major contributions to AD, AA, PO and CED (11.7 to 16.8%). Substrate emissions at landfill were more significant for AD and CED (10.9 and 10.5%).

CONCLUSIONS

Results for tomato production in the Netherlands system demonstrated that climate strategy was the main contributor to all impact categories because of the natural gas consumption for greenhouse heating. The use of a CHP plant could significantly compensate for the environmental impacts of natural gas consumption because of the high amount of electricity produced as a by-product and delivered to the public grid.

Substrate was a major burden because of the high energy consumption in the manufacturing process. The EUPHOROS project focuses on this subject in workpackage 3, with better options for substrate recycling and manufactures being evaluated.

Waste management is highly dependent on government regulations of each country. Nevertheless, there is a European regulation that states that, by 2020, EU countries should recycle 50% of paper, plastic and glass of all domestic waste, and 70% of non-hazardous waste from construction and demolition. Recycling as much as possible of all materials from greenhouse production would obviously be a major move forward, and should be achieved as soon as possible.

From a methodological point of view further research should focus on allocation methods in order to reach a general consensus method.

Production in the Netherlands is an efficient process in which most inputs are carefully considered, resulting in a notably high crop yield. Nevertheless the high yield achieved is through intensive use of technology, materials and energy. Although it is clear that energy is the major burden, improvements in aspects such as substrate and plastic materials should be considered, as well as the reduction, re-use and recycling of these materials.

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Tables

Table 1. Materials and quantities considered in greenhouse structure, auxiliary equipment and climate system for the Venlo greenhouse.

Material	Element	Quantity/ha	Unit
	Structure		
Aluminium	Gutters, ridges, bars, ventilator opening mechanism, energy screens	28109. 8	kg
Concrete	Foundations and main path	45.5	m^3
Glass	Covering and walls	118927.3	kg
Polyester	Floor material and screens	1452.5	kg
Steel	Roof bars, girders, stability braces, rails, posts, tie beams, foundations reinforcements, ventilator opening mechanism, high wire system	109828.7	kg
	Auxiliary equipment		
LDPE	Benches, drippers, microtubes, pipes,	790.6	kg
Polyester	Inside tanks	78.1	kg
Polystyrene	Substrate layers	918.7	kg
PVC	Distribution system	143.3	kg
Steel	Water tanks	3598.7	kg
	Climate system		
Aluminium	Pipes, pipe rails	8541.5	kg
Paint	Pipes	1470.5	kg
PE	Tubes	56.3	kg
Polyester	Inside tanks	38.3	kg
PVC	Distribution equipment	214.9	kg
Steel	Boiler, condensers, pumps, cogenerating system, pipes, CO_2 support hook	77767.2	kg

Table 2. Energy consumption and production in a Venlo greenhouse for tomato crop.

Source	Process	Quantity/ton tomato	Unit
Natural gas	Cogeneration and heating	1145	m^3
Electricity	Greenhouse consumption	177	kWh
Electricity	Produced by cogeneration	3150	kWh

Table 3. LCIA results for impact categories (IC) per FU, for tomato greenhouse crop in the Netherlands, with cogeneration. Production of electricity is considered an avoided electricity burden.

IC	Unit	Total	Structure	Climate system	Auxiliary equipment	Fertilizers	Pesticides	Waste
AD	kg Sb eq	**5.6E+00**	3.4E-01	**5.0E+00**	1.4E-01	9.9E-02	1.6E-03	3.3E-03
AA	kg SO_2 eq	**1.2E+00**	3.0E-01	**6.6E-01**	8.8E-02	1.1E-01	1.8E-03	2.3E-03
EU	kg PO_4^{-3} eq	**-1.1E+00**	**9.7E-02**	-1.3E+00	2.1E-02	1.6E-02	6.1E-04	9.1E-04
GW	kg CO_2 eq	**7.8E+02**	5.3E+01	**6.6E+02**	1.4E+01	4.8+01	2.0E-01	2.1E+00
PO	kg C_2H_4	**1.9E-01**	1.4E-02	**1.6E-01**	6.5E-03	2.2E-03	1.1E-04	7.6E-05
CED	MJ	**1.2E+04**	8.2E+02	**1.1E+04**	3.1E+02	2.0E+02	3.9E+00	7.9E+00

Table 4. LCIA results for total tomato greenhouse crop and climate system in the Netherlands per FU, with energy allocation of natural gas in CHP.

No	Unit	Total	Climate system
AD	kg Sb eq	1.5E+01	1.5E+01
AA	kg SO_2 eq	2.9E+00	2.4E+00
EU	kg PO_4^{-3} eq	7.2E-01	5.8E-01
GW	kg CO_2 eq	2.0E+03	1.9E+03
PO	kg C_2H_4	2.1E-01	1.9E-01
CED	MJ	3.1E+04	3.0E+04

Figures

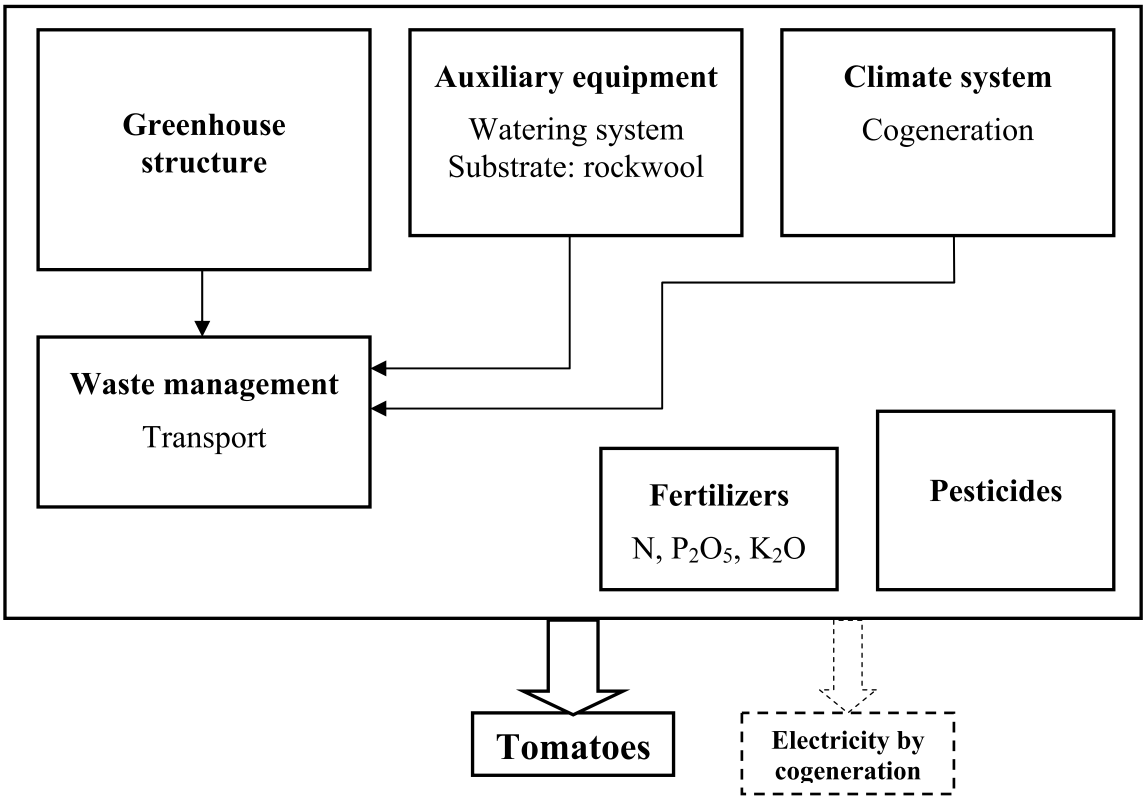

Fig. 1. Flow diagram for tomato production system in a Venlo greenhouse.

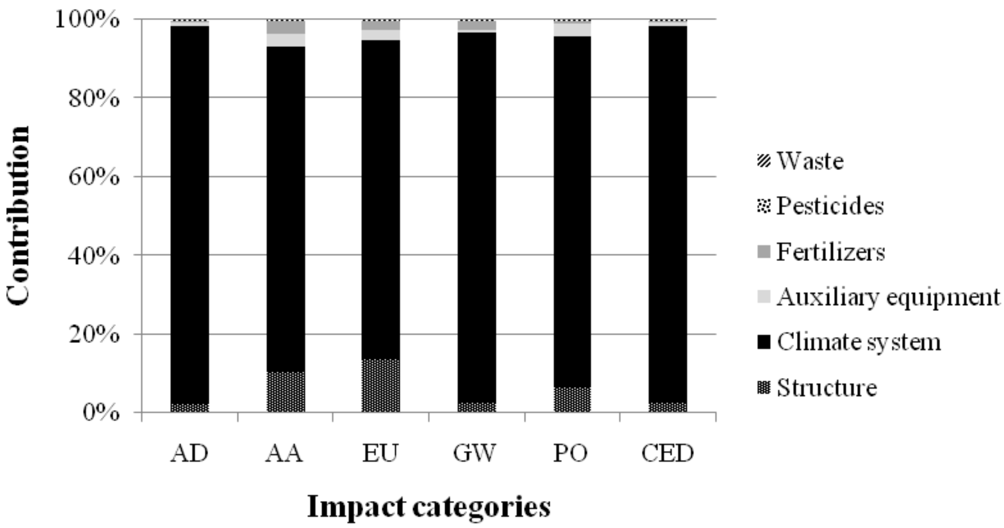

Fig. 2. Stages contribution to different impact categories for glasshouse tomato production. Energy allocation of natural gas consumption in CHP, in the Netherlands. Impact categories: AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand.

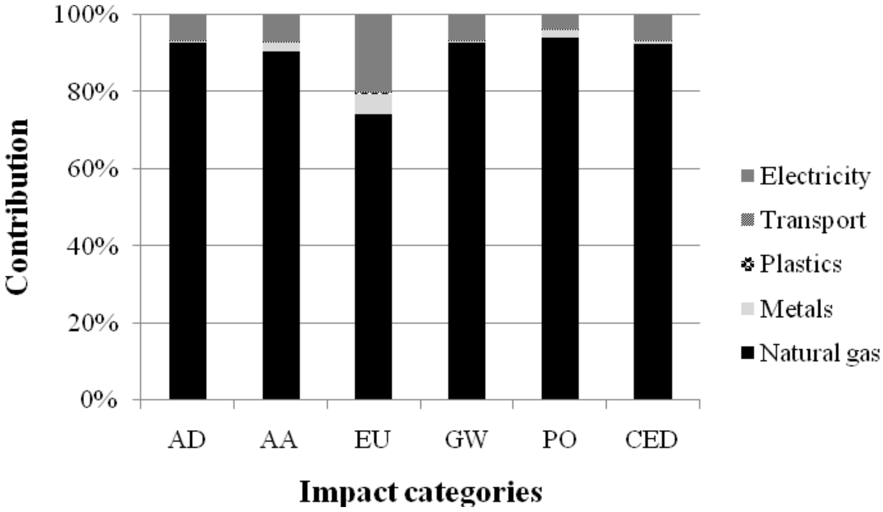

Fig. 3. Climate control system processes contribution to impact categories in a glasshouse tomato crop in the Netherlands. Energy allocation of natural gas in CHP. Impact categories: AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand.

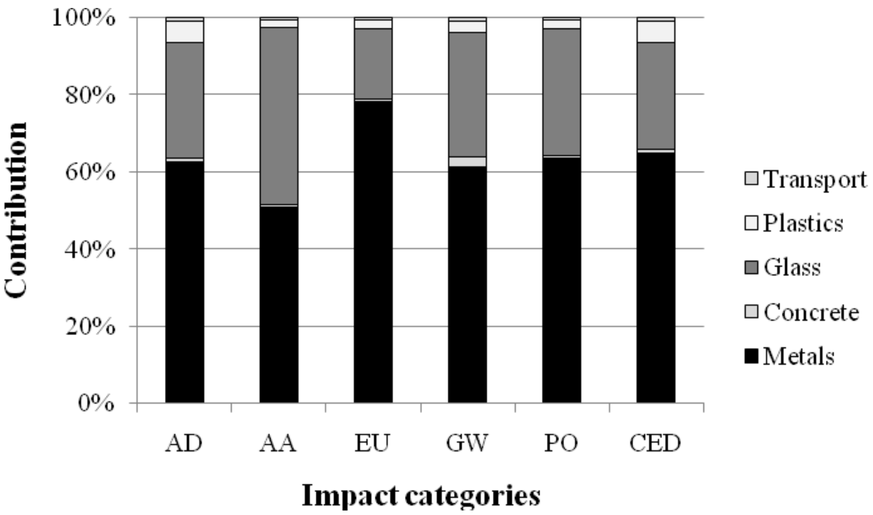

Fig. 4. Structure materials contribution to impact categories for a tomato crop in a Venlo glasshouse, in the Netherlands. Impact categories: AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand.

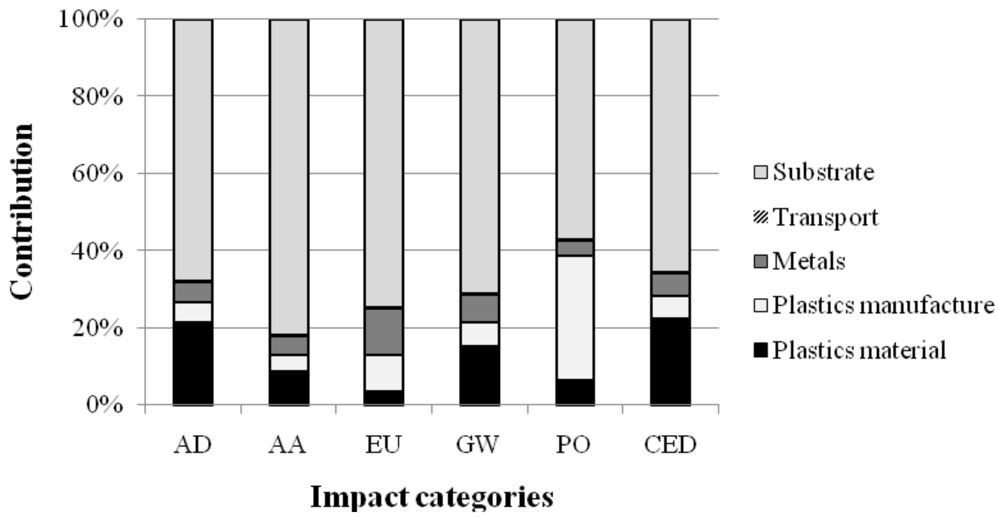

Fig. 5. Auxiliary equipment processes contribution to impact categories for tomato production in the Netherlands. Impact categories: AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand.

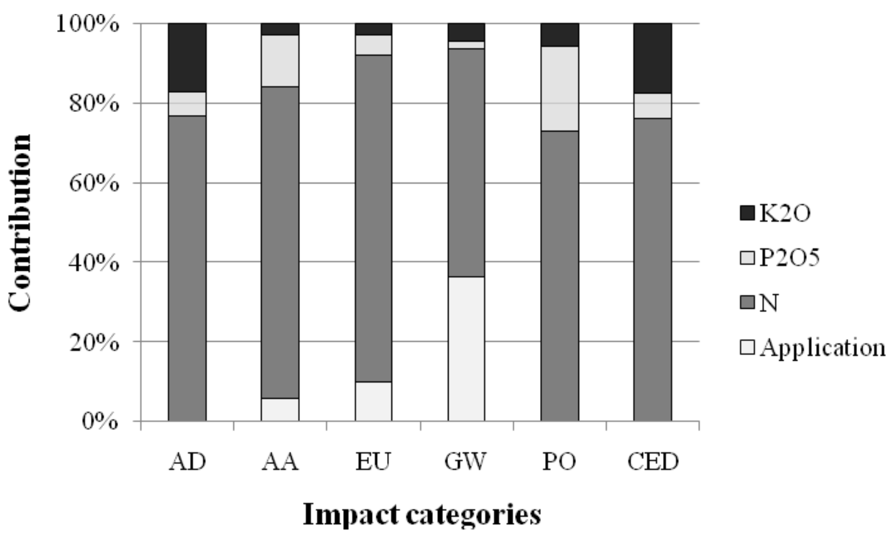

Fig. 6. Fertilizers contribution to impact categories for a glasshouse tomato crop in the Netherlands. Impact categories: AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand.