Assessment of Environmental and Resource Vulnerabilities in the Dutch Tomato Horticulture's 2040 Energy Transition goals

A Life Cycle Assessment Perspective

By

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Abstract

The Dutch greenhouse horticulture sector aims to be climate-neutral by 2040, yet the path forward is anything but straightforward. This thesis examines cradle-to-gate environmental impacts and resource vulnerabilities of seven fossil-free energy configurations for tomato cultivation, benchmarked against today's natural-gas Combined Heat and Power (CHP) systems.

Using an attributional Life Cycle Assessment (LCA) complemented by GeoPolRisk resource-criticality metrics, the thesis modelled geothermal networks, residual-heat networks, electric heat pumps (with and without Aquifer Thermal Energy Storage, dehumidifiers, solar arrays, and batteries). An Excel-based decision-support tool translates these complex trade-offs with varying CO_2 enrichment rates, coproduct allocations, and electricity sourcing, into an intuitive dashboards for growers or other decision makers.

The analysis reveals that CO_2 enrichment practices dominate climate change outcomes. When growers match enrichment to CHP's output, alternative systems offer little net GHG improvement. Cutting enrichment to more justified agronomically levels unlocks clear climate benefits across electrification and network scenarios and boosts the fraction of biogenic carbon uptake from 12.5% toward 28%. The allocation method also significantly impacts results, attributing all emissions to heat (common industry practice) exaggerates CHP's footprint, whereas economic allocation paints a more balanced picture of the heat, electricity, and CO_2 coproducts.

Electrification pathways can reduce fossil-fuel use and CO_2 emissions, yet they shift burdens elsewhere. Renewably powered heating increases water consumption and heightens demand for critical raw materials, exposing growers to supply-chain and geopolitical risks. No single technology emerges as a silver bullet. Each entails environmental trade-offs among climate impact, resource scarcity, water use and other impact categories.

Developed within the interdisciplinary Thesis Lab "The Future of Energy in the Horticulture Sector" this research bridges LCA modelling with grower insights. The accompanying decision-support tool empowers stakeholders to tailor assumptions, explore "what-if" scenarios, and pinpoint where efficiency gains, especially in CO_2 dosing and coproduct attribution, will deliver the greatest environmental return. Achieving true climate neutrality in horticulture demands more than swapping fuels. It calls for systems-level thinking, optimized operational practices, and transparent accounting.

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Nomenclature

List of Abbreviations

Abbreviation	Definition
ADP	Abiotic Depletion Potential
ALCA	Attributional Life Cycle Assessment
ATES	Aquifer Thermal Energy Storage
CCS	Carbon Capture and Storage
CF	Characterisation Factor
CHP	Combined Heat and Power
COP	Coefficient of Performance
CRM	Critical Raw Materials
DAC	Direct Air Capture
EU	European Union
GHG	Greenhouse Gas
HHI	Herfindahl-Hirschman Index
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PEF	Product Environmental Footprint
PV	Photovoltaic
SOP	Surplus Ore Potential
WI	Waste Incineration
WKK	Warmtekrachtkoppeling (Dutch term for CHP)
WKO	Warmte Koude Opslag (Dutch term for ATES)

Glossary

Term	Definition
Abiotic Depletion Potential (ADP)	An indicator measuring the depletion of non-living (abiotic) resources.
Aquifer Thermal Energy Storage (ATES)	A system that stores thermal energy in groundwater for seasonal heating and cooling. The English term for WKO.
Attributional Life Cycle Assessment (ALCA)	An LCA method that evaluates the environmental impacts of a product or system based on current conditions, disregarding broader market changes.
Background Process	Processes in LCA that are not directly controlled, typically upstream or downstream.
Carbon Capture and Storage (CCS)	A technology to capture and store CO_2 emissions from industrial sources.
Characterisation	A step in LCA that quantifies the impact of emissions using characterization factors.
Characterisation Factors (CFs)	Values used in LCA to convert total emissions or resource use into one impact indicator.
Coefficient of Performance (COP)	A ratio that measures the efficiency of heating or cooling systems.
Combined Heat and Power (CHP)	A system that simultaneously generates electricity and useful heat from the same energy source. The English term for WKK.
Consequential Life Cycle Assessment (CLCA)	An LCA method that evaluates the environmental impacts of a product or system that considers broader market effects and system changes.
CO_2 Enrichment	The process of increasing carbon dioxide concentration in greenhouses to enhance plant growth.
Critical Raw Materials (CRM)	Materials essential for an economy but with high supply risk.
Cutoff	A modelling term in LCA where certain flows are excluded based on relevance or data availability.
Direct Air Capture (DAC)	The capture of CO_2 directly from the atmosphere.

Ecoinvent	A comprehensive LCI database used in LCA modelling.
Endpoint	An LCA indicator that reflects damage to areas of protection.
Environmental Footprint (EF)	An LCIA method for the assessment of a product or system environmental impact.
Foreground Process	Processes in LCA that are directly controlled and in the study.
Functional Unit	The quantified description of a product system used as an unified reference point in LCA.
GeoPolEndpoint	An LCA method for assessing geopolitical risks at the endpoint level.
GeoPolRisk	A method to assess geopolitical and supply risks of raw materials in LCA.
Greenhouse Gas (GHG)	Gases that contain heat in the atmosphere and contribute to global warming.
Herfindahl-Hirschman Index (HHI)	A measure of market concentration used in resource risk assessment.
Impact Assessment	A phase in LCA where environmental impacts are evaluated based on inventory data.
International Organization for Standardization (ISO)	An international body that sets standards including those for LCA.
Inventory Analysis	A phase in LCA where all inputs and outputs of a system are quantified.
Life Cycle Assessment (LCA)	A method to assess the environmental impacts associated with a system or a product throughout its entire life cycle.
Life Cycle Impact Assessment (LCIA)	A part of the LCA method where inventory data is translated into environmental impacts.
Life Cycle Inventory (LCI)	The phase in LCA where data on inputs and outputs is collected.
Midpoint	An LCA indicator that reflects potential environmental impacts before damage occurs.

Normalization	A step in LCA that compares impact results to a reference value.
OpenLCA	An open-source software used for conducting LCA studies.
ReCiPe	An LCIA method for the assessment of a product or system environmental impact.
Resource Depletion	The consumption of natural resources faster than they can be replenished.
Surplus Ore Potential (SOP)	A resource depletion indicator in the ReCiPe LCIA method.
System Boundary	A delineation of which processes are included in the LCA study.
Warmte Koude Opslag (WKO)	Dutch term for ATES, a thermal energy storage system.
Warmtekrachtkoppeling (WKK)	Dutch term for CHP, combined heat and power.
Waste Incineration (WI)	A process of burning waste materials to generate energy.

1
Introduction

This thesis is part of the interdisciplinary Thesis Lab "The Future of Energy in the Horticulture Sector," a collaboration between Leiden University, Delft University of Technology, and Erasmus University Rotterdam. It brings together students and stakeholders to explore the future of energy in Dutch horticulture, with Glastuinbouw Nederland acting as the primary case holder. The focus is on the environmental implications of the sector's ambition to strive for climate neutrality by 2040.

The Dutch horticulture sector holds a prominent position both nationally and globally. It is critical to the Dutch economy, producing a wide range of essential and luxury crops for international markets (Ministerie van Economische Zaken, 2011).Despite its reputation for innovation and efficiency, the sector continues to face significant environmental challenges (Moons et al., 2021). These challenges stem largely from its high energy consumption, greenhouse gas emissions, and resource extraction (LDE Centre for Sustainability, 2024). This creates a dilemma for decision-makers, maintaining economic viability or reducing environmental harm. Improvements in one area often come at the expense of the other (Antle & Ray, 2020).

The definition of climate neutrality however, remains ambiguous. Conversations with stakeholders suggest that the goal is primarily interpreted as the elimination of fossil fuel use. This interpretation focuses on reducing direct emissions, particularly those associated with natural gas combustion. While this is a meaningful step toward mitigating climate change, it does not necessarily eliminate emissions across the entire life cycle of production. Nor does it account for other environmental impacts unrelated to climate change. The sector's current focus on Scope 1 and 2 emissions overlooks upstream and downstream processes that may also contribute to environmental degradation. The aim is not to challenge the sector's ambition but rather to highlight that a transition away from fossil fuels may still involve significant environmental burdens. A more consistent and scientifically grounded attribution of emissions is needed to ensure that sustainability claims are robust and comprehensive.

From an Industrial Ecology perspective, systems thinking and life cycle analysis are implemented to assess the environmental implications of future energy scenarios in Dutch tomato horticulture. The goal is to provide actionable insights for growers and policymakers navigating the transition. Rather than focusing solely on theoretical modelling, the research translates complex environmental data into a practical decision-support tool. To enable stakeholders to explore trade-offs between energy choices, emissions, and resource risks. It incorporates resource criticality indicators, based on GeoPolRisk, to reflect the broader vulnerabilities associated with the energy transition.

The research aims to fill a gap in the academic literature by applying Life Cycle Assessment (LCA) to future energy scenarios for tomato cultivation in the Netherlands. Most studies focus on current emissions from natural gas use or compare imported versus locally produced crops. Few have explored the environmental implications of alternative energy systems in a future-oriented context. In addition to academic contribution, it supports the Thesis Lab's broader mission of helping growers navigate the transition towards climate neutrality. By providing data-driven insights into the environmental and resource-related impacts of different energy configurations, aiming to inform strategic decisions within the sector.

The central research question guiding this thesis is: How do 2040 fossil-free energy transition pathways in Dutch tomato horticulture influence cradle-to-gate environmental impacts and resource risks, and how are environmental scores shaped by sectoral practices of enrichment and attribution? To answer this question, several sub-questions need to be addressed. These include an exploration of the sector's 2040 climate goals, the sources of future energy and materials, and the methods of meeting CO_2 enrichment demands without fossil fuels. The analysis also needs to examine the primary processes and material inputs required for both fossil-based and non-fossil-based tomato production, identify the key contributors to environmental impacts under different energy scenarios, and investigate how allocational choices and CO_2 enrichment practices influence outcomes.

First relevant literature and stakeholder insights are reviewed. This is followed by the description of the goal and scope for this study. Procedurally, the conceptual frameworks will be outlined, followed by a detailed presentation of the LCA and resource risk results. The findings will then be interpreted through a sensitivity analysis. The decision-support tool developed is reflected on and the implications are given. The results will then be discussed and the final chapter will conclude with a summary and recommendations.

2

Literature Review

A Life Cycle Assessment (LCA) is a standardized methodology used to evaluate the environmental impacts of a product or process across its entire life cycle, from raw material extraction to disposal (Guinée, 2002). It is particularly well-suited to greenhouse horticulture, where energy, water, and material flows interact in complex and often non-linear ways (Alhashim et al., 2021). Its strength lies in the ability to compare systems with multiple inputs and outputs, identify environmental hotspots, and evaluate trade-offs between impact categories such as climate change, eutrophication, water use, and resource depletion. Moreover, LCA provides a structured framework for scenario analysis, which is essential when assessing future energy systems that are not yet fully implemented (Bisinella et al., 2021).

2.1. Tomato Life Cycle Assessment

Tomatoes are a common reference crop in horticultural LCA studies due to their economic relevance and the controlled nature of their production environments (Alhashim et al., 2021). Early work by Pluimers et al. (2000, 2001) identified greenhouse gas emissions, acidification, and eutrophication as key impact categories in Dutch greenhouse systems. Later studies, such as Vermeulen (2010), compared tomato production with and without Combined Heat and Power (CHP), showing that CHP systems can reduce relative emissions under certain conditions.

More recent research has expanded the scope of analysis. Ali et al. (2023), for example, explored alternative systems such as unheated polytunnels, while Ordikhani et al. (2021) included crops like pistachios and apples in their assessments. However, most of these studies remain focused on carbon emissions and rarely address the broader environmental or resource implications of energy transitions. Few have modelled future-oriented scenarios or incorporated resource criticality assessments.

The existing literature also varies widely in terms of system boundaries, functional units, and allocation methods (Moons et al., 2022; Torres Pineda et al., 2021). This inconsistency complicates direct comparison and underscores the need for a consistent and transparent modelling approach.

To support environmental assessment in horticulture, several tools have been developed in recent years. Platforms such as Greenhouse Sustainability (2024) and Gibbs (2024) offer LCA-based interfaces to help growers track and reduce their carbon footprints. With the FloriPEFCR, developed by Broekema et al. (2024), providing standardized rules for assessing the environmental footprint of floriculture products using 16 impact categories and a weighted PEF score.

While these tools are valuable, they lack flexibility. They are designed primarily for carbon accounting and do not capture other environmental impacts. Moreover, they tend to rely on fixed assumptions and do not allow users to explore alternative scenarios or allocation methods. Limiting their usefulness for strategic planning, particularly in a sector undergoing rapid technological and regulatory change.

The horticulture sector transitions will rely on renewable energy sources. As a result the demand for critical raw materials (CRMs) such as lithium, cobalt, and copper is expected to rise (*Critical Raw Materials Act - European Commission*, n.d.). Traditional LCA methods include indicators like Abiotic Depletion Potential (ADP) and Surplus Ore Potential (SOP), but these do not account for geopolitical and economic supply risks (Li et al., 2014). This is a significant omission, especially given the increasing concentration of CRM supply chains in politically unstable regions (*Critical Raw Materials - European Commission*, n.d.).

To address this gap, newer methods such as GeoPolRisk and GeoPolEndpoint have been developed (Koyamparambath et al., 2024; Santillán-Saldivar et al., 2022). These methods provide characterization factors for 46 materials and can be integrated into LCA to evaluate supply chain vulnerabilities. Although their application in horticulture remains limited, they offer a valuable perspective on the systemic risks associated with the energy transition.

2.2. Climate Neutrality, Energy Supply, and CO_2 Enrichment

The Netherlands has committed to achieving climate neutrality by 2050, in line with the European Union's broader climate objectives under the European Green Deal. This commitment is formalized in the Dutch Climate Act (Klimaatwet), which sets legally binding targets to reduce greenhouse gas (GHG) emissions by 55% by 2030 and to reach net-zero emissions by 2050 (Erbach & Dewulf, 2024).

In response, the Dutch greenhouse horticulture sector has set an even more ambitious target: to become climate-neutral by 2040. However, the interpretation of "climate neutrality" within the sector is not uniform. Stakeholder consultations, including those with Delphy and Glastuinbouw Nederland, suggest that the most consistently cited objective is the elimination of fossil fuel use (Glastuinbouw Nederland, 2023). While this goal aligns with broader climate ambitions, it does not necessarily guarantee a reduction in total life cycle emissions. Alternative energy systems may introduce indirect emissions upstream or downstream, creating a tension between operational goals and systemic environmental outcomes (Laurent et al., 2018).

Achieving this transition will require a fundamental transformation of the sector's energy infrastructure. Currently, greenhouse horticulture relies heavily on Combined Heat and Power (CHP) installations fuelled by natural gas (also called WKK). Future scenarios, however, anticipate a diversified energy mix that emphasizes electrification, geothermal heat, and residual heat networks (PBL, 2024) According to Glastuinbouw Nederland's updated energy vision, by 2040, 90% of the sector's heat demand is expected to be met by sustainable sources, with a 35% reduction in total heat demand compared to 2017 due to energy efficiency improvements (Glastuinbouw Nederland, 2023).

Key technologies identified in this roadmap include geothermal energy, heat pumps, often paired with Aquifer Thermal Energy Storage (ATES) (also called WKO) and district heating systems such as WarmtelinQ. These are complemented by innovations in energy-saving techniques like LED lighting, dehumidification, and advanced climate control under the "Het Nieuwe Telen" framework (Glastuinbouw Nederland, 2023). Spatial distribution also plays a critical role in the feasibility of these systems. Large-scale geothermal and residual heat networks are more viable in densely clustered greenhouse areas, while smaller or more isolated growers may need to rely on all-electric solutions or bio-based fuels (PBL, 2024).

The Planbureau voor de Leefomgeving (PBL) supports this trajectory, identifying greenhouse horticulture as one of the few agricultural domains capable of achieving climate neutrality by 2040 or earlier, primarily through renewable electricity and sustainable heat (PBL, 2024). However, this transition depends on several enabling conditions, including public investment, regulatory support, and the availability of critical raw materials for electrification technologies (Jones & Ginley, 2021).

One of the most pressing challenges in this transition is the continued need for CO_2 enrichment, which remains essential for maintaining crop yield and quality (Wang et al., 2022). In conventional systems, CO_2 is primarily sourced from the combustion of natural gas in CHP units. As fossil-based energy systems are phased out, alternative CO_2 supply strategies must be developed to ensure productivity while meeting climate goals.

Currently, the sector requires approximately 2.5 Mton of CO_2 annually, but only about 0.7 Mton is supplied via the OCAP network or in liquid form, leaving a significant gap (Smit, 2024). To address this, Glastuinbouw Nederland's updated strategy emphasizes diversification, including CO_2 capture from waste incineration, biogas upgrading, industrial symbiosis, and direct air capture (DAC) (Mikunda et al., 2015; Smit, 2024).

Each alternative CO_2 sourcing route presents trade-offs in terms of cost, infrastructure, and environmental impact. For instance, DAC offers a theoretically unlimited CO_2 source but is currently energy-intensive and expensive (Ozkan, 2025). In contrast, CO_2 from waste incineration is more readily available but may carry higher environmental burdens depending on the capture and purification technology used (Mikunda et al., 2015).

3

Goal & Scope

The LCA adheres to the ISO 14040 and 14044 standards for consistent and transparent reporting. In line with these principles, this chapter outlines the specific goal and scope of the LCA conducted for Dutch tomato horticulture in 2040.

3.1. Goal

The goal is to explore how shifting from fossil-based to fossil-free energy systems affects the environmental impact of tomato production in the Netherlands. Different energy setups and CO_2 enrichment strategies are compared to see how they influence impact scores. This is to identify where environmental trade-offs emerge and how future-oriented configurations perform under consistent modelling.

Another goal is to understand how sectoral practices and attribution choices shape the scores. This includes how multifunctional systems like CHP are handled, and CO_2 flow allocation logic influences the framing of environmental burdens. The aim is to measure both the environmental impacts, as well as the risk with the reliance on more scarce resources.

3.2. Scope

A cradle-to-gate Life Cycle Assessment (LCA) is performed to assess the environmental performance of tomato production under various future energy scenarios. This approach is commonly used and includes all emissions and resource uses up to the point where the tomatoes leave the greenhouse, while excluding downstream processes such as packaging, retail, and consumption (Canaj et al., 2020).

The environmental impacts are characterized using the ReCiPe 2016 method, chosen for its broad coverage and compatibility with earlier studies. ReCiPe provides both midpoint and endpoint indicators across a wide range of environmental categories (Huijbregts et al., 2017). To complement this, the Product Environmental Footprint (PEF) method is used specifically for assessing Abiotic Depletion Potential (ADP), allowing for comparison with Surplus Ore Potential (SOP) and the GeoPolRisk based method. Economic allocation is applied over multifunctional processes, to reflect sectoral principles. Economic and infrastructural constraints such as grid congestion are not explicitly modelled.

LCA is particularly suited, because it models the environmental burdens associated with current and projected production systems without accounting for broader market effects (Guinée, 2002). This allows for a consistent comparison between fossil-based and non-fossil-based energy systems, for the improvement of decision making using a fixed functional unit.

3.2.1. Function, Functional Unit, Alternatives, Reference flows

The function for this thesis is defined as "The production of 1kg of tomatoes in greenhouses in the Netherlands." The quantity of tomatoes in the function is chosen based on the quantity of tomatoes produced in the Ecoinvent foreground process that has been used as a blueprint for this adapted process.

Following this the functional unit is defined as "The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail."

There are eight alternatives modelled for energy and CO2 provision for tomato horticulture in the Netherlands in 2040, which are:

- Tomatoes grows using heat from Combined Heat and Power and CO2 from OCAP
- Tomatoes grows using heat from Geothermal and CO2 from OCAP
- Tomatoes grows using heat from a Heat network and CO2 from OCAP
- Tomatoes grows using heat from Electric Heat Pumps and CO2 from OCAP
- Tomatoes grows using heat from Electric Heat Pumps and an ATES (WKO) system and CO2 from OCAP
- Tomatoes grows using heat from Electric Heat Pumps and Dehumidifiers and CO2 from OCAP
- Tomatoes grows using heat from Electric Heat Pumps and Solar Panels and CO2 from OCAP
- Tomatoes grows using heat from Electric Heat Pumps and Solar Panels with Batteries and CO2 from OCAP

Which provides the following reference flows for tomatoes:

- The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using a fossil based Combined Heat and Power generation from natural gas, and CO2 from OCAP.
- The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using a non-fossil based Geothermal network, and CO2 from OCAP.
- The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using a non-fossil based heat residual network, and CO2 from OCAP.

- The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using non fossil based Electric Heat pumps, and CO2 from OCAP.
- The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using non fossil based Electric Heat pumps with an ATES (WKO) systems, and CO2 from OCAP.
- The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using non fossil based Electric Heat Pumps with dehumidifiers, and CO2 from OCAP.
- The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using non fossil based Electric Heat pumps with solar panels, and CO2 from OCAP.

The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using non fossil based Electric Heat pumps with solar panels with batteries, and CO2 from OCAP.

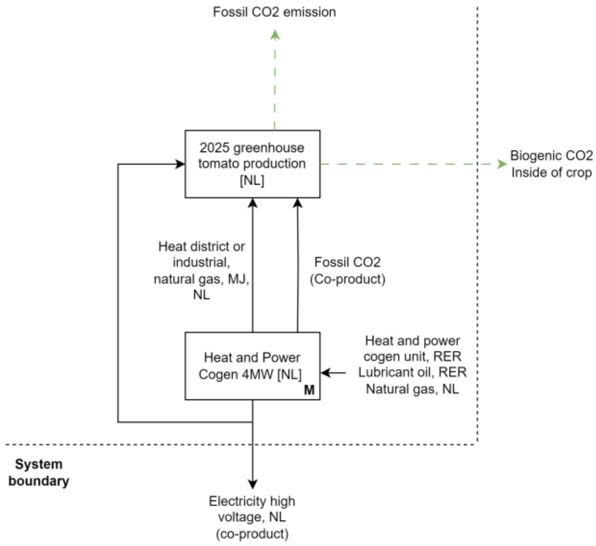
3.2.2. CO_2 Attribution

One of the central methodological challenges in this study lies in the allocation of emissions within multi product processes and waste treatment processes. The former is Combined Heat and Power (CHP) systems, which simultaneously produce heat, electricity, and usable CO_2. The latter is OCAP enrichment, which treats the waste CO_2 and transforms it into a good. In practice, emissions are often attributed entirely to heat and waste treatment, which simplifies calculations but obscures the multifunctionality of the systems. Instead an economic allocation approach is adopted, distributing environmental burdens based on the market value of each output. This shows a more balanced comparison between fossil-based and alternative energy systems and reflects the real-world decision-making context of growers and energy providers.

CO_2 enrichment presents another unique modelling challenge. In fossil-free systems, CO_2 must be externally sourced. This is typically from OCAP, waste incineration, or other industrial processes. The environmental burden of this CO_2 depends on how it is allocated and whether it is treated as biogenic. Following the Ecoinvent convention, this thesis considers CO_2 absorbed by plants as biogenic and impact-neutral, while vented CO_2 is attributed to the growing of tomatoes as fossil CO2 emission (See figure 1 and Figure 2). However, stakeholder perspectives on this issue vary. Some argue that plants act as temporary carbon sinks and should be credited accordingly, while others contend that re-emitted CO_2 should carry a positive characterization factor regardless of origin (Leinonen, 2022). The problem with the first argument is that it neglects the CO2 that is not sequestered and still vented into the environment. It is an option in the tool to not account for the CO2 enrichment and thus the emissions, however it is recommended to not use the option in the tool to represent the environmental impact.

Figure 1

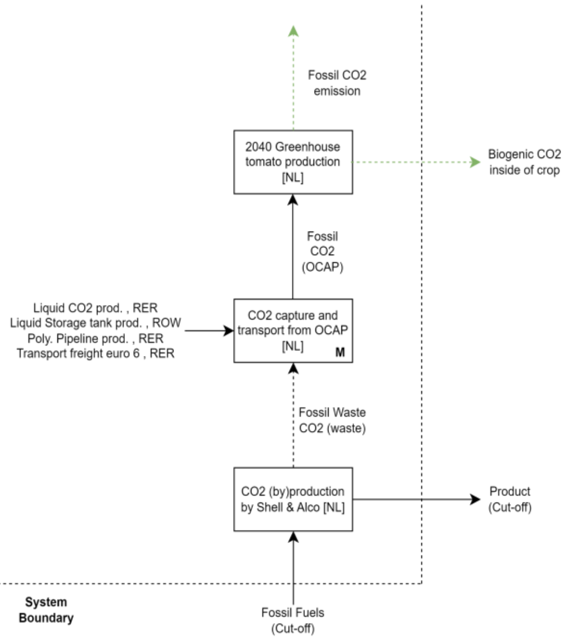
CO2 Attribution from CHP for 1kg Tomato Production: Fossil vs Biogenic.



Note. This figure shows a section of the LCA flowchart for tomato production using a natural gas-powered Combined Heat and Power (CHP) system. CO2 emitted during energy generation is partially absorbed by the crop for enrichment. Based on molecular uptake modelling, 12.5% of the added CO2 is considered biogenic and does not contribute to global warming potential (GWP), while the remaining 87.5% is vented and treated as fossil CO2 emissions.

Figure 2

CO2 Attribution from Enrichment in Fossil-Free Tomato Production: Fossil vs Biogenic.



Note. This figure shows a section of the LCA flowchart for tomato production using a fossil-free heating system. Because no CO2 is generated on-site, enrichment CO2 must be externally sourced via OCAP. Of the CO2 added, 12.5% is absorbed by the crop and considered biogenic, carrying no global warming potential (GWP). The remaining 87.5% is vented and treated as fossil CO2 emissions.

4
Methodological Framework

To address the main research question, multiple modelling methods are required, each targeting a different aspect of the analysis. The methodological framework consists of three main components. First, an attributional Life Cycle Assessment (LCA) is used to evaluate the environmental impacts of fossil-free energy transition pathways in Dutch tomato horticulture. This includes an extended sensitivity analysis to explore how modelling choices influence outcomes. Second, a resource risk assessment framework is integrated to evaluate how the transition affects the demand for materials with potential supply constraints. Third, an Excel-based decision support tool is developed to translate LCA results into comparative scores that reflect potential stakeholder practices.

4.1. Attributional LCA Modelling

The modelling framework compares fossil-based and fossil-free energy systems in Dutch greenhouse horticulture using an attributional life cycle approach. System boundaries and functional units are kept consistent across scenarios to ensure comparability. Sector-specific conventions are followed, especially around CO_2 enrichment, energy demand, and the treatment of multifunctional systems like combined heat and power (CHP). The framework is designed to reflect future-oriented production setups while staying grounded in current practices. It allows for scenario-based modifications, making it possible to explore how changes in energy sources, enrichment strategies, and market conditions affect environmental performance. Rather than modelling broad systemic shifts, the focus is on direct environmental burdens linked to each configuration under clearly defined assumptions.

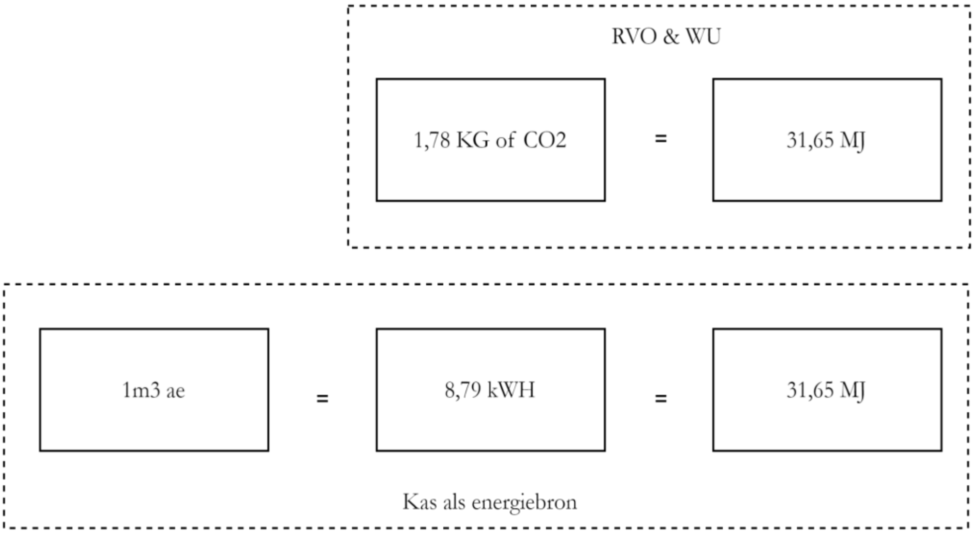
The LCA is implemented using OpenLCA software and the Ecoinvent 3.9.1 cutoff database and the baseline model is adapted from an Ecoinvent process representing tomato production in a 7-hectare Dutch greenhouse between 2009 and 2012. This model has been updated using recent data from Delphy and other literature sources to reflect future-oriented scenarios. Key modifications include updated energy demand and CO_2 enrichment levels, adjusted heating technologies and electricity sources, and regionalized market data to better represent Dutch conditions. This information was provided as tomato production over one square meter, and manually converted to production per kilogramme of tomatoes.

4.1.1. Natural Gas Use Conversion

To stay consistent with sectoral conventions, energy conversion factors are based on values provided by Kas als Energiebron, and CO_2 emissions from natural gas combustion are calculated using a conversion factor of 56.4 kg CO_2 per GJ, as recommended by the RVO and Wageningen University (Fennis & Larrivee, 2024) (see figure 3). This is a slightly higher CO2 conversion rate compared to Ecoinvents 54.3kg CO2 per GJ.

Figure 3

Natural Gas Conversion Rates Used in LCA Modelling (Fennis & Larrivee, 2024; Zijlema, 2024).



Note. This figure presents the conversion factors used to model energy and emissions from natural gas in tomato production. Based on data from RVO and Wageningen University, 1 m^3 of natural gas (a.e.) corresponds to 31.65 MJ of energy and results in 1.78 kg of CO_2 emissions.

4.2. Resource Risk Assessment

To address the geopolitical and economic risks associated with the supply of critical raw materials (CRMs), the study incorporates elements of the GeoPolRisk and GeoPolEndpoint methods. The partial inclusion, rather than the entire inclusion, is because several limitations emerged during the application of the GeoPolRisk method. The method lacks transparency in how characterization factors are derived and updated, does not integrate well with OpenLCA, and does not account for all sources of critical materials. It focuses on the presence of the exact raw materials either directly mined or sourced from the market, neglecting additional sources from which CRM's may be derived (See the spodumene problem in Chapter 9. Discussion). As a result, the method is used in a limited and exploratory capacity. Instead of applying characterization factors across the entire life cycle inventory, the analysis focuses on identifying the presence and relative importance of high-risk materials in each energy system. A subset of materials with the highest characterization factors and

Herfindahl-Hirschman Index (HHI) scores is highlighted to illustrate potential vulnerabilities in supply chains (see table 1).

Table 1

Resources Evaluated for Supply Risk in the Energy Transition of Dutch Horticulture (Koyamparambath et al., 2024).

Resources chosen based on the highest Herfindahl-Hirschman Index score		
	HHI	**GeoPol CF**
Gallium	0,94	9,93
Niobium	0,86	0,61
Rhodium	0,74	50524,50
Mercury	0,72	0,74
Platinum	0,57	165,5
Tellurium	0,54	18,2
Cobalt	0,49	8,23
Resources chosen based on the highest Characterisation Factor in the GeoPolRisk method		
Palladium	0,33	2051,66
Gold	0,05	29,72
Boron	0,32	10,65
Tin	0,17	3,65
Rhenium	0,28	2,83
Arsenic	0,37	2,31
Molybdenum	0,23	1,59
Uranium	0,25	1,35
Selenium	0,2	1,13
Lithium	0,34	0,95

Note. This table lists the key material resources considered in the adapted risk assessment for the energy transition of the Dutch horticulture sector. Since the GeoPolRisk method has over 50 resources it evaluates, only a select amount of resources with the highest (dimensionless) HHI score and (dimensionless) GeoPolRisk Characterisation Factor will be evaluated.

This approach is meant to complement, rather than replace, traditional resource indicators such as ADP and SOP. By combining these methods, a more nuanced and multi-dimensional perspective on resource risk is shown. It additionally acknowledges the methodological constraints of current criticality tools.

4.3. Scenario-Based Decision-Support Tool

The Excel-based LCA tool translates complex environmental data into an accessible, interactive format that allows growers, or policymakers to explore the implications of different energy transition pathways. It enables users to toggle between key assumptions such as CO_2 enrichment levels, allocation choices, and energy source combinations and simulate a wide range of future scenarios. The tool focuses on four key environmental indicators selected based on the highest scoring normalized categories and stakeholder consultations: fossil fuel use, greenhouse gas emissions, material resource use, and water use. Categories such as eutrophication, acidification, and toxicity, which are typically relevant in agricultural LCAs are excluded for two reasons (Withers et al., 2014). First, pesticide use remains consistent across all modelled scenarios, making toxicity-related impacts less variable and therefore less informative. Second, greenhouse water systems in the Netherlands are strictly regulated, significantly reducing the risk of runoff-related environmental harm (Van Der Salm et al., 2020).

By embedding flexibility, the tool facilitates scenario-based exploration of environmental outcomes under varying assumptions. Rather than prescribing a single optimal solution, it allows users to examine trade-offs and sensitivities across different configurations. This supports more informed and context-specific decision-making, particularly in a sector where environmental, economic, and operational considerations are tightly interlinked.

4.3.1. Allocation Choices in LCA Tool

Given the uncertainty surrounding future energy mixes and CO_2 sourcing strategies, a robust sensitivity analysis in the LCA is developed. This includes variations in CO_2 demand, allocation methods, and energy source combinations. These scenarios are embedded within an Excel-based decision-support tool that allows users to toggle between assumptions and explore trade-offs. For example, the baseline scenario assumes CO_2 enrichment levels equivalent to current CHP output, while alternative scenarios use lower enrichment levels around 50% of CHP levels (Gelder et al., 2012). Users can also choose whether CO_2 emissions from enrichment are attributed to growers or considered burden-free, and can model different combinations of energy sources and CO_2 supply strategies.

4.3.2. Recommended choices for the LCA tool

CO_2 Enrichment Scenarios

The decision-support tool includes multiple attribution options for CO_2 enrichment, reflecting both stakeholder perspectives and methodological considerations. One such option reflecting no CO_2 emissions burden called "0kg CO_2 import" is considered unfair from an LCA standpoint. This scenario does not imply that tomatoes are grown without CO_2 enrichment, as that would drastically reduce yields. Instead, it reflects a viewpoint held by some growers. That is that the environmental burden of CO_2 should not be attributed to growers, since they are not the original emitters. However, from an LCA perspective, this is problematic. CO_2 used for enrichment is a product with economic value, purchased and applied by growers. Even if the CO_2 would otherwise be emitted, growers are responsible for its use and only partial sequestration. Additionally, if the alternative for CO_2-producing companies is long-term storage, then diverting it for horticulture increases the net environmental burden, especially in terms of greenhouse gas emissions.

While this option is included in the tool to reflect stakeholder input, it is not recommended for use in environmental assessments aiming for methodological rigor. A more defensible option is the reduced CO_2 enrichment scenario called "0,53kg CO_2 import". According to a Wageningen report, selective dosing and more frugal application can significantly lower CO_2 demand without compromising tomato yields (Gelder et al., 2012). This scenario is considered fair and is included in the tool as a valid alternative.

CO_2 Enrichment Source

The choice of CO_2 enrichment scenario has a major impact on results, as CO_2 enrichment and its subsequent release are the dominant contributors to GHG emissions in renewable energy systems. While CO_2 is primarily sourced from OCAP, not all growers will be located in the west of the Netherlands where OCAP is available. Therefore, the sensitivity analysis includes an alternative: CO_2 from waste incineration. This source is more polluting across most impact categories and is never the preferred option, but its inclusion reflects real-world variability in supply chains.

Economic Role of Byproducts

Both electricity and CO_2 are economically valuable byproducts for growers. CO_2 is essential for maintaining yields, and its absence would require costly alternatives. Electricity serves dual roles: powering operations (e.g. LED lighting, automation) and generating revenue when sold during peak demand periods. In some cases, electricity sales surpass tomato production as the primary income source (van 't Hoog, 2022).

Because these byproducts are economically integral to greenhouse operations, they should be attributed with their associated environmental burdens. The tool allows users to override this attribution, but doing so risks misrepresenting the environmental impact of combined heat and power (CHP) systems. This practice is strongly discouraged.

Renewable Electricity and Burden-Free Claims

Some stakeholders have argued that certified renewable electricity is climate-neutral and should carry no environmental burden. However, the LCA methodology does not support this claim. While renewables avoid fossil combustion, they still have environmental impacts (Gayen et al., 2024).

The tool includes a burden-free electricity option called "no responsibility" to reflect policy scenarios where such accounting is permitted. However, it is recommended not to use this option in assessments aiming for comprehensive and accurate environmental accounting.

Summary of Attribution Recommendations

Table 2 summarizes which attribution choices within the decision-support tool are considered fair and methodologically sound.

Table 2

Assessment of Attribution Choices in the Decision-Support Tool for Environmental Impact of 1 kg of Tomatoes.

Choices made for the LCA	Valid	Choices made for the thesis lab	Valid	Choices that the sector makes	Valid
High CO2 enrichment (1.2kg)	**Yes**	Low CO2 enrichment (0.53kg)	**Yes**	No CO2 enrichment responsibility	**No**
CO2 from OCAP	**Yes**	CO2 from OCAP	**Yes**	CO2 from OCAP	**Yes**
Economic heating allocation (56%)	**Yes**	Economic heating allocation (56%)	**Yes**	Complete allocation to heating (100%)	**No**
Renewable electricity (with emissions)	**Yes**	Renewable electricity (with emissions)	**Yes**	Renewable electricity (with no responsibility for emissions)	**No**

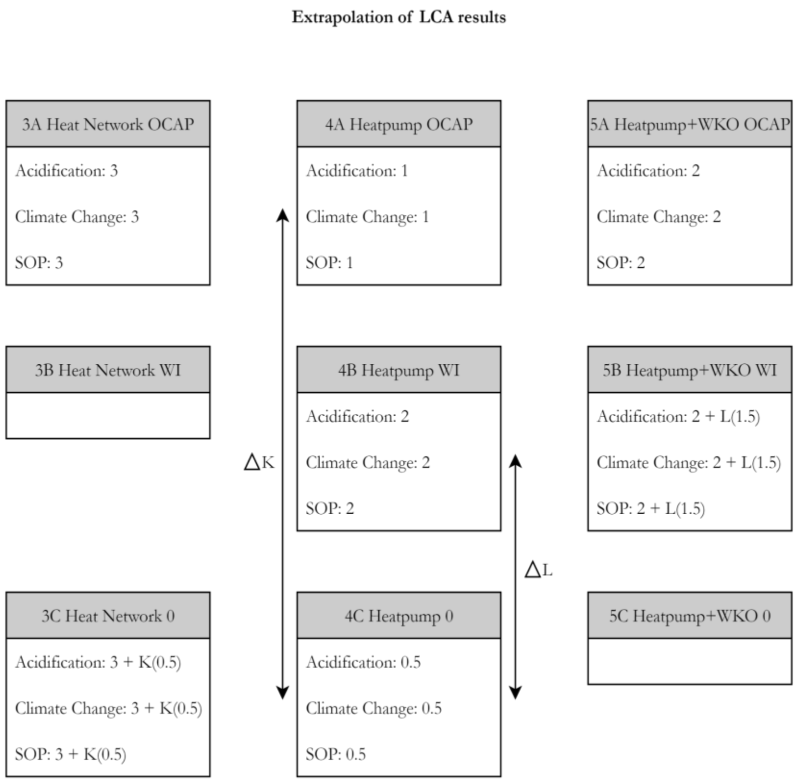
Note. This table outlines the attribution options available in the decision-support tool and evaluates their methodological validity. Each choice influences how environmental burdens are assigned to tomato production, particularly in relation to energy use, CO_2 sourcing, and coproduct allocation. An expanded version of this table with explanations for the invalid choices can be found in Appendix H.

4.2.3. Result Extrapolation method

To reduce the number of full LCA models required, an extrapolation based modelling strategy is employed. Figure 4 gives a visual representation of this method. Three CO_2 sourcing scenarios are modelled: OCAP-supplied CO_2 (OCAP), CO_2 from waste incineration (WI), and no CO_2 responsibility to growers (0). Rather than modelling each system with each CO_2 source, each system is first only modelled with OCAP-supplied CO_2. Then a single system is modelled with WI and no CO_2 responsibility (System 4A,4B,4C). The differences in environmental impact between these scenarios (Delta K and Delta L) are then applied to other energy systems (system 3 and 5) to extrapolate their impacts under alternative CO_2 sourcing conditions. This approach is possible since the only difference between the systems amongst themselves is the CO_2 enrichment source. This enables flexible scenario building in the Excel tool without requiring dozens of separate additional LCA models. This way system 1A through 8A must be calculated, and 1B/C, through 8B/C's environmental impact score can be calculated without having to perform additional LCAs.

Figure 4

Scenario Extrapolation Framework for LCA Results (1kg Tomatoes).



Note. This figure illustrates the extrapolation method used to estimate environmental impact scores for tomato production systems with varying CO2 sourcing strategies. Full LCA models were conducted for systems using OCAP-sourced CO2 (A variants). The impact differences from waste incineration (B variants) and no CO2 responsibility (C variants) were calculated for one system and then applied to others using delta values (ΔK and ΔL), enabling efficient scenario modelling without redundant LCAs.

5

Results - Inventory analysis

This chapter presents the inventory analysis that underpins the Life Cycle Assessment (LCA) of energy transition scenarios in Dutch tomato horticulture. The inventory phase compiles all relevant inputs and outputs associated with each modelled scenario. These data form the foundation for the impact assessment and interpretation that follow.

5.1. System Boundaries

A system boundary indicates what is included within the product system, not all inputs and outputs in practice will be included in the system boundaries. This boundary indicates what processes and related emissions the grower will seem responsible for. In the current system, CHP provides both heat and electricity, covering much of the greenhouse's operational demand. However part of it is also sold to the market for use. This means part of the electricity and its related environmental emissions will be allocated away. When alternative systems are used, this electricity must be purchased separately.

5.1.1. Cut-offs

Certain capital goods, such as minor infrastructure components or auxiliary equipment, are excluded due to data limitations. While the most significant capital goods will be accounted for, some elements, particularly those assumed to have little environmental impact, remain omitted.

For instance, the shared geothermal plant construction foreground that was created requires more than just the four modelled in-flows. These exclusions reflect limitations in available datasets rather than simplifications of the system. All alternative product systems still exhibit comparable complexity, as shown in the Consistency and Completeness Chapter, ensuring that the overall comparability remains valid.

However, the accuracy of the results is affected to some extent. These limitations and their implications are further discussed in Chapter 9.5.Limitations.

5.1.2. Flowcharts

The main product system is based on the "tomato production, fresh grade, in heated greenhouse" process from Ecoinvent. Key processes such as greenhouse production, heating, and waste treatment have been adapted using updated data provided by Delphy. One notable addition is CO_2 enrichment, which was missing in the original dataset and has now been included as a new foreground process. This results in a representation of 2040 greenhouse tomato production that mirrors the 2025 system, still relying on combined heat and power (CHP) and maintaining the status quo.

Each energy scenario is then modelled using a framework, with flowcharts developed to visualize the system boundaries, inputs, and outputs. These flowcharts are based on economic allocation and assume a high CO_2 enrichment demand equivalent to that produced by CHP based systems. The CO_2 is modelled as being supplied by OCAP.

Alternative sourcing flowcharts from waste incineration and no supply are shown in Appendix B, since these are only modelled for the sensitivity analysis. Waste incineration represents growers who are unable or unwilling to connect to OCAP. The no-supply scenario reflects growers who choose not to take accountability for the CO_2 used in enrichment, as previously discussed.

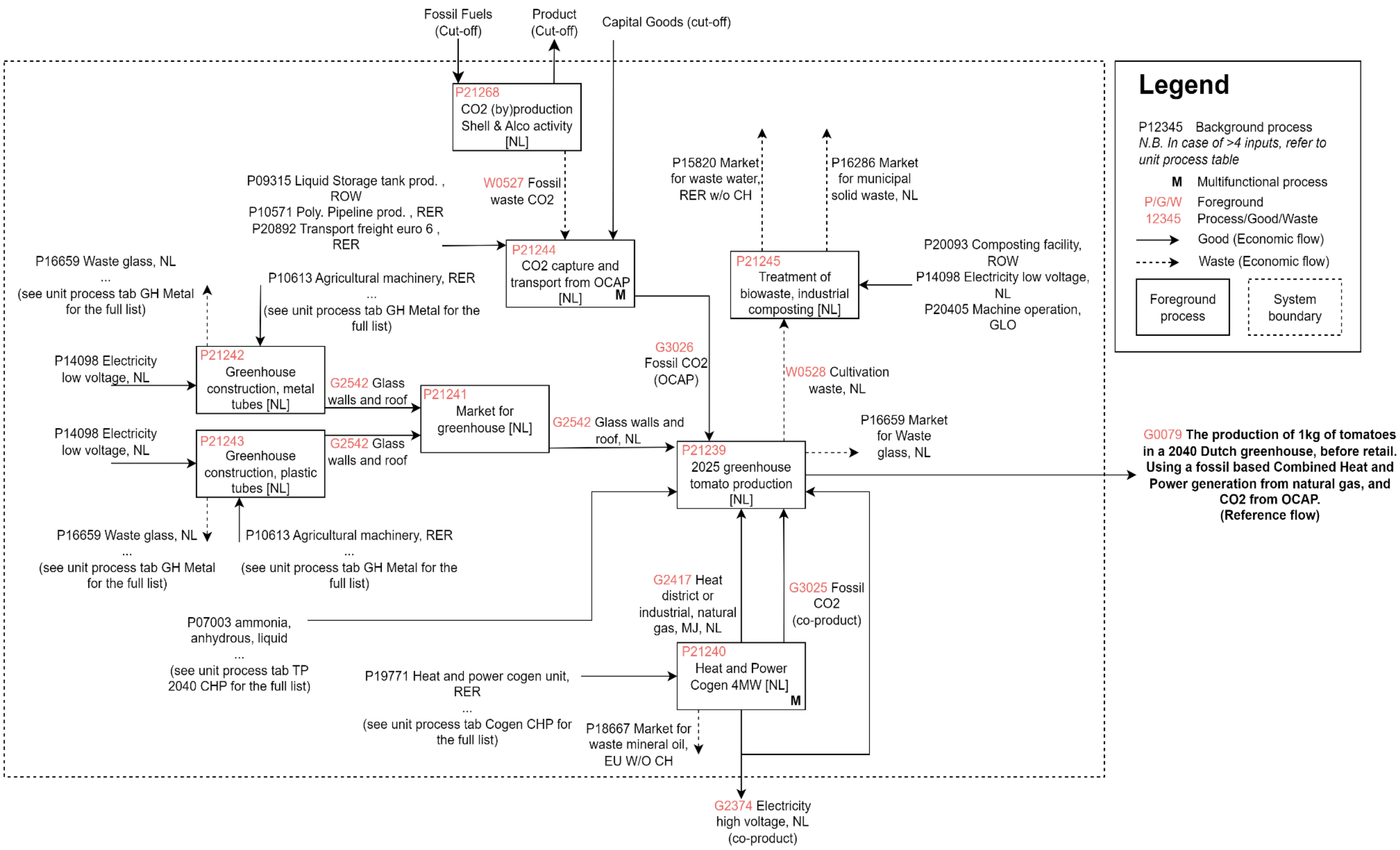
This modular approach enables the environmental impact of CO_2 sourcing to be added or removed from each energy configuration without requiring a full LCA for every possible combination. This is further explained in the Reduced modelling method through extrapolation chapter. Full modelling details for each scenario are provided in Appendix C.

System 1 CHP

This baseline scenario represents the 2040 tomato production system using natural gas-powered Combined Heat and Power (CHP) for both heat and electricity. CO_2 enrichment is partially sourced from OCAP, and emissions are economically allocated across heat, electricity, and CO_2.

Figure 5

LCA Flowchart: Tomato Production Using CHP and OCAP-Sourced CO_2.

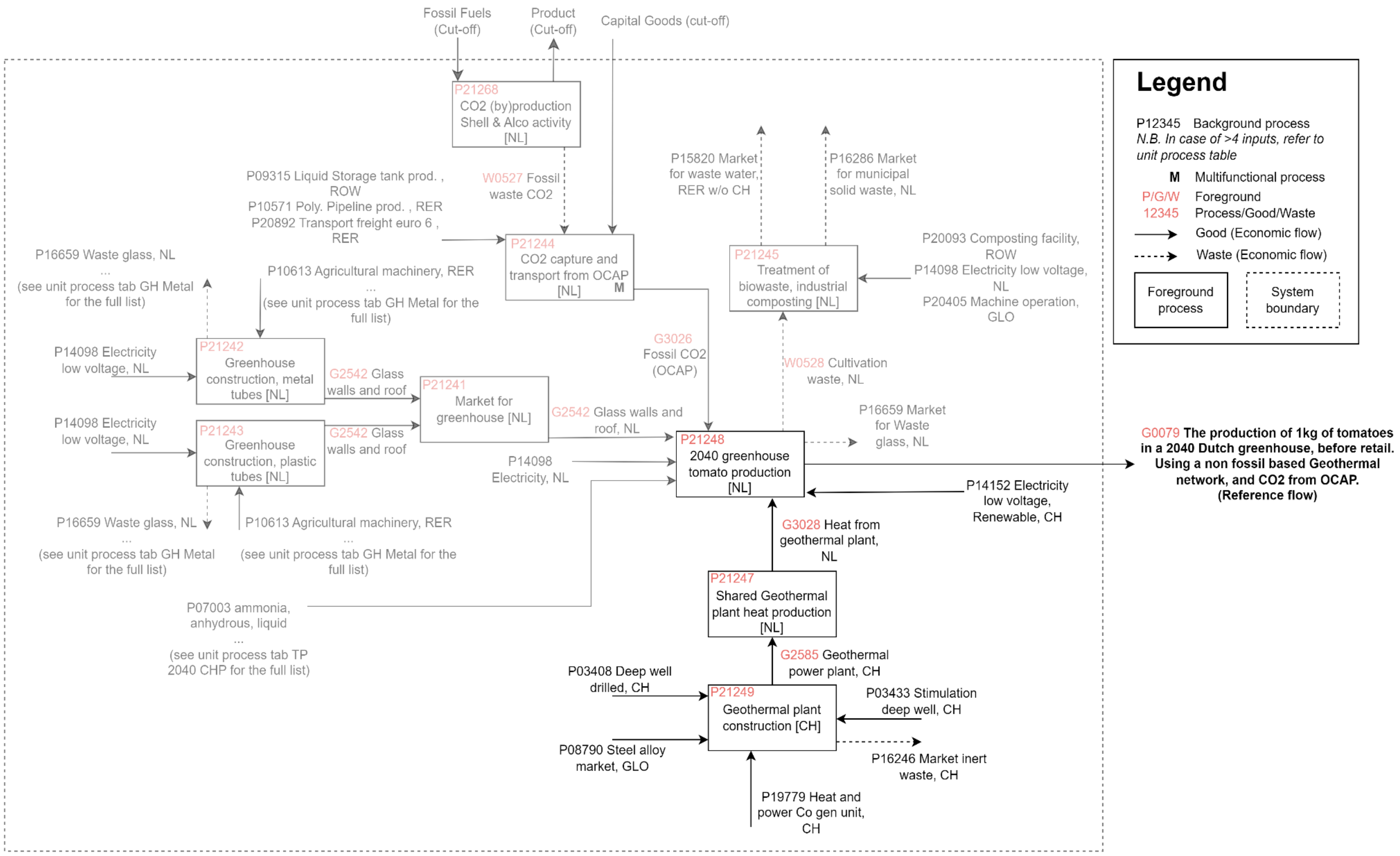


System 2 Geothermal Heat Network

This scenario replaces fossil-based heating with geothermal energy, modelled after the Vierpolders installation. CO_2 enrichment is maintained at CHP-equivalent levels via OCAP.

Figure 6

LCA Flowchart: Tomato Production Using Geothermal Heat and OCAP-Sourced CO_2.

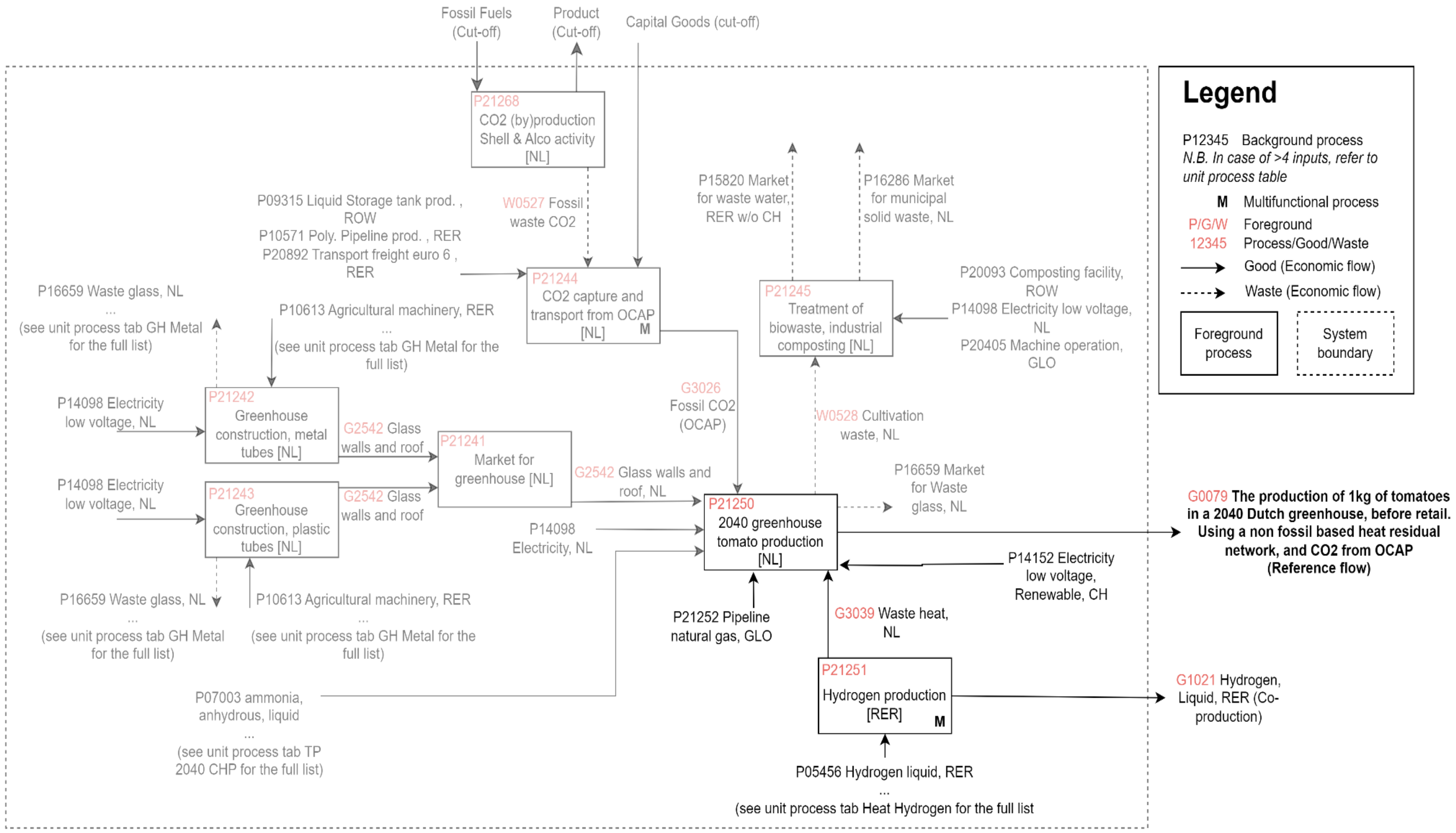


System 3 Residual Heat Network

Heat is supplied via a district heating network using waste heat from hydrogen production. Emissions are mostly allocated to hydrogen, resulting in lower environmental impact for the heat. CO_2 enrichment is provided by OCAP.

Figure 7

LCA Flowchart: Tomato Production Using Residual Industrial Heat and OCAP-Sourced CO_2.

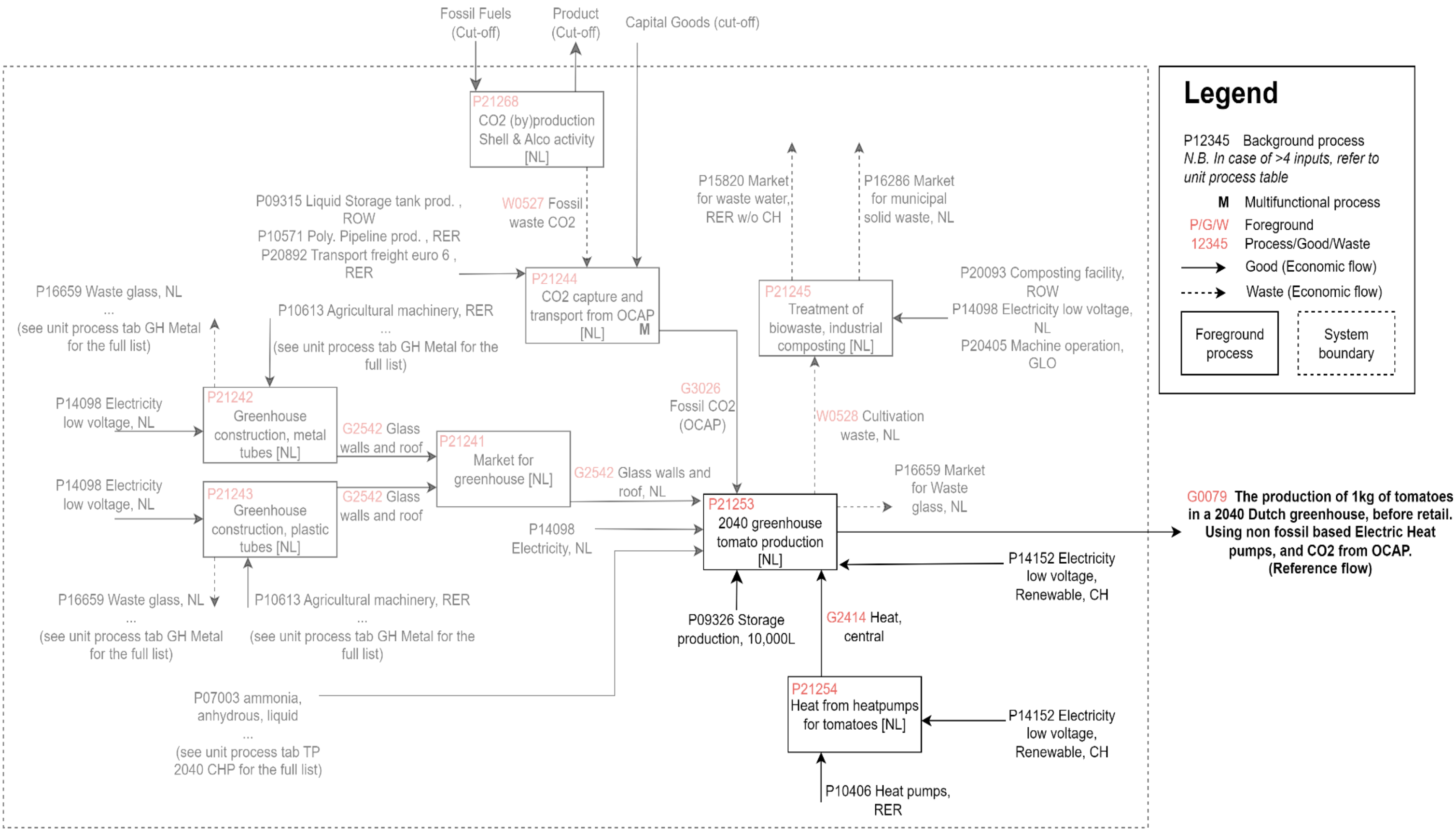


System 4 Electric Heat Pumps

This scenario models full electrification using heat pumps, scaled beyond practical limits for comparison purposes. Electricity is sourced from the Dutch renewable grid. CO_2 enrichment is provided via OCAP.

Figure 8

LCA Flowchart: Tomato Production Using Heat Pumps and OCAP-Sourced CO_2.

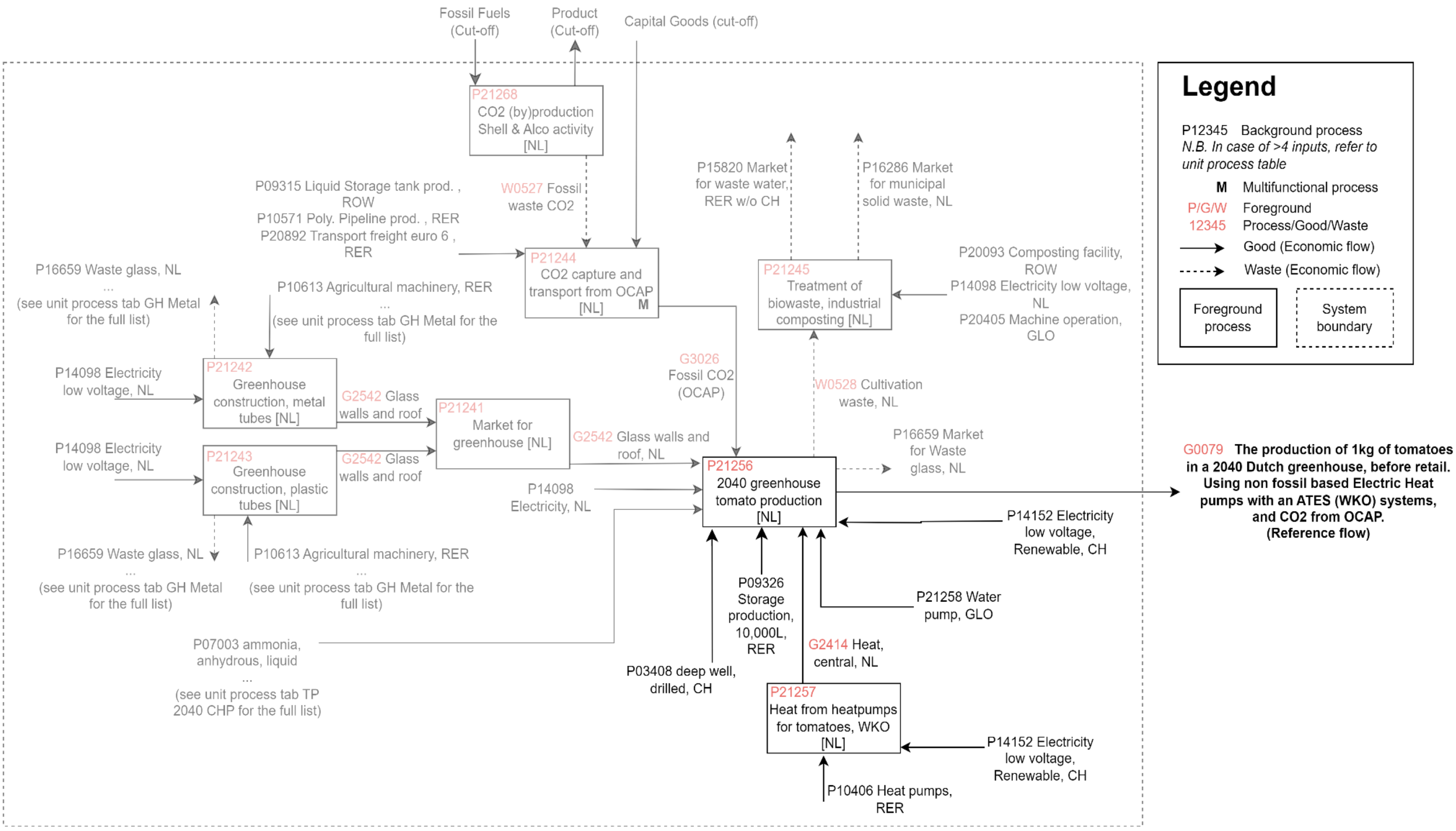


System 5 Electric Heat Pumps With ATES (WKO).

Heat pumps are combined with Aquifer Thermal Energy Storage (ATES) to improve seasonal efficiency. The system is scaled to simulate full electrification. CO_2 enrichment is provided via OCAP.

Figure 9

LCA Flowchart: Tomato Production Using Heat Pumps In Combination With ATES and OCAP-Sourced CO_2.

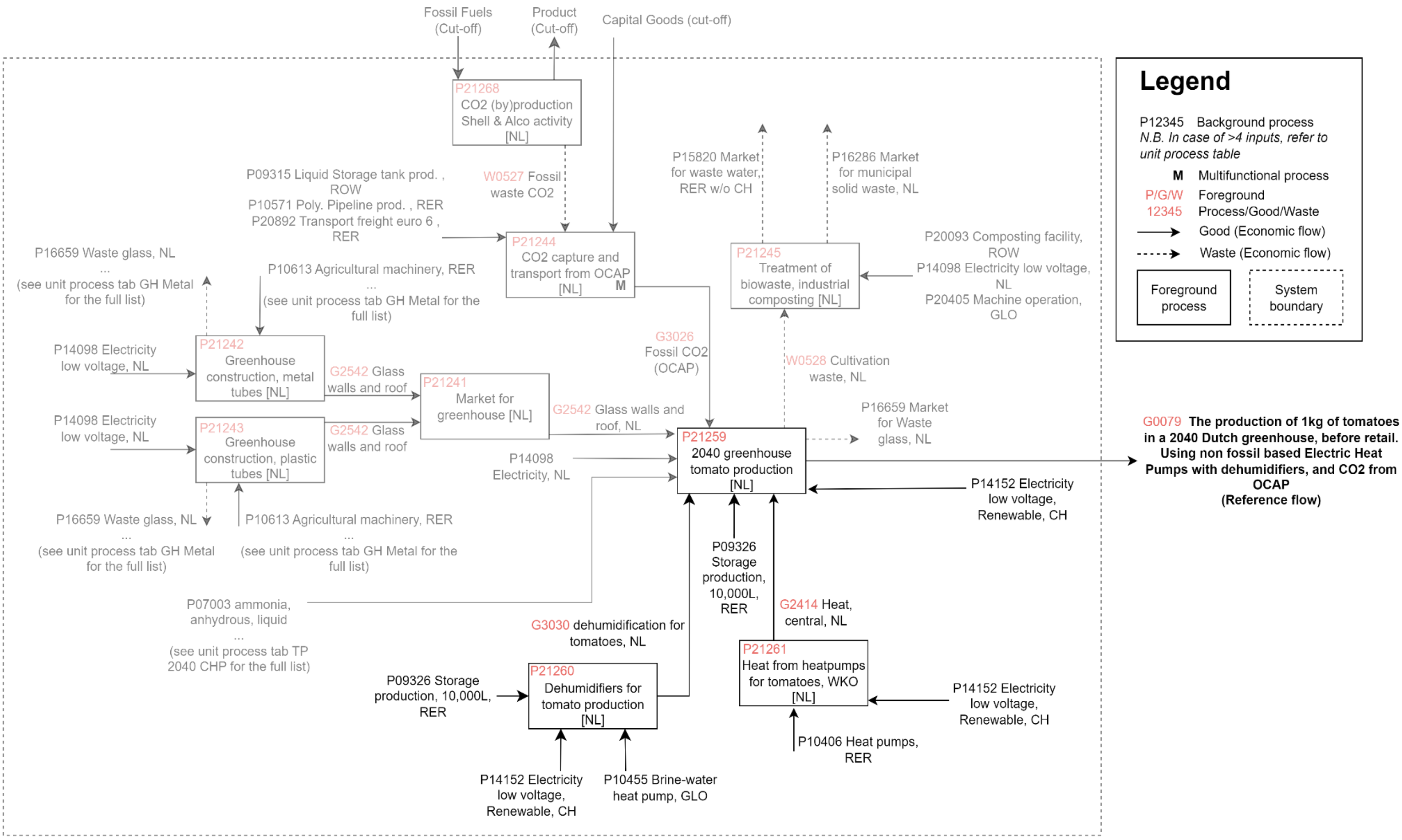


System 6 Electric Heat Pumps With Dehumidifiers

This configuration adds dehumidifiers with heat recovery to the heat pump system, increasing electrification potential. Electricity demand rises slightly. CO_2 enrichment is provided via OCAP.

Figure 10

LCA Flowchart: Tomato Production Using Heat Pumps In Combination With Dehumidifiers and OCAP-Sourced CO_2.

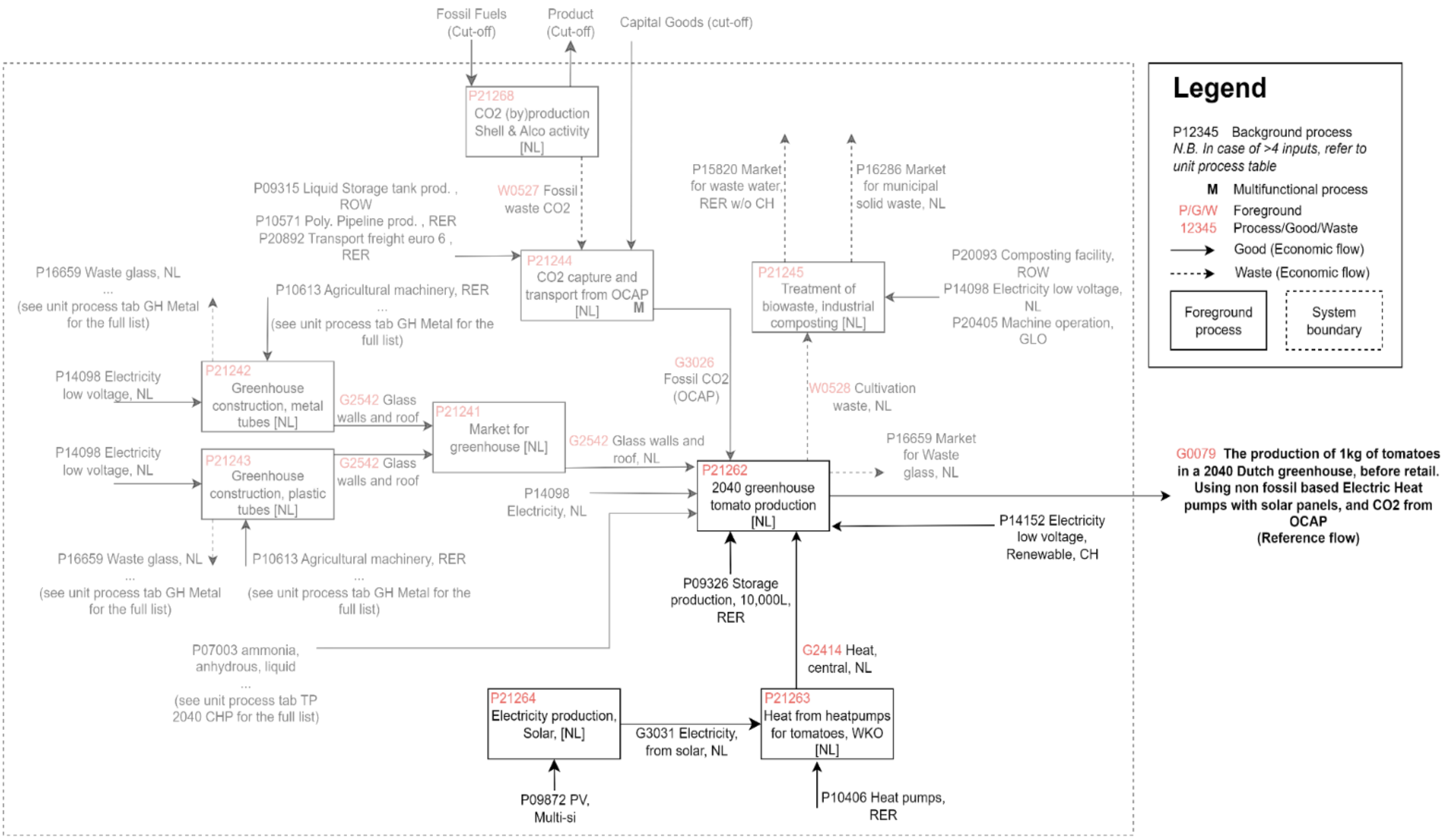


System 7 Electric Heat Pumps With Solar Panels

Electricity for heat pumps is generated on-site using solar PV panels. The grid is used as a virtual battery. This increases grid dependency and introduces material impacts from panel production. CO_2 is sourced from OCAP.

Figure 11

LCA Flowchart: Tomato Production Using Heat Pumps Powered by Solar and OCAP-Sourced CO_2.

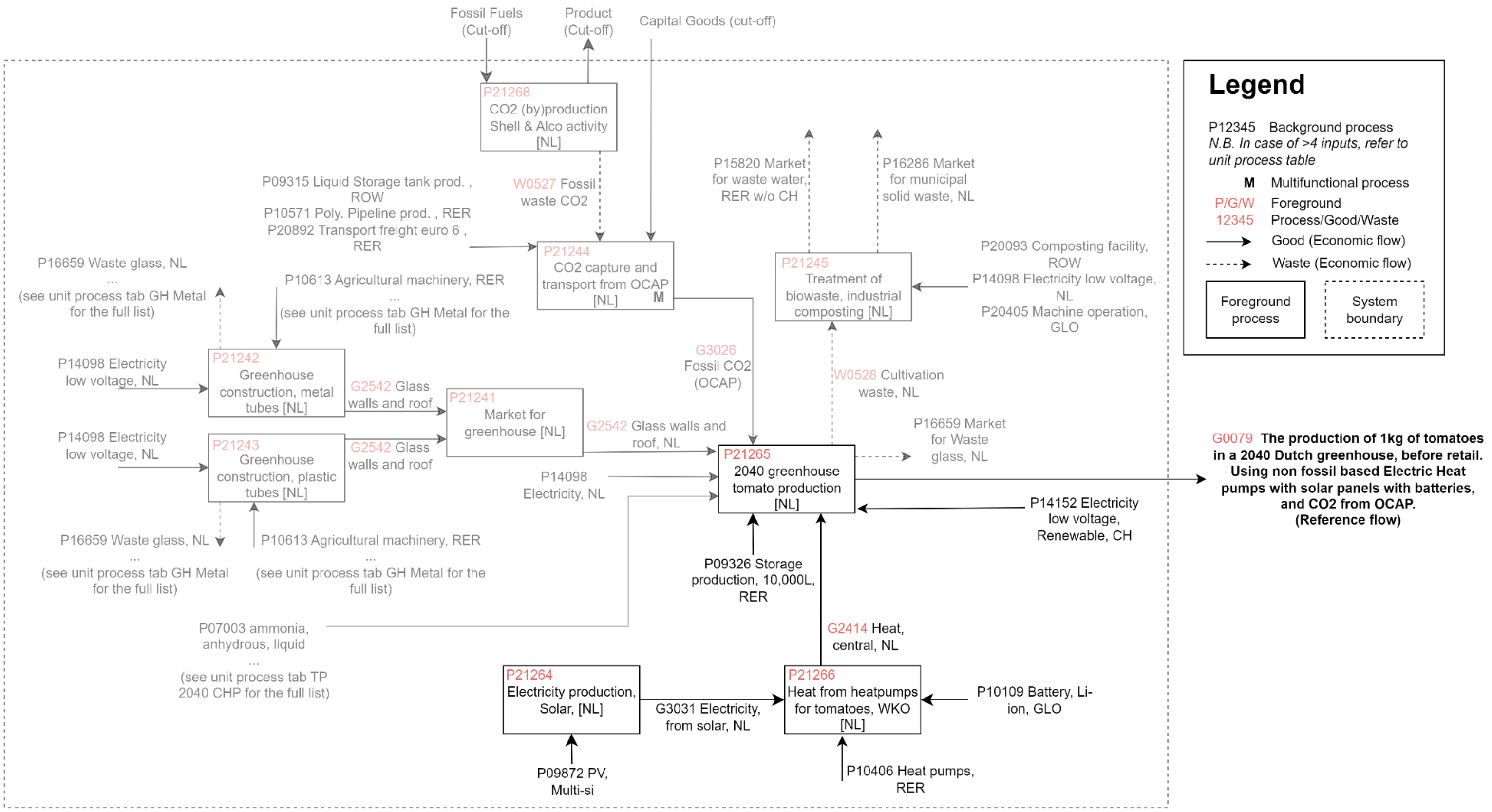


System 8 Electric Heat Pumps With Solar Panels and Batteries.

This scenario adds battery storage to the solar-powered system (System 7) to enable overnight heating. It is the most autonomous configuration but also the most resource-intensive due to battery production.

Figure 12

LCA Flowchart: Tomato Production Using Heat Pumps Powered by Solar and Batteries, and OCAP-Sourced CO_2.



5.1.3. Data Collection

The data used in this thesis is primarily derived from a combination of secondary literature and communication with stakeholders in the Dutch greenhouse horticulture sector. These include Delphy, Glastuinbouw Nederland, and Tomato World, who provided both quantitative data and qualitative insights into current and projected greenhouse operations, energy use, and CO_2 enrichment practices.

The development of flowcharts for each energy scenario required a careful synthesis of empirical data and modelling assumptions. In many cases, direct data for future-oriented technologies or configurations was unavailable, necessitating the use of proxies and scaling techniques.

For example, the geothermal scenario is based on the shared geothermal installation in Vierpolders, which reportedly offsets approximately 8.8 million m^3 of natural gas annually, which is equivalent to 262 million MJ of thermal energy. The exact breakdown of this energy use is not specified, it is conservatively assumed to represent net heat delivery, excluding electricity generation or CHP-related losses.

To model this example, the Ecoinvent 3.9.1 foreground process for a 5.5 MWel geothermal CHP unit was used as a proxy. This process was scaled by a factor of 3.1 to approximate the 20 MW thermal capacity of the Vierpolders installation. Since the Vierpolder installation is designed for heat-only delivery, the electricity cogeneration component was removed. Additionally, the modelled well depth was adjusted from 5000 meters to 2200 meters to reflect the actual geological conditions in the Westland region. The installation footprint was estimated at 4000 m^2, based on google maps imagery.

Similar modelling strategies were applied across all scenarios, with adjustments made to reflect Dutch market conditions, regional infrastructure, and sector-specific practices. Where necessary, assumptions were transparently documented and sensitivity analyses were conducted to test the robustness of key parameters. As mentioned before, a full list of data sources, proxies, and modelling choices is provided in the Appendix C.

5.1.4. Unit Processing

To ensure transparency, reproducibility, and traceability within the Life Cycle Assessment (LCA), each modelled system is broken down into discrete unit processes. These unit processes represent the fundamental building blocks of the life cycle inventory and are used to capture the environmental and economic inflows and outflows associated with each scenario. (See Appendix D for the full Unit Process Record)

Each unit process is documented using a structured format that includes, Inputs and outputs that are categorized based on whether they are directly modeled (foreground) or drawn from the Ecoinvent 3.9.1 cutoff database (background). Newly created foreground processes are assigned unique product numbers to facilitate integration within the OpenLCA modeling environment and to ensure consistency across scenarios.

To provide a comprehensive overview, each modeled system is represented in a foreground process table. These tables include custom product numbers assigned to newly created foreground processes, facilitating traceability and integration within the OpenLCA modeling environment. Figure 13 provides an example of this format.

Figure 13

Unit Process Table: Tomato Production Using CHP and OCAP CO_2.

2040 tomato production using CHP								* Indicates that the information is trough personal coomuncation	
#	Process	P number	Adapted from ecoinvent process number	Literature data used for	Geographical representation	Temporal representation	Technological representation	Source	Comments
1	Tomato production (2025 replication)	P21239	P00335	Heating, CO2, Waste treatment	Based on NL	2009-2022	Conventional production, with amendments made to update the heating and CO2 supply	Delphy*, Tomato World*	
2	Heat and power co-generation (for the production of tomatoes)	P21240	P14934 & P13520	CO2 enrichment	Based on RER w/o CH adapted to NL	2000-2022	Adapted to include 100% CO2 capture and use for enrichment & Adapted to represent a Jenbacher J624	Tomato World*	Cost of CO2 from CHP
3	CO2 capture and transport from OCAP	P21244	NA	CO2 capture and transport	Based on NL	Assumed between 2018-2025	Assumed representative	https://www.tomatoworld.nl/media/1857/ocap_factsheet_english_tcm978-561158.pdf	Cost of CO2 Capture and Storage
4	Market for greenhouse	P21241	P19647	NA	Based on GLO adapted to NL	2015-2022	Assumed representative	NA	Adapted the metal and plastic tubes to be produced the Netherlands
5	Greenhouse construction, glass walls and roof, metal tubes	P21242	P19604	NA	Based on FR adapted to NL	2005-2022	Adapted electricity provision to NL & Adapted Waste concrete treatment to RER w/o CH	NA	
6	Greenhouse construction, glass walls and roof, plastic tubes	P21243	P19606	NA	Based on FR adapted to NL	2005-2022	Adapted electricity provision to NL & Adapted Waste concrete treatment to RER w/o CH	NA	
7	Treatment of biowaste	P21245	P17259	NA	Based on CH adapted to NL	2011-2022	Adapted electricity provision to NL & Adapted waste treatment to NL & Adapted waste water to RER w/o CH	Delphy*	
8	Waste CO2 as fossil	P21246	NA	Treatment of CO2	Based on NL	Assumed around 2020	Assumed representative	NA	This process only outputs CO2 to define it as a waste product. Other in and outputs are attributed to the CO2 from OCAP. Other products, resources used or emissions are cut-off since they would not be allocated to the CO2.
9	CO2 from OCAP at lower input (copy)	P21267	NA	CO2 capture and transport	Based on NL	Assumed between 2018-2025	Assumed representative	NA	Same as the CO2 from OCAP however the ammount of CO2 lost to the environment has been reduced to 72% instead of 87.5% to replicate the non linear uptake by biogenic crops
10	carbon dioxide production, liquid | carbon dioxide, liquid | Cutoff, U (copy)	P21268	P05427	NA	RER	2011-2015	Assumed representative	NA	This process is a copy of liquification of CO2 as a process for the production of CO2 for OCAP

Note. This table presents the unit process breakdown for tomato production using a CHP system with OCAP-sourced CO_2, corresponding to the flowchart in Figure 5. It includes adapted foreground processes, product numbers, data sources, and geographic and temporal representations. These unit processes form the basis for the life cycle inventory in OpenLCA.

Each unit process described in the foreground table is documented using a structured format that includes:

- Quantitative flow data: All material and energy flows are expressed in standardized units (e.g., MJ, kg, kWh).
- The provider flow: Indicating where materials are sourced from in the supply chain, including their product number and geographical representation.
- Data sources and assumptions: Where applicable, each flow is accompanied by a citation or explanation of the modelling assumption used. This includes scaling factors, proxy selections, and regional adjustments.

Figure 14 illustrates how unit processes are broken down into their respective inputs and outputs, along with associated data sources and assumptions. This format is consistently applied across all custom foreground processes developed for this thesis.

Figure 14

Unit Process Breakdown for CO2 capture and transport from OCAP

Unit process: CO2 capture and transport from OCAP
P number: P21244

<table>
<tr><td colspan="8">Economic flows, in:</td></tr>
<tr><td>Amount</td><td>Unit</td><td>Flow Name</td><td>Provider</td><td>Provider P number</td><td>Location</td><td>Data source</td><td>Additional documentation</td></tr>
<tr><td>1.37E-7</td><td>Item(s)</td><td>liquid storage tank, chemicals, organics</td><td>liquid storage tank production, chemicals, organics | liquid storage tank, chemicals, organics | Cutoff, U (copy) - RoW</td><td>P09315</td><td>RoW</td><td>https://www.tomatoworld.nl/media/1857/ocap_factsheet_english_tcm978-561158.pdf</td><td></td></tr>
<tr><td>2.28E-6</td><td>km</td><td>polyethylene pipe, DN 200, SDR 41</td><td>polyethylene pipe production, DN 200, SDR 41 | polyethylene pipe, DN 200, SDR 41 | Cutoff, U (copy) - RER</td><td>P10571</td><td>RER</td><td>https://www.researchgate.net/publication/272380887_Start_of_a_CO2_Hub_in_Rotterdam_Connecting_CCS_and_CCU?enrichId=rgreq-d8848a2e2d74576cedd691c5993c19c3-XXX&enrichSource=Y292ZXJQYWdlOzI3MjM4MDg4NztBUzoyMjg1NDQ3NjA1MTI1MTNAMTQzMTUwMDcyNTUzOQ%3D%3D&el=1_x_2</td><td></td></tr>
<tr><td>0.096</td><td>t*km</td><td>transport, freight, lorry >32 metric ton, EURO6</td><td>transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, U (copy) - RER</td><td>P20892</td><td>RER</td><td>https://www.tomatoworld.nl/media/1857/ocap_factsheet_english_tcm978-561158.pdf</td><td></td></tr>
<tr><td>1.0</td><td>kg</td><td>Fossil CO2 (waste)</td><td>carbon dioxide production, liquid | carbon dioxide, liquid | Cutoff, U (copy)</td><td>P21268</td><td>NL</td><td></td><td>CO2 captured at production from Shell & Alco</td></tr>
<tr><td colspan="8">Economic flows, out:</td></tr>
<tr><td>Amount</td><td>Unit</td><td>Flow Name</td><td>Provider</td><td>Provider P number</td><td>Location</td><td>Data source</td><td>Additional documentation</td></tr>
<tr><td>1.0</td><td>kg</td><td>CO2 (OCAP)</td><td>CO2 capture and transport from OCAP</td><td>P21244</td><td>NL</td><td>https://www.tomatoworld.nl/media/1857/ocap_factsheet_english_tcm978-561158.pdf</td><td>CO2 to enrich the crop</td></tr>
<tr><td colspan="8">Environmental flows, in</td></tr>
<tr><td>Amount</td><td>Unit</td><td>Flow Name</td><td>Compartment</td><td></td><td></td><td>Data source</td><td>Additional documentation</td></tr>
<tr><td colspan="8">Environmental flows, out</td></tr>
<tr><td>Amount</td><td>Unit</td><td>Flow Name</td><td>Compartment</td><td></td><td></td><td>Data source</td><td>Additional documentation</td></tr>
</table>

Note. This table shows the economic and environmental in and outflows in an individual foreground process. This process is the same as the one visually represented in Figure 2.

Where no direct Ecoinvent process exists, proxies are selected based on functional similarity and adjusted using sector-specific data. For instance, dehumidifiers are modelled using air-water heat pump proxies, and ATES systems are represented using deep well drilling and water pumps. These adaptations are documented in Appendix D, along with the rationale for each modelling choice, aligned with ISO 14040/44 standards.

5.1.5. Multifunctionality and Allocation

As mentioned, a key methodological challenge in Life Cycle Assessment (LCA) arises when dealing with multifunctional systems, which are processes that have multiple purposes. In the context of Dutch greenhouse horticulture, Combined Heat and Power (CHP) systems are an example, simultaneously generating heat, electricity, and usable CO_2 for crop enrichment. Alongside this, a location will also take place in the enrichment of tomatoes with CO2 provided via OCAP. It produces both CO2 used by the horticulture sector and simultaneously treats the waste produced by Shell and Alco. This multifunctionality necessitates a clear and consistent allocation strategy to distribute environmental burdens across co-products in a way that reflects their relative value or characteristics.

CHP allocation

This thesis adopts an economic allocation approach, in which emissions are distributed based on the market value of each output. This method is particularly appropriate when the physical properties of outputs are not directly comparable, such as between heat and CO_2. For the CHP allocation, the values were based on yield times price (see table 3). A visual representation of this allocation is also provided in Figure 15.

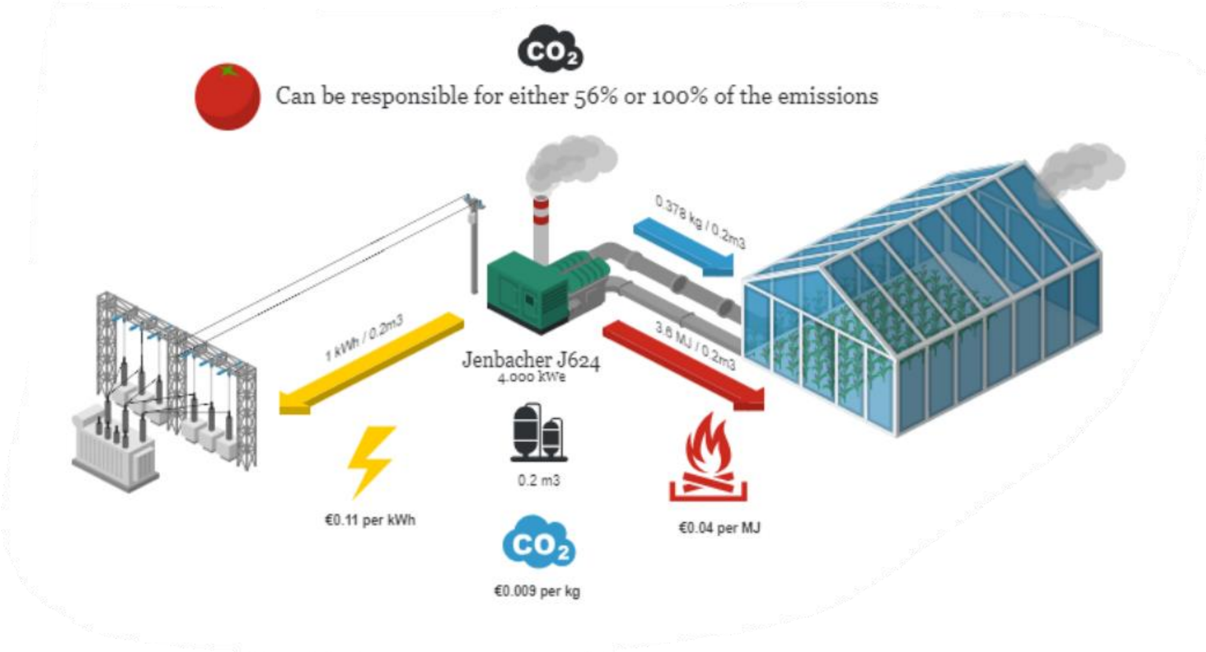
Table 3
Allocation of CHP Products by Economic Value in Tomato Cultivation (Jenbacher J624).

	Electricity (kWh)	Heat (MJ)	CO2 (kg)
Price per unit	€0.11	€0.04	€0.009
Produced per 0.2m3 of gas	1 kWh	3.6 MJ	0.378 kg
Allocation %	43%	56%	1%

Note. This table presents the economic allocation of the outputs generated by a Jenbacher J624 combined heat and power (CHP) unit used in greenhouse tomato production. The allocation is based on the market value of heat, electricity, and CO_2, and determines how environmental burdens are distributed across these coproducts.

Figure 15

Conceptual visualisation of economic allocation of CO2 emitted in the production of 1kg of tomatoes heated by CHP.



Note. This figure illustrates the economic allocation method used to attribute CO_2 emissions from the combined heat and power (CHP) system to the production of 1kg of tomatoes. Emissions are distributed among co-products based on their relative economic value, ensuring accurate representation in the life cycle inventory.

OCAP allocation

In addition to the allocation challenges posed by CHP systems, attributional complexity also arises with externally sourced CO_2 provided through OCAP. The CO_2 supplied via OCAP originates as a fossil-based waste stream from industrial emitters such as Shell and Alco. Initially, this CO_2 has no economic value. It only becomes a marketable product after undergoing capture, purification, and transport—processes that transform it from a waste stream into a usable good.

As a result, not all environmental impacts associated with the OCAP process are attributed to tomato production. A portion of the burden remains with the original emitters, reflecting the fact that the CO_2 would otherwise have been released into the atmosphere as industrial waste. This attribution is based on economic allocation principles, which distribute environmental burdens according to the market value of each output (see Table 4).

Table 4

Economic Allocation of CO_2 Used for Tomato Enrichment.

	Shell & Alco (OCAP)	**Tomato grower**
Cost of	(Treatment of waste CO2) €0.03	(CO2 bought from OCAP) €0.06
% of emitted CO2 the party is responsible for	33%	67%
kg of emitted fossil CO2 the party is responsible for	0.29	0.58 kg

Note. This table shows the economic allocation of CO_2 used for enrichment in the production of 1 kg of greenhouse tomatoes. The allocation is based on the market value of CO_2 as an input and disposal, determining its share of environmental burdens in life cycle modelling.

However, this assumption is contingent on current industrial practices. If Shell and Alco begin storing their CO_2 rather than emitting it, the environmental burden associated with its release would shift. In that case, the tomato grower's use of the CO_2 would represent a new emission rather than a diverted waste stream, and the full environmental impact would need to be attributed to the horticultural system.

Fossil vs Biogenic CO_2 Modelling

The fate of the CO_2 after enrichment introduces even further complexity. While a portion is absorbed by plants and thus treated as biogenic CO2, a significant share of up to 87.5% is vented back into the atmosphere (Vermeulen & Lans, 2011). This vented CO_2 is attributed to the grower, and not back to the original suppliers of OCAP. This is consistent with Ecoinvent conventions and LCA best practices. The biogenically uptake amount of 12.5% is in line with molecular calculations of biogenic CO2 uptake by tomatoes (Gutiérrez-Cabanillas et al., 2024).

Lack of allocation in the sector

The sector's current accounting practices often oversimplify emissions attribution, leading to unfair and incomplete assessments. Typically, emissions are calculated by multiplying natural gas consumption by a fixed CO_2 emission factor, and any reduction in gas use is credited as a direct CO_2 savings.

For example Glastuinbouw Nederland reports that 900 million cubic meters of natural gas are saved annually, resulting in an estimated 1.6 megatons of CO_2 emissions avoided (*Investeringsplan Energietransitie Glastuinbouw*, n.d.). However, this calculation assumes that the gas would have been used solely for heat production. In reality, when natural gas is burned in a combined heat and power (CHP) system, it produces both heat and electricity. That same volume of gas could generate approximately 1.62×10^{10} MJ of heat and 4.5×10^{9} kWh of electricity.

While the heat is used for greenhouse heating, the electricity is often surplus and sold to external users. Yet the sector's accounting method ignores this electricity output entirely. It attributes all the CO_2 emissions to the heat, as if the electricity were never produced. This creates a misleading picture that overstates the emissions savings from geothermal heating and fails to recognize that part of the environmental burden should be allocated to the electricity consumers. By neglecting the electricity co-product, the sector's method misrepresents the true distribution of environmental responsibility and introduces inconsistencies into sustainability assessments.

5.2. Inventory Results

The inventory analysis compiled approximately 250 environmental inflows and over 1,900 outflows for each modelled energy scenario. These inventories include detailed data on energy inputs, material use, infrastructure, and emissions, forming the foundation for the subsequent impact assessment.

In the CHP-based production system, natural gas is the dominant input and the primary source of greenhouse gas emissions. In contrast, the geothermal system demonstrates significantly lower direct fossil-based emissions yet exhibits a much higher water input, about fourteen times greater than that of the CHP system.

Each scenario's inventory reflects the specific configuration of heating technologies, CO_2 enrichment strategies, and supporting infrastructure. The full list of inventory flows is provided in Appendix E.

5.3. Resource Risk Results

The resource risk analysis highlights key insights into the material dependencies introduced by different energy transition pathways. These insights are derived from comparing the presence and relative importance of critical raw materials (CRMs) across scenarios. The assessment evaluates the total mass of specific resources embedded in the system inventories. By quantifying the material inputs required, the analysis reveals how shifts in energy sourcing affect exposure to resource-related risks.

Table 5 provides an overview of the resource risk results, showing the comparative demand for CRMs across scenarios. It illustrates which materials become more prominent in low-carbon alternatives and serves as the basis for identifying potential vulnerabilities. These vulnerabilities are assessed qualitatively, by examining the dominance of single suppliers and the global production volumes of each material.

Table 5

Percentage Increase in Resource Demand for Fossil-Free Tomato Systems Compared to CHP.

Resource	Geothermal (%)	Heat Network (%)	Heat Pump (SOLE) (%)	Heat Pump (WKO) (%)	Heat Pump (DEH) (%)	Solar (IND) (%)	Solar (BAT) (%)
Gallium	-6,9	-4,8	-1,7	-2,1	11,3	-4,2	-1,5
Niobium	-22,7	-22,9	-32,0	-29,6	-26,1	-32,4	-31,9
Rhodium	-33,6	-28,3	-18,4	-19,7	-17,6	-33,7	-31,2
Mercury	9,5	20423,8	15,2	14,8	19,0	17,1	21,9
Platinum	-27,5	-22,0	-9,4	-11,1	-8,7	-27,6	-25,2
Tellurium	45,8	56,5	101,1	95,9	100,7	46,9	49,2
Cobalt	60,0	68,1	101,8	98,2	103,5	60,3	62,0
Palladium	12,9	19,8	43,5	40,8	44,6	13,0	15,2
Gold	9,9	29,3	19,0	18,2	18,8	63,4	90,0
Boron	57,4	60,3	111,2	106,5	109,9	68,0	68,0
Tin	-21,6	-15,3	-13,9	-14,6	-13,9	-19,5	-15,7
Rhenium	45,8	56,9	101,5	95,6	100,4	46,8	49,2
Arsenic	45,9	56,8	102,4	95,6	100,7	47,1	49,3
Molybdenum	45,8	56,5	101,3	95,9	101,0	47,0	49,2
Uranium	9,4	28,1	1,9	2,4	3,5	2,6	3,3
Selenium	45,8	56,6	101,4	96,1	101,0	47,0	49,4
Lithium	0,3	0,3	0,3	0,3	0,3	0,3	6310,3

Note. This table presents the percentage increase in resource demand for fossil-free tomato production systems compared to the fossil-based CHP reference system. The comparison is based on the production of 1 kg of tomatoes and highlights the material intensity of alternative technologies. A negative value entails that there is a percentual decrease in the material demand if the CHP system is converted to the alternative.

Firstly, mercury appeared as a significant contributor in the heat network scenario. This is due to outdated data in the Ecoinvent 3.9.1 database, where hydrogen production still includes legacy processes using mercury-based filters. In practice, such technologies have largely been phased out (IEA, 2024). This result should therefore be interpreted with caution.

Secondly, electrically heated systems that rely on purchasing renewable electricity show a substantial increase in material demand. For many components, the demand for CRMs nearly doubles compared to fossil-based systems. This is primarily due to the upstream infrastructure required for renewable energy generation.

Thirdly, Solar involving battery storage shows a disproportionate increase in lithium demand. This aligns with broader concerns in the energy transition discourse, where lithium availability and supply chain concentration are increasingly scrutinized (Nature, 2025).

While the per-kilogram differences in material demand may appear modest, they become significant at commercial scale. For instance, a 30% increase in niobium or rhodium demand across multiple 5-hectare greenhouses could have notable implications, especially given the global market dominance of a few supplier countries (Nassar et al., 2020). Similarly, increased demand for cobalt and palladium in some electrified systems raises concerns about ethical sourcing and long-term supply chain stability (IEA, 2025b).

6

Impact Assessment

ReCiPe serves as the primary LCIA method, ensuring consistency with prior LCA studies on Dutch tomato production. It offers both midpoint and endpoint indicators, enabling detailed category-level analysis and broader aggregation into human health, ecosystems, and resource availability (Huijbregts et al., 2017).

The PEF method is used selectively, for assessing Abiotic Depletion Potential (ADP). This indicator is relevant given the sector's increasing reliance on electrification technologies that depend on critical raw materials (CRMs) (European Commission, 2021).

Each method uses distinct characterisation factors (CFs). ReCiPe's Surplus Ore Potential (SOP) focuses long-term effort required to extract lower-grade ores or resources, while PEF's ADP focuses on the long-term production rates relative to known crustal content availability (van Oers et al., 2020; Vieira et al., 2017).

6.1. Characterisation

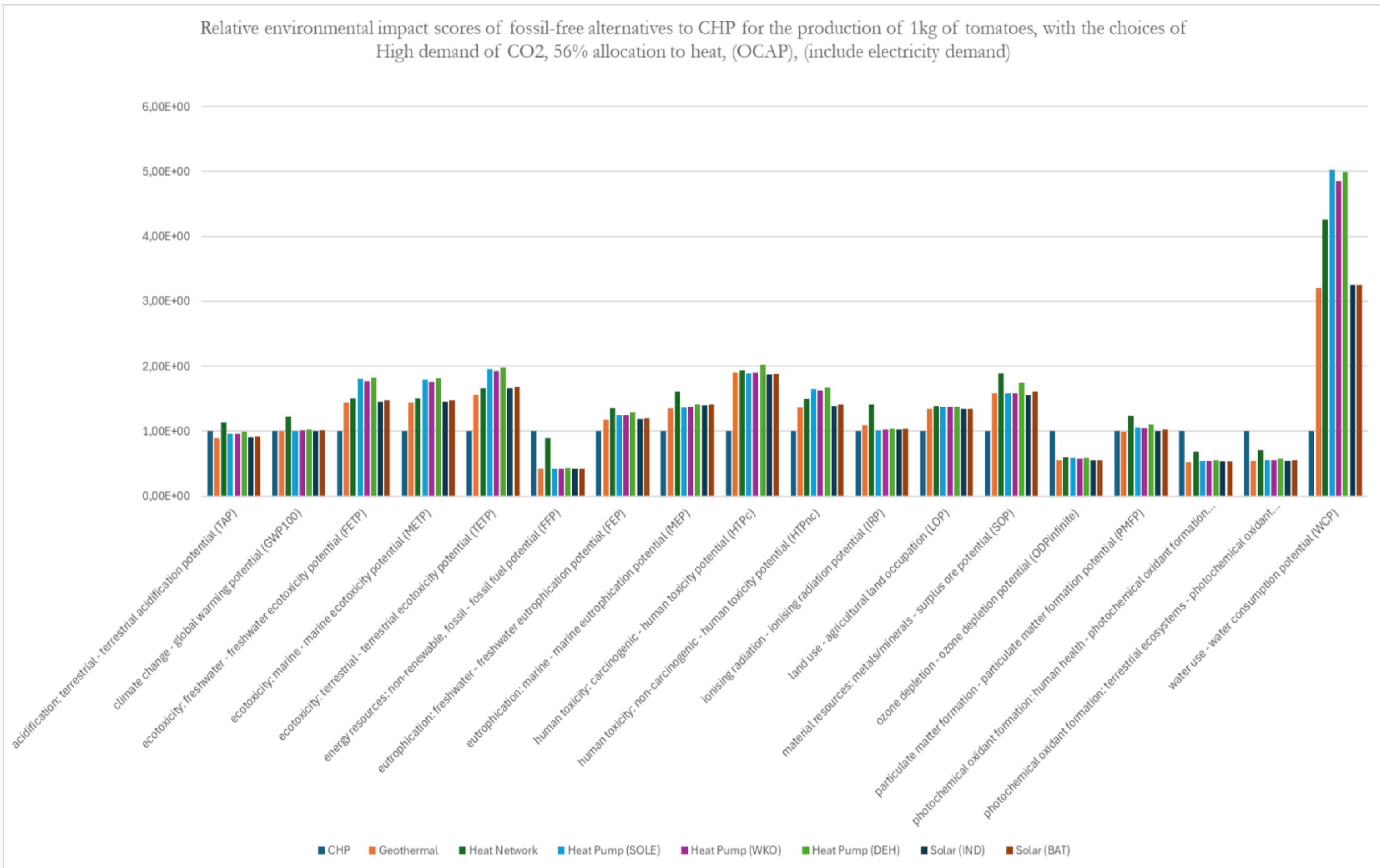
This section presents the characterised environmental impacts of tomato production using the ReCiPe 2016 method. ReCiPe provides midpoint indicators for a broad range of environmental impact categories, including climate change, fossil resource use, water consumption, eutrophication, and human toxicity (Huijbregts et al., 2017). Each emission or resource input is multiplied by a characterisation factor (CF) that reflects its relative contribution to a specific environmental burden. For example, 1 kg of methane has a higher CF for climate change than 1 kg of CO_2, due to its greater global warming potential over a 100-year timespan (IPCC, 2024). This translates inventory flows into impact scores, enabling comparison across categories such as climate change, fossil resource use, water consumption, and eutrophication. These results will form the foundation for the identification of environmental hotspots.

The characterisation results form the foundation for identifying environmental hotspots and evaluating trade-offs between different energy systems. Results are calculated for each of the eight modelled energy scenarios and further explored through sensitivity analyses that vary CO_2 enrichment levels and allocation assumptions. Impacts are expressed in equivalent units such as kg CO_2-eq for climate change and kg Sb-eq for resource depletion, to allow for consistent comparison.

The characterisation results reveal that no single energy system is environmentally superior across all categories. Electrification reduces climate impacts but introduces trade-offs in water use and resource depletion. For climate change, which is one of the sector's primary concerns, the CO_2 emissions from alternative sources are only marginally lower than those from combined heat and power (CHP). This is largely due to enrichment-related emissions, which offset much of the climate benefit of switching energy sources. Figure 16 visualises the characterised results across impact categories, comparing each fossil-free system relative to the CHP-based reference. In this chart, the CHP system is set to one, allowing for easy comparison of relative performance.

Figure 16

Characterised LCA Results for Fossil-Free Tomato Systems Relative to CHP.



Note. This chart gives Characterised life cycle impact assessment (LCIA) results for fossil-free tomato production systems, shown relative to the CHP-based reference system. The figure compares environmental impacts across multiple categories, where the CHP based alternative is always set to one. The exact values can be found in Table A1 [Appendix A](#)

These results highlight the complexity of environmental decision-making in greenhouse horticulture. While electrification appears promising for reducing fossil fuel use, it may exacerbate other environmental pressures. Crucially, although the primary goal of electrification is to reduce greenhouse gas (GHG) emissions, the characterisation results show that overall climate impacts remain largely unchanged. This is problematic, as the shift away from fossil fuels is largely motivated by the desire to lower the sector's carbon footprint. If CO_2 emissions remain constant despite electrification, the environmental trade-offs may not justify the transition. Chapter 7 (Interpretation) further explores this issue by examining process contributions, shedding light on why GHG emissions are not significantly reduced.

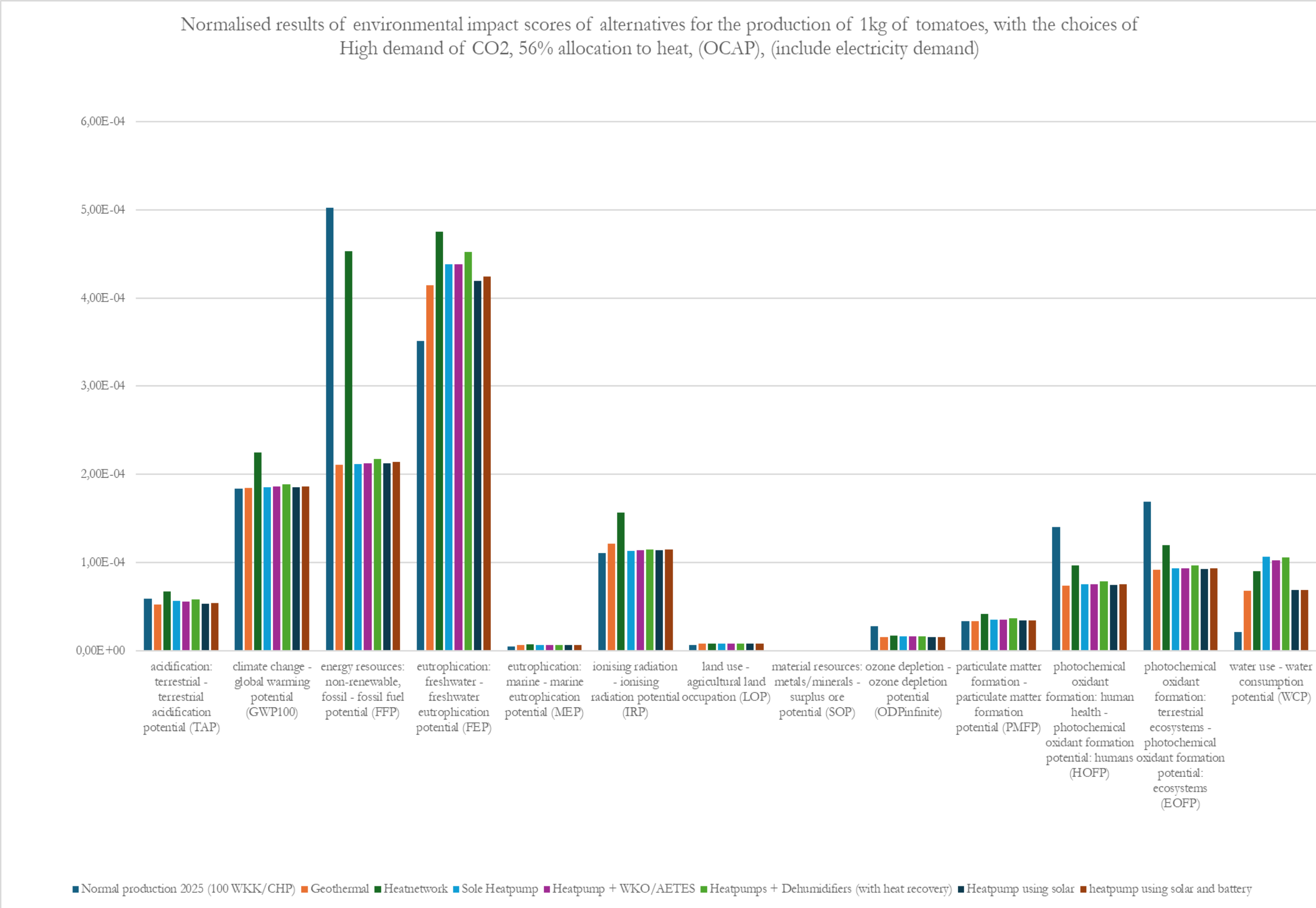
6.2. Normalisation

Normalisation is an important step in Life Cycle Impact Assessment (LCIA) that helps contextualise the characterised results by expressing them relative to a reference situation. While normalisation is a subjective weighing step, expressing characterised impact scores into a common unit, it also enables a more direct comparison across different impact categories. The ReCiPe 2016 normalisation factors applied here are based on the average per capita environmental footprint in Europe for the year 2010 (Huijbregts et al., 2017). By using the global average as the reference, the normalised results reflect the relative contribution of the functional unit to global environmental issues. This allows for the identification of impact categories where tomato production has a disproportionate contribution (European Commission, n.d.).

The normalised results reveal that categories such as eutrophication, fossil resource use, and climate change dominate the impact profiles across all scenarios. Water use becomes particularly prominent in electrified systems, especially those relying on renewable electricity. These categories are therefore partially prioritised in the contribution analysis and in the design of the Excel-based decision-support tool. Other categories, including eco- and human toxicity, are also significant. However they are excluded due to large uncertainties in their normalisation factors and limited actionability for stakeholders (Crenna et al., 2019). The normalized results are visualised in Figure 17.

Figure 17

Normalized LCIA Results Across Systems for 1kg of Tomatoes.



Note. The chart presents the normalized life cycle impact assessment (LCIA) results for the production of 1 kg of tomatoes, calculated using the ReCiPe 2016 method at the midpoint level. The full table of results can be found in Table A2 in Appendix A.

These findings highlight that environmental performance in the horticulture sector cannot be assessed through carbon metrics alone. While climate neutrality remains a central goal, the prominence of eutrophication, water use, and other categories with high relative impacts suggests that problem-shifting is a real risk. In particular, freshwater eutrophication emerges as a disproportionately high-impact category, indicating that nutrient-related emissions may pose significant environmental challenges.

This has important implications for sustainability planning. If the sector focuses exclusively on reducing fossil fuel use and greenhouse gas emissions, it may inadvertently increase pressure on aquatic ecosystems or intensify resource depletion. A narrow framing of climate neutrality could therefore undermine broader environmental goals.

6.3. Missing CF and Flows

Despite the comprehensive coverage of environmental flows in the ReCiPe 2016 and PEF methods, certain limitations remain due to missing characterisation factors (CFs) and uncharacterised flows in the Ecoinvent 3.9.1 database (Huijbregts et al., 2017). These gaps can affect the completeness, comparability, and interpretability of the impact results, particularly in foreground processes where emissions or resource flows are only partially represented.

This issue is especially relevant for emerging technologies and trace materials used in batteries, solar panels, and CO_2 capture systems. Scenarios involving newer, more complex technologies may appear environmentally cleaner than they truly are, due to incomplete representation of rare earth elements, specialty chemicals, and advanced electronics, which lack full CF coverage.

Notably, the CO_2 capture and enrichment processes modelled do not include all capital goods required for capture and purification infrastructure. As a result, this alternative may appear to have lower impacts than it actually does, introducing a systematic bias in comparative assessments.

These exclusions and cut-offs are not expected to drastically alter the comparative conclusions for climate change and fossil fuel use, which remain robust. However, they do introduce uncertainty in absolute impact scores.

These limitations underscore the need for continued development of life cycle databases and impact assessment methods to better capture the environmental profiles of emerging technologies. The next chapter further highlights the discrepancies between the alternatives and to what degree the systems differ.

7

Interpretation

This chapter synthesizes the results presented in Chapter 6 and provides a deeper analysis of their implications. It examines the consistency, the contributions to environmental impacts, explores trade-offs between scenarios, and reflects on the robustness of the findings in light of methodological choices.

7.1 Consistency and Completeness

Ensuring methodological consistency and data completeness is essential for the validity of comparative Life Cycle Assessments (LCAs). Consistency refers to the uniform application of modelling assumptions, system boundaries, allocation methods, and data sources across all energy scenarios. Completeness refers to the extent to which all relevant environmental flows, processes, and impacts are included in the analysis.

Key modelling choices were applied consistently across scenarios:

- Economic allocation was used for multifunctional systems (CHP, CO2 enrichment and hydrogen production), distributing consumed goods, produced wastes, emissions and extractions based on market value.
- CO_2 enrichment was modelled using a baseline demand of 1.2 kg CO_2/kg tomato, with sensitivity analyses at 0.53 kg and 0 kg to reflect stakeholder perspectives.
- Electricity sourcing was assumed to be from renewable sources, with sensitivity results to reflect the current grid mix or battery storage.
- The same foreground processes were adapted from Ecoinvent 3.9.1 and modified to reflect Dutch conditions, ensuring regional consistency.

While the LCA includes over 2,000 environmental flows per scenario, some limitations remain. For example some alternatives might look favourable in specific categories like water use, due to an absence of renewable energy usage. The energy mix used was that of Switzerland which gets part of its renewable energy from hydroelectric dams. This requires large water reservoirs that make the use of fully electrified systems using renewables seem more problematic than the systems who do not make use of it. Other limitations which may affect the compatibility are:

- Capital goods (e.g., geothermal wells, solar panels, batteries) which are included where data is available, excludes some auxiliary infrastructure (e.g., control systems, minor piping) due to data gaps.

- CO_2 enrichment infrastructure which are modelled using proxies (e.g., OCAP pipelines), of which not all purification and compression steps are fully represented.
- Water use and toxicity, which are included in the impact assessment, however lacks characterization factors, particularly for emerging technologies and trace metals.
- Seasonal variation in energy demand and CO_2 uptake which are not modelled dynamically, which may affect the accuracy of annualized results.

To ensure the reliability and comparability of environmental assessments, it is essential to maintain methodological consistency across life cycle assessment (LCA) models. Table 6 provides an overview of key modelling choices made in the evaluation of tomato production systems.

Table 6
Assessment of Methodological Consistency in LCA Modelling of Tomato Production.

	Reliability	Completeness	Temporal coverage	Geographical coverage	Technological coverage
CHP	Very high	High	High	Very high	Very high
Geothermal	High	Medium	High	High	High
Heat Network	High	Medium	Medium	High	Medium
Heat Pump (SOLE)	High	Medium	Medium	High	High
Heat Pump (WKO)	High	Medium	Medium	High	High
Heat Pump (DEH)	High	Medium	Medium	High	Medium
Solar (IND)	High	Medium	High	Medium	High
Solar (BAT)	Medium	Medium	Medium	Medium	Medium
Consistency	Mostly consistent	Mostly consistent	Mostly consistent	Somewhat consistent	Somewhat consistent

Note. This table evaluates the consistency of methodological choices in life cycle assessment (LCA) models for tomato production, scoring them from very low to very high. An expanded version with explanations per score can be found in the UPR in APPENDIX D.

Table 6 highlights that while most systems achieve high reliability and geographical coverage, completeness and consistency vary. Across the eight modelled energy scenarios, several patterns emerged regarding data quality, modelling assumptions, and representativeness. The baseline CHP scenario is the most robust, benefiting from recent and region-specific data. Most alternative systems are modelled with reasonable accuracy but rely on proxies or assumptions that introduce slight inconsistency.

7.2. Contribution - Process

Characterisation and normalisation provide insight into the overall magnitude and relative importance of impact categories. They do not reveal where impacts originate within the system. The contribution analysis addresses this by identifying the main contributors to each impact category.

One of the primary motivations for energy transition in the horticulture sector is the reduction of fossil fuel use. This section identifies the most impactful processes across key environmental categories, based on a contribution analysis. These categories which are selected for their high normalisation scores and relevance to sectoral goals include: non-renewable energy use, material resource demand, water consumption, freshwater eutrophication, and climate change.

Table 7 gives an overview of the most impactful process within these categories. Appendix F gives an extended overview of the top three contributing processes.

Table 7

Dominant Process Contributors per Impact Category in Tomato Production.

	CHP		Geothermal		Heat network		Heat pump		Heat pump + WKO		Heat pump + dehumidifers		Solar panels		Solar panels + batteries	
Impact category	*Process with the largest contibution*	*%*	*Process with the largest contibution*	*%*	*Process with the largest contibution*	*%*	*Process with the largest contibution*	*%*	*Process with the largest contibution*	*%*	*Process with the largest contibution*	*%*	*Process with the largest contibution*	*%*	*Process with the largest contibution*	*%*
energy resources: non-renewable	petroleum and gas production, offshore | natural gas, high pressure	0,446	petroleum and gas production, offshore | natural gas, high pressure	0,188	hydrogen cracking, APME | hydrogen, liquid	0,518	petroleum and gas production, offshore | natural gas, high pressure	0,187	petroleum and gas production, offshore | natural gas, high pressure	0,188	petroleum and gas production, offshore | natural gas, high pressure	0,183	petroleum and gas production, offshore | natural gas, high pressure	0,188	petroleum and gas production, offshore | natural gas, high pressure	0,188
material resources: metals/minerals	rare earth element mine operation and beneficiation, bastnaesite and monazite ore | iron ore concentrate	0,627	rare earth element mine operation and beneficiation, bastnaesite and monazite ore	0,683	rare earth element mine operation and beneficiation, bastnaesite and monazite ore | iron ore concentrate	0,559	rare earth element mine operation and beneficiation, bastnaesite and monazite ore	0,668	rare earth element mine operation and beneficiation, bastnaesite and monazite ore	0,67	rare earth element mine operation and beneficiation, bastnaesite and monazite ore	0,685	rare earth element mine operation and beneficiation, bastnaesite and monazite ore	0,673	rare earth element mine operation and beneficiation, bastnaesite and monazite ore	0,655
Water use	Tomato production (2025 replication), fresh grade, in heated greenhouse	0,335	electricity production, hydro, reservoir, alpine region, renewable energy products | electricity, high voltage, renewable energy products	0,607	electricity production, hydro, reservoir, alpine region, renewable energy products | electricity, high voltage, renewable energy products	0,456	electricity production, hydro, reservoir, alpine region, renewable energy products | electricity, high voltage, renewable energy products	0,742	electricity production, hydro, reservoir, alpine region, renewable energy products | electricity, high voltage, renewable energy products	0,733	electricity production, hydro, reservoir, alpine region, renewable energy products | electricity, high voltage, renewable energy products	0,734	electricity production, hydro, reservoir, alpine region, renewable energy products | electricity, high voltage, renewable energy products	0,599	electricity production, hydro, reservoir, alpine region, renewable energy products | electricity, high voltage, renewable energy products	0,598
eutrophication: freshwater	treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining	0,461	treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining	0,452	treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining	0,416	treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining	0,439	treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining	0,439	treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining	0,441	treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining	0,456	treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining	0,443
Climate change	Heat and power co-generation (for the production of tomatoes), natural gas, 4MW electrical, lean burn | electricity, high voltage	0,47	CO2 from OCAP	0,478	CO2 from OCAP	0,392	CO2 from OCAP	0,475	CO2 from OCAP	0,474	CO2 from OCAP	0,468	CO2 from OCAP	0,476	CO2 from OCAP	0,474

Note. The table identifies the single most impactful process within each selected environmental category.

The analysis reveals that in many scenarios, the largest contributors to environmental impact are background processes, rather than direct activities within the greenhouse. This includes upstream emissions from electricity generation, material extraction, and infrastructure development. Figures 18 to 22 show how the most contributing process in each system compares to the total scores. In the energy and material impact categories heat networks stand out due to the modelling decision of the residual heat coming from the multifunctional hydrogen production. Since part of the heat is a by-product some significant environmental impacts related to hydrogen production are allocated to the growing of tomatoes in this system (see figures 18 & 19).

Figure 18

Energy Resource Impact Scores of All Alternatives for Tomato Production Systems.

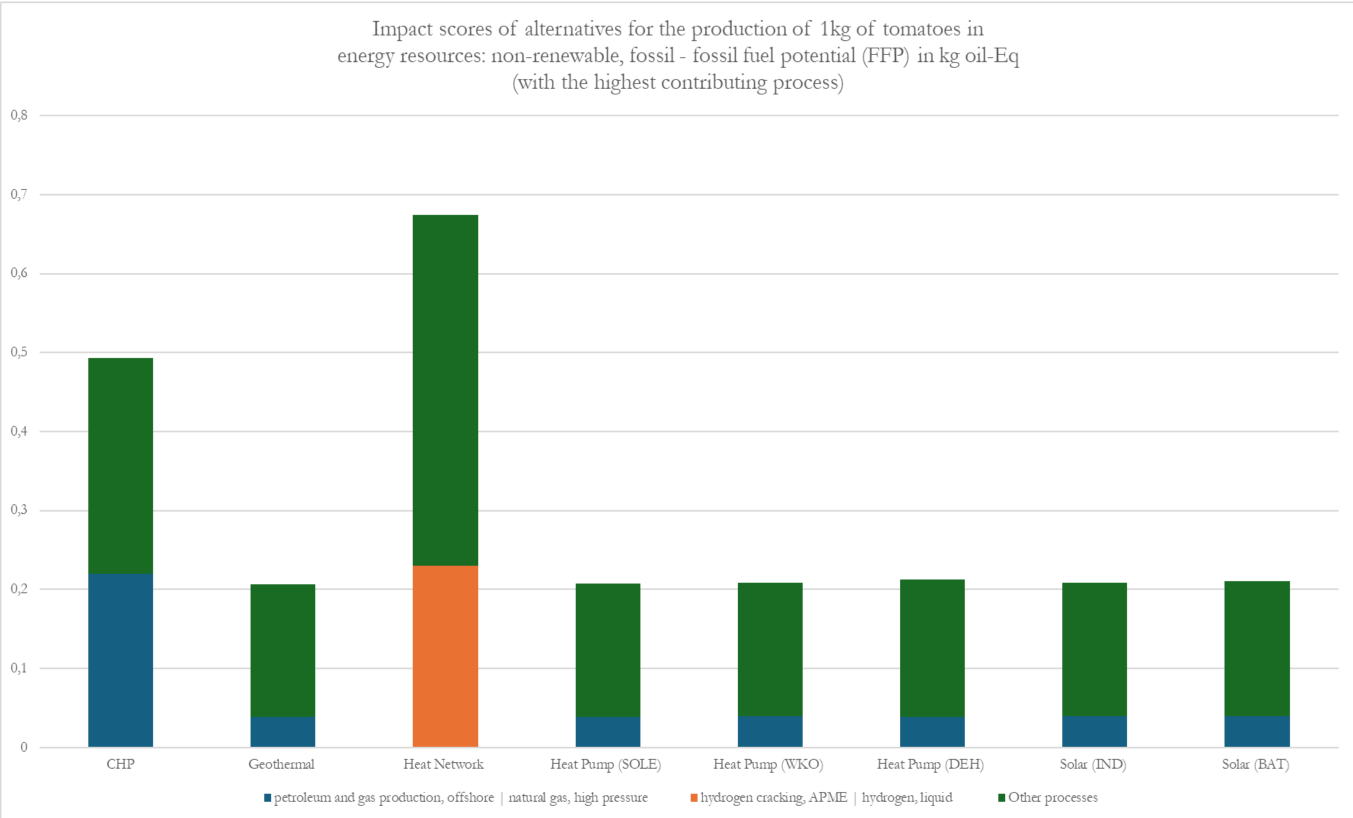
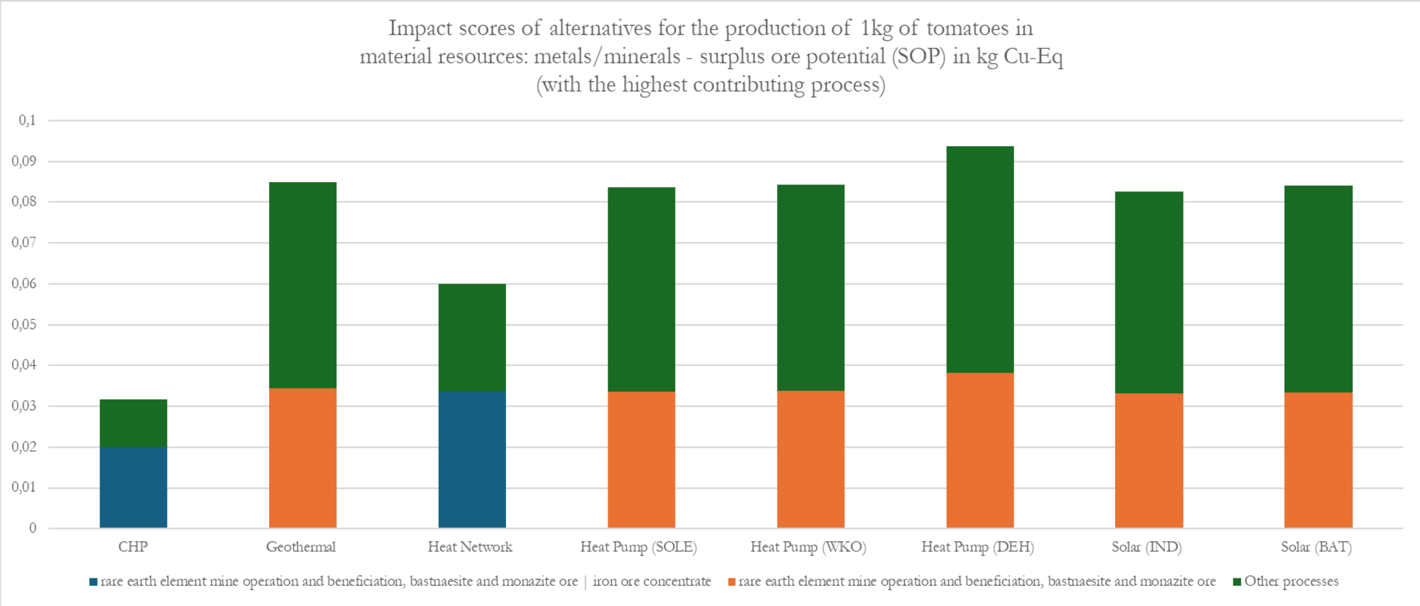


Figure 19

Material resource Impact Scores of All Alternatives for Tomato Production Systems.



Eutrophication and Climate change scores stay fairly stable across most alternatives while water use increases drastically across fossil-free systems (see figures 20, 21, 22) . The water use increase is in large part due to renewable electricity, which is a proxy from Switzerland which has hydropower. This is a limitation that is further discussed in Chapter 9. Discussion.

Figure 20

Water use Impact Scores of All Alternatives for Tomato Production Systems.

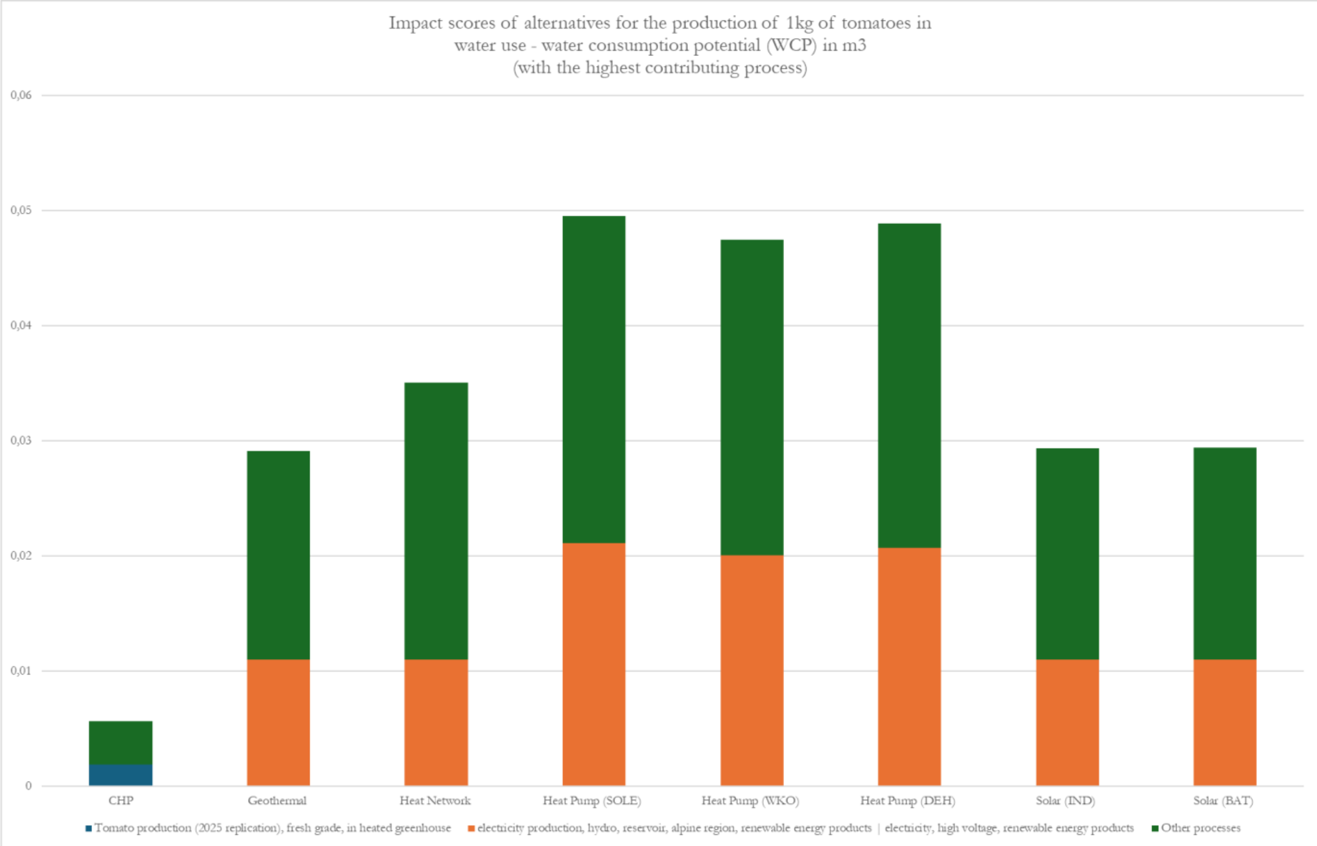


Figure 21

Eutrophication Impact Scores of All Alternatives for Tomato Production Systems.

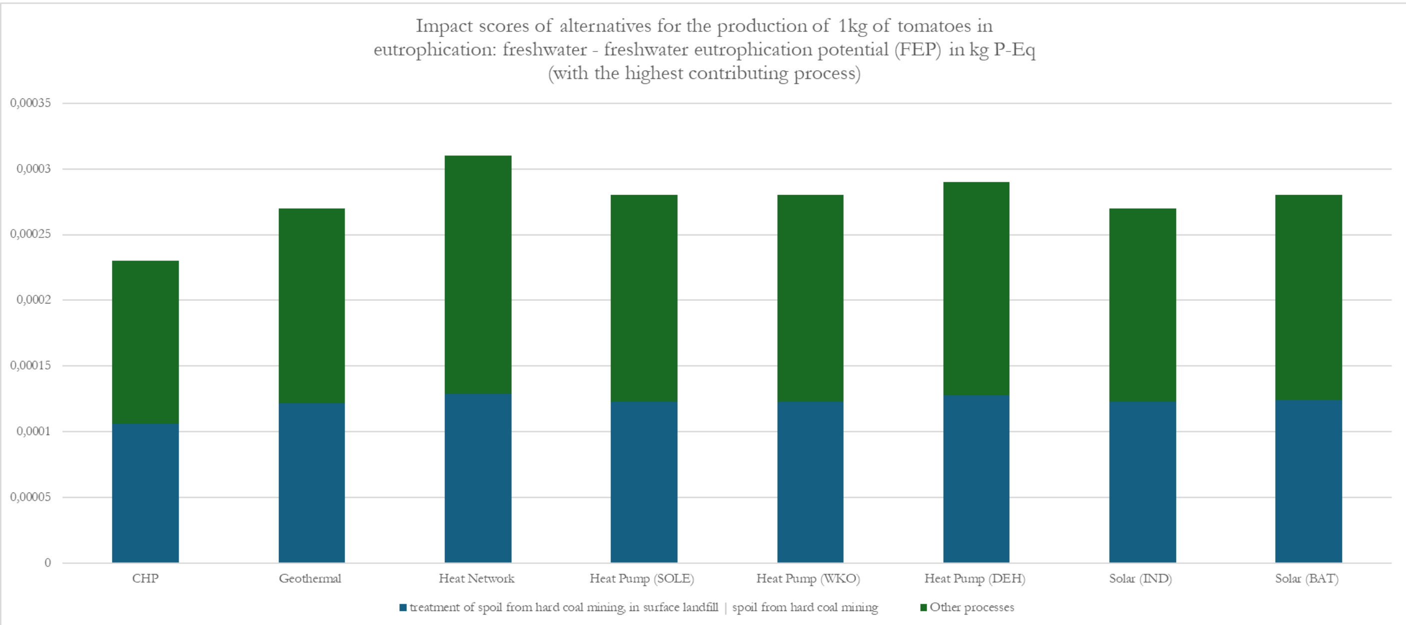
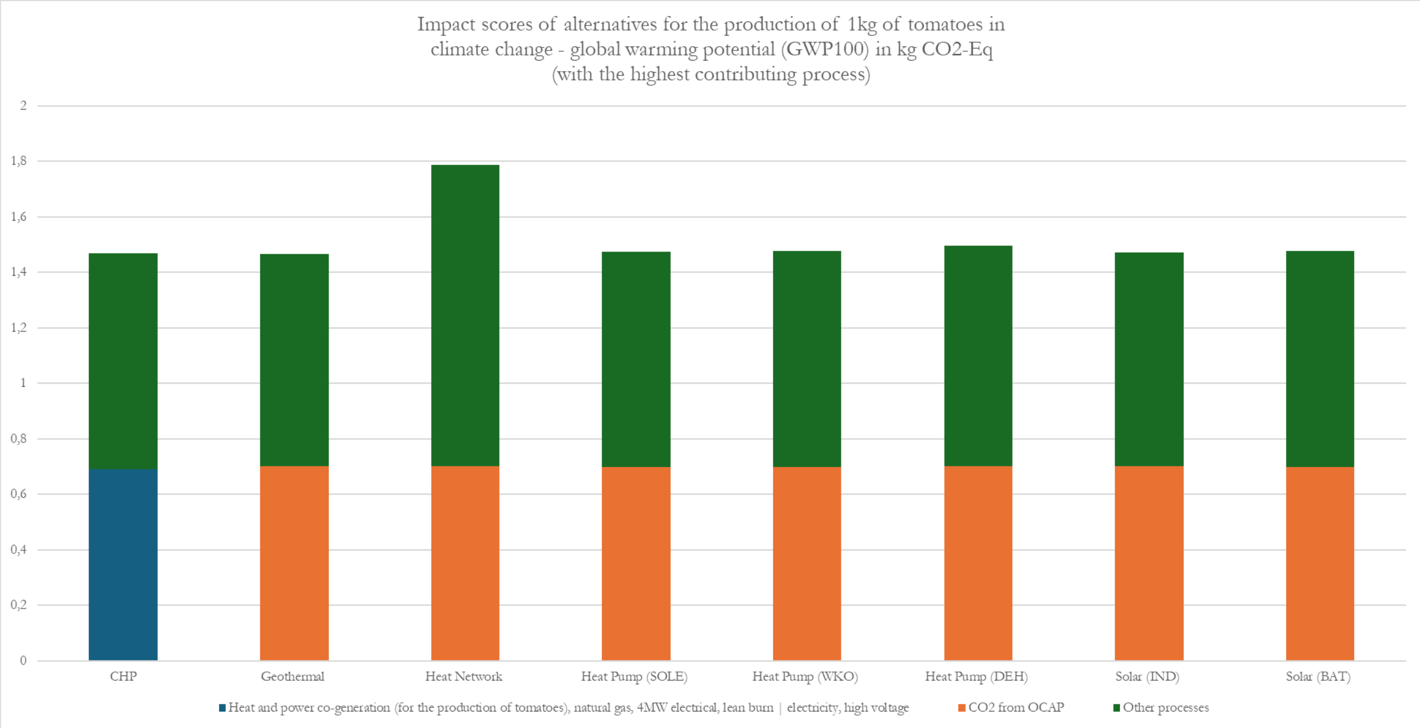


Figure 22

Climate change Impact Scores of All Alternatives for Tomato Production Systems.



Overall, the process contribution analysis highlights the importance of upstream processes, particularly electricity generation and infrastructure. The notable exception to the upstream contribution being the largest impact, is CO_2 enrichment, which remains a significant source of greenhouse gas emissions in fossil-free systems. Fossil fuels usage is by far the largest contribution to climate change as can be seen in the CHP alternative. While the CO2 is used to enrich tomatoes, the venting of CO2 remains. The CO2 produced by the generation of energy is still modelled as an emission from the burning of fossil fuels. Hence the CHP usage being the largest emission for climate change. For the fossil free systems the CO2 is no longer produced but still needed. Since the LCA is made to represent the CHP system as much as possible, an equal amount of CO2 is modelled to be bought and also vented. Meaning a similar amount of CO2 is emitted in this process. This enrichment exceeds the amount of CO2 produced by any other process within the alternative systems.

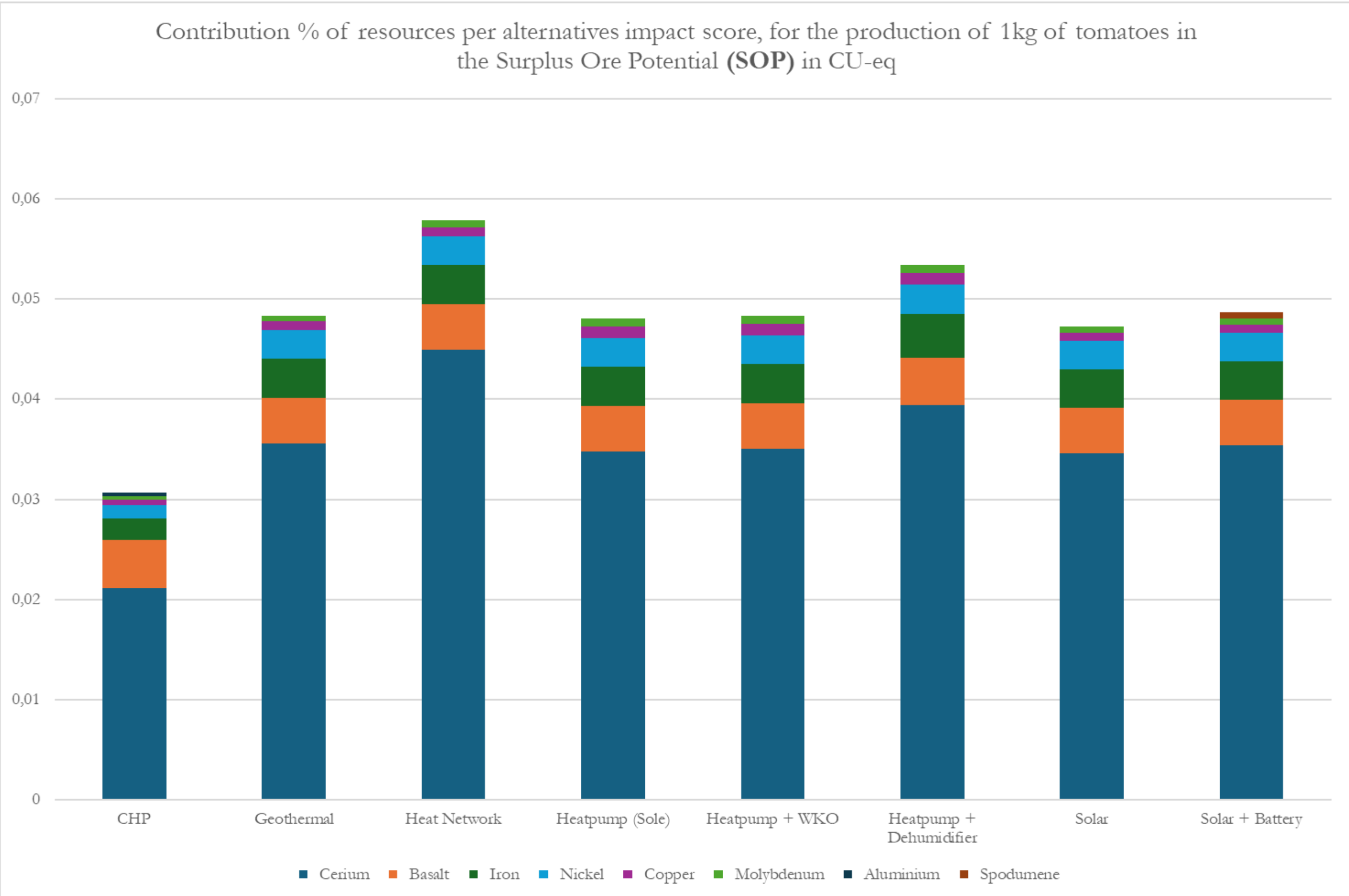
7.3. Contribution - environmental

While the previous section examined which processes contribute most to the overall environmental impacts, the environmental contribution analysis shifts the focus to the distribution of impacts across environmental categories. The abiotic resource depletion is the main focus for this analysis.

The environmental impact in abiotic resource depletion is not solely determined by the volume of material used, but also by its scarcity, economic importance, and difficulty of extraction. This can be seen when using the ReCiPe impact family, where the most significant contributors to material resource use were identified as cerium, basalt, and iron (see Figure 23). These scores come from the multiplication of the inventory of the resources (see Figure 24) with the characterization factor given to resources by the ReCiPe impact family. So while iron is the most voluminous flow, its low SOP characterisation factor results in a relatively minor impact. In contrast, cerium used in small quantities, has a disproportionately high impact due to its scarcity and extraction intensity.

Figure 23

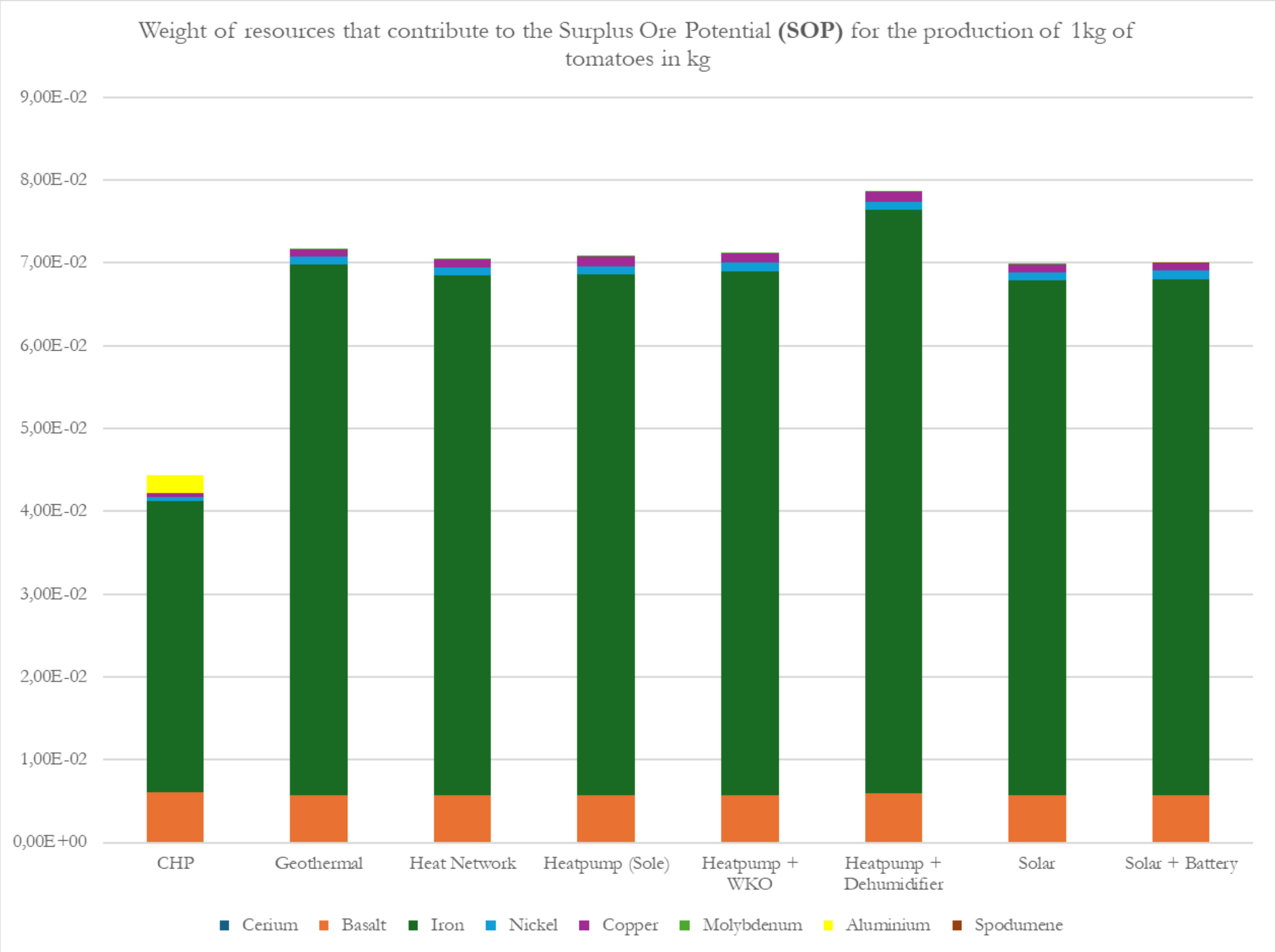
Top Resource Contributors to Surplus Ore Potential in Tomato Production (1kg).



Note. This figure shows the contribution of key materials to the Surplus Ore Potential (SOP) for the production of 1kg of tomatoes across all modeled systems.

Figure 24

Mass of Key Resources Driving SOP in Tomato Production (per kg).

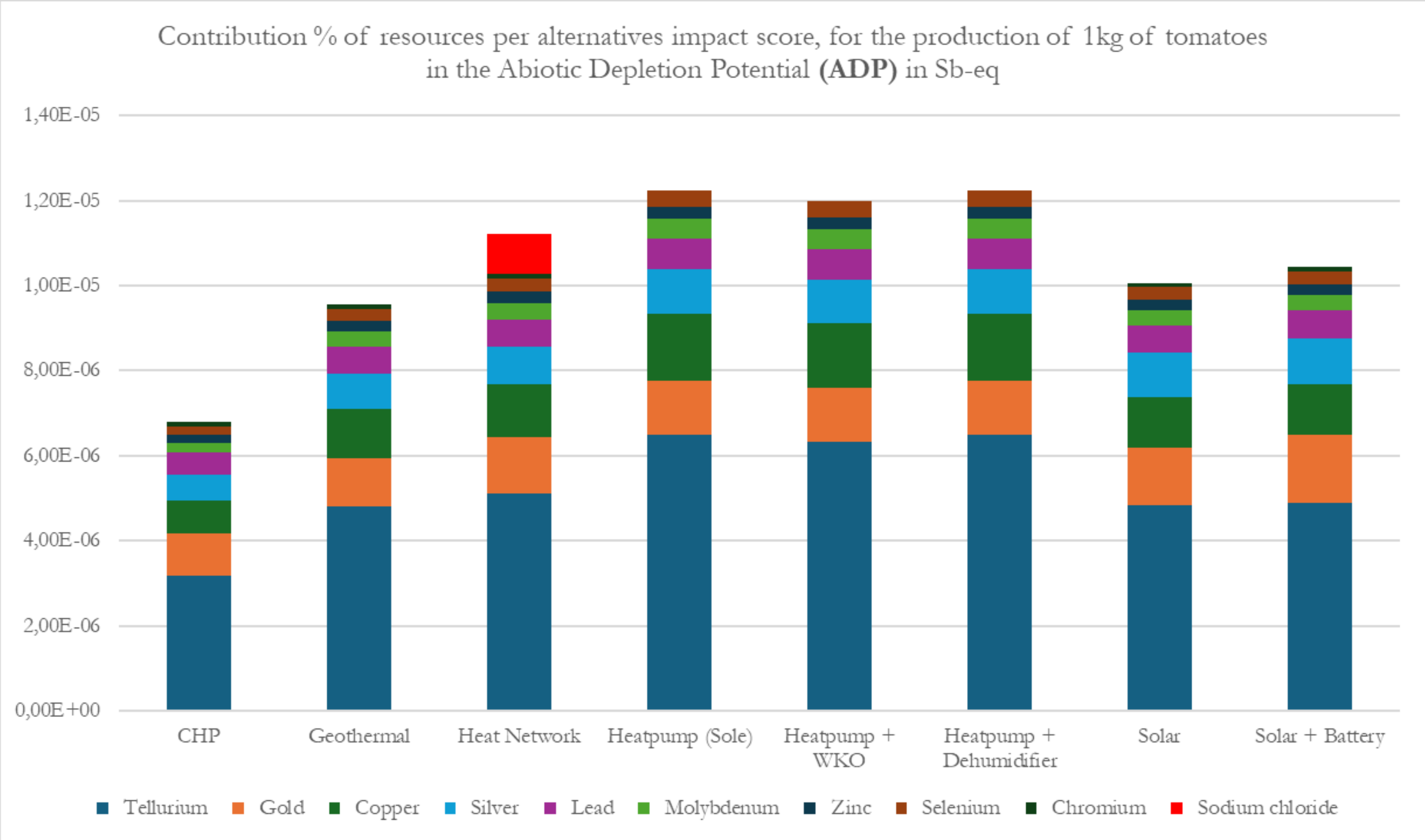


Note. This figure presents the absolute mass of the most influential materials contributing to the Surplus Ore Potential (SOP) for the production of 1kg of tomatoes.

The impact category of Abiotic Depletion as used in the EF method (using ADPs characterization factors), in contrast, highlights materials like tellurium, gold, and copper (see Figure 25). These are not flagged by SOP but are considered as significant due to their high depletion rates relative to known reserves (European Commission, 2021).

Figure 25

Top Resource Contributors to ADP in Tomato Production (1kg).

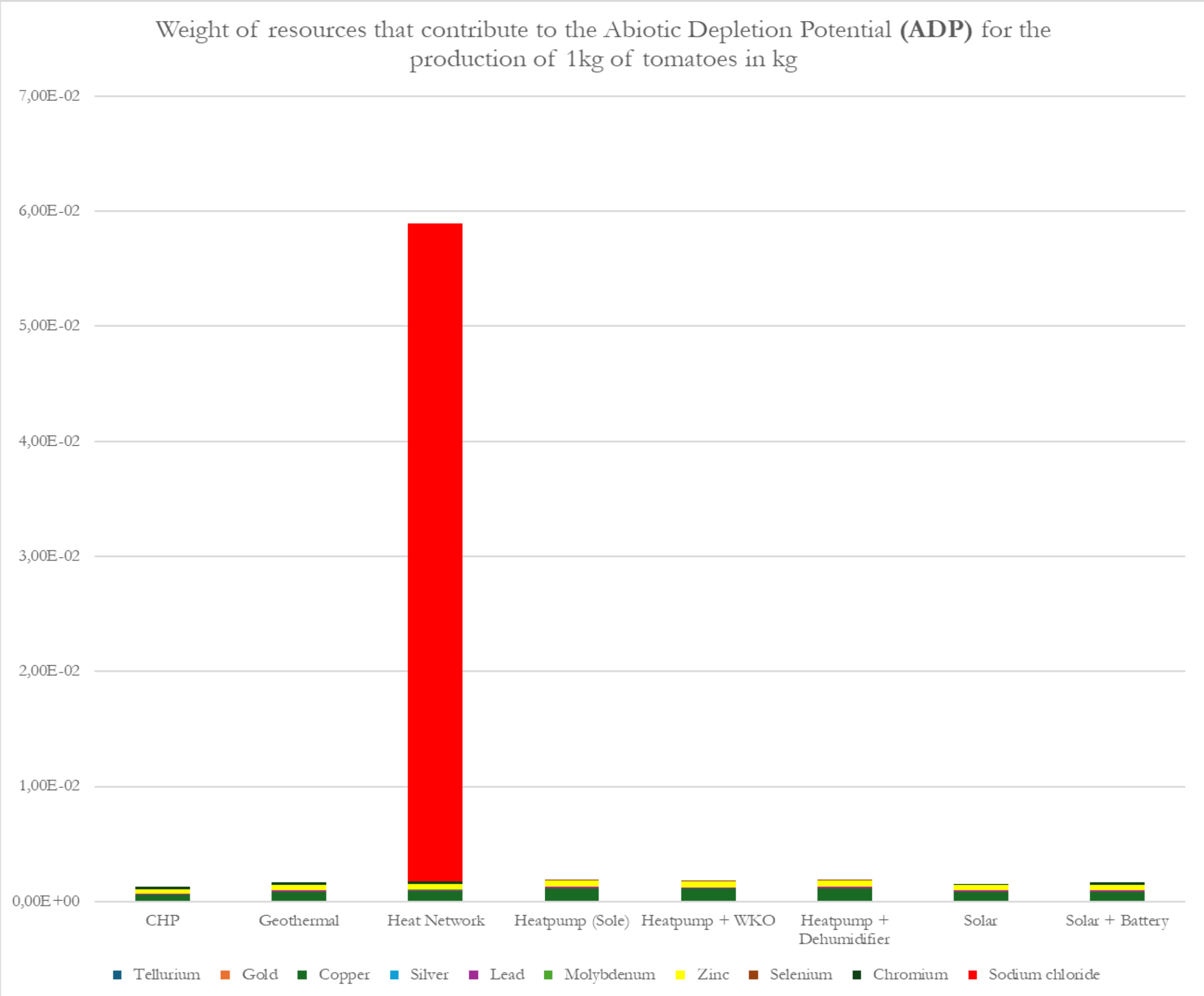


Note. This figure illustrates the contribution of key materials to the Abiotic Depletion Potential (ADP) for the production of 1kg of tomatoes across all systems.

This divergence between SOP and ADP underscores the importance of using multiple indicators to capture the full spectrum of resource-related risks. The interpretation of results for resource-related impact categories, depends heavily on the underlying problem definition of the assessment method used. Different models conceptualise resource use in different ways. For example, sodium chloride appears in large quantities due to its use in hydrogen production (see figure 26), yet contributes minimally to resource depletion under ADP due to its abundance and low scarcity-based weighting. Which highlights how certain substances may dominate inventory flows without significantly influencing impact scores.

Figure 26

Mass of Key Resources Driving ADP in Tomato Production (per kg).



Note. This figure presents the absolute mass of the most influential materials contributing to the Abiotic Depletion Potential (ADP) for the production of 1kg of tomatoes.

The comparison between SOP and ADP reveals that resource-related impacts are highly dependent on the chosen assessment method. This demonstrates the need for multi-indicator approaches to avoid overlooking critical resource risks. For decision-makers in greenhouse infrastructure and energy planning, this means considering both material volume and strategic importance when evaluating sustainability trade-offs.

7.4. Sensitivity analysis

The allocation and modelling choices made in this study significantly influence the comparative results of different energy systems, and reflect different perspectives on what fair attributions are. Neglecting the co-products of electricity and CO2, and attributing all emissions to heat causes Combined Heat and Power (CHP) systems to appear more polluting. Since part of the emissions are no longer moved outside of the system boundary, the heating of tomatoes is now also responsible for the emissions that are caused by another party using the electricity that is sold.

Simultaneously, excluding CO_2 enrichment emissions from the grower shifts environmental burden away from fossil-free systems. The sentiment that growers are not the ones responsible for the CO2 vented, when it is imported as a waste product, means that the vented CO2 would not end up as the growers responsible emissions. making the fossil-free systems seem like they are less CO2 intensive than CHP. To reflect these divergent perspectives, a series of sensitivity analyses is included. These are then embedded in the accompanying Excel-based decision-support tool.

Although the modelled systems are argued to be fair comparisons, conversations and secondary sources of stakeholders in the sector have revealed notable perceptual differences. Stakeholders frequently claim that switching to an alternative heating source results in a reduction in natural gas use, and therefore in CO_2 emissions (Glastuinbouw Nederland, n.d.). However, this interpretation assumes that heat production is the sole emitting product in CHP systems. This is while CHP systems also produce electricity and usable CO_2 for enrichment, both of which should be accounted for accordingly.

The aim of this sensitivity analysis is not to prescribe a definitive interpretation. It is to offer a transparent framework that accommodates diverse viewpoints. By testing the robustness of results under varying assumptions, such as the attribution of co-product emissions and the responsibility for CO_2 enrichment, this analysis empowers decision-makers to understand how methodological choices shape environmental outcomes. Appendix F presents alternative LCA results that reflect these differing perspectives, enabling more informed and context-sensitive decisions.

7.4.1. Reduced CO_2 Enrichment

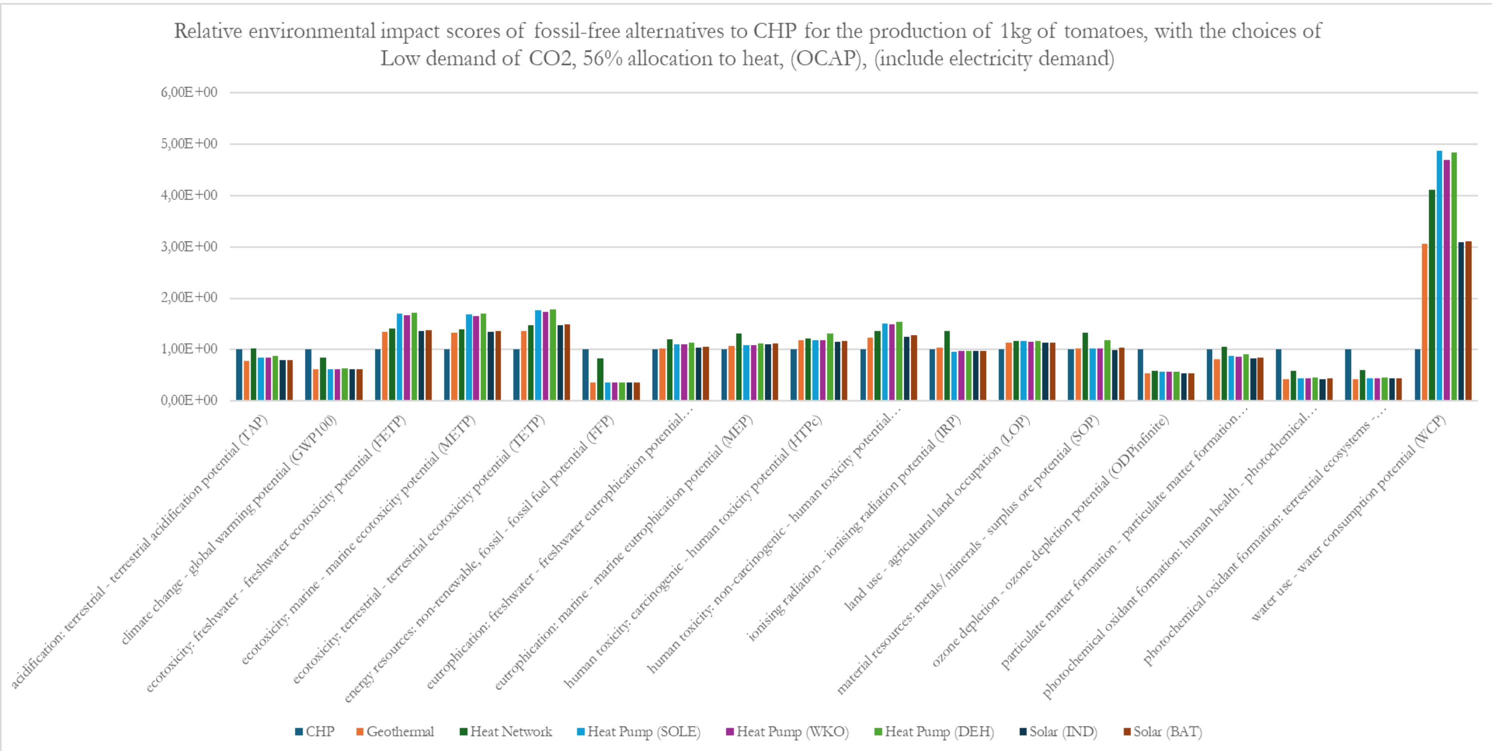
The CO_2 import for enrichment in fossil-free systems is made to match the output of CO2 from that of the CHP system. This has a substantial impact on the climate change scores of alternative energy systems. In fact, the associated CO_2-equivalent emissions are so significant that they largely negate the climate benefits of transitioning away from fossil-based heating.

In practice, a CO_2 enrichment level of 1.2 kg/kg would likely result in an average atmospheric concentration of around 1200 ppm inside the greenhouse. This is well above the agronomic optimum for tomato cultivation, which typically ranges between 600 and 1000 ppm (Gelder et al., 2012; Mamatha et al., 2014). Consequently, a large portion of the CO_2 is not absorbed by the crop and is instead vented back into the environment. At this modelled rate, nearly 90% of the CO_2 is released directly into the atmosphere. The CO2 can also not be considered biogenic since it originates from a fossil based industry.

A report by Wageningen University suggests that tomato yields can be maintained with a CO_2 enrichment level of approximately 0.53 kg per kilogram of tomatoes (Tuyll et al., 2022). This lower input significantly improves the environmental performance of alternative systems, as shown in Figure 27 and Table 8. Additionally, the proportion of CO_2 that is absorbed by the crop increases from 12.5% to approximately 28%, further reducing the net climate impact.

Figure 27

Characterised LCA Scores of Fossil-Free Systems vs CHP (with Enhanced CO_2 Enrichment).



Note. This figure presents the characterised life cycle assessment (LCA) results of fossil-free tomato production systems relative to the CHP baseline, incorporating an improved CO_2 enrichment strategy.

Table 8

Percentage Increase in Characterised Scores Compared to CHP System (With Improved CO_2 Enrichment).

Impact categories	Unit	CHP	Geothermal (%)	Heat Network (%)	Heat Pump (SOLE) (%)	Heat Pump (WKO) (%)	Heat Pump (DEH) (%)	Solar (IND) (%)	Solar (BAT) (%)
acidification: terrestrial - terrestrial acidification potential **(TAP)**	kg SO2-Eq	2,40E-03	-22,0	2,3	-15,3	-15,8	-12,6	-20,8	-19,4
climate change - global warming potential **(GWP100)**	kg CO2-Eq	1,46E+00	-38,4	-16,4	-37,8	-37,6	-36,3	-37,9	-37,6
ecotoxicity: freshwater - freshwater ecotoxicity potential **(FETP)**	kg 1,4-DCB-Eq	6,59E-02	19,8	23,6	41,1	39,1	41,9	20,6	21,6
ecotoxicity: marine - marine ecotoxicity potential **(METP)**	kg 1,4-DCB-Eq	8,38E-02	19,4	23,3	40,4	38,4	41,3	20,3	21,3
ecotoxicity: terrestrial - terrestrial ecotoxicity potential **(TETP)**	kg 1,4-DCB-Eq	3,10E+00	20,3	26,2	43,0	40,8	43,8	26,3	27,3
energy resources: non-renewable, fossil - fossil fuel potential **(FFP)**	kg oil-Eq	4,93E-01	-64,8	-16,6	-64,6	-64,4	-63,5	-64,4	-64,1
eutrophication: freshwater - freshwater eutrophication potential **(FEP)**	kg P-Eq	2,28E-04	2,2	16,6	8,0	7,9	11,3	3,5	4,6
eutrophication: marine - marine eutrophication potential **(MEP)**	kg N-Eq	2,03E-05	4,8	23,8	6,0	6,3	9,4	8,2	9,5
human toxicity: carcinogenic - human toxicity potential **(HTPc)**	kg 1,4-DCB-Eq	1,13E-01	14,0	16,3	13,6	14,1	23,5	11,8	12,2
human toxicity: non-carcinogenic - human toxicity potential **(HTPnc)**	kg 1,4-DCB-Eq	7,13E-01	14,9	23,4	33,3	31,7	34,7	16,2	17,8
ionising radiation - ionising radiation potential **(IRP)**	kBq Co-60-Eq	5,33E-02	3,0	26,4	-2,7	-2,3	-1,5	-2,2	-1,7
land use - agricultural land occupation **(LOP)**	m2*a crop-Eq	3,73E-02	11,3	14,6	13,6	13,5	14,3	11,1	11,4
material resources: metals/minerals - surplus ore potential **(SOP)**	kg Cu-Eq	3,17E-02	1,7	24,4	1,2	1,7	14,2	-0,8	2,7
ozone depletion - ozone depletion potential **(ODPinfinite)**	kg CFC-11-Eq	1,68E-06	-45,9	-41,2	-43,0	-43,2	-42,9	-45,8	-45,7
particulate matter formation - particulate matter formation potential **(PMFP)**	kg PM2.5-Eq	8,59E-04	-18,4	5,1	-12,4	-12,7	-8,2	-16,7	-15,1
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans **(HOFP)**	kg NOx-Eq	2,88E-03	-57,7	-41,5	-56,5	-56,4	-54,5	-57,1	-56,6
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems **(EOFP)**	kg NOx-Eq	2,99E-03	-57,1	-40,3	-55,9	-55,8	-53,8	-56,4	-55,9
water use - water consumption potential **(WCP)**	m3	5,65E-03	42,1	63,8	79,5	75,8	78,7	43,0	43,2

Note. This table presents the percentage increase in characterised environmental impact scores for each fossil-free alternative system relative to the CHP baseline, assuming an improved CO_2 enrichment strategy.

While the Climate change impact score improves compared to high levels of CO2 feedstock, it still raises the question if the trade-offs are fully worth the improvement. This is since there are still many other categories in which renewables score worse than the CHP based system. This argument is only enforced by the question if the economic investment is a worthwhile trade-off. The overall environmental advantage remains nuanced.

7.4.2. Unattributed CO_2 Enrichment

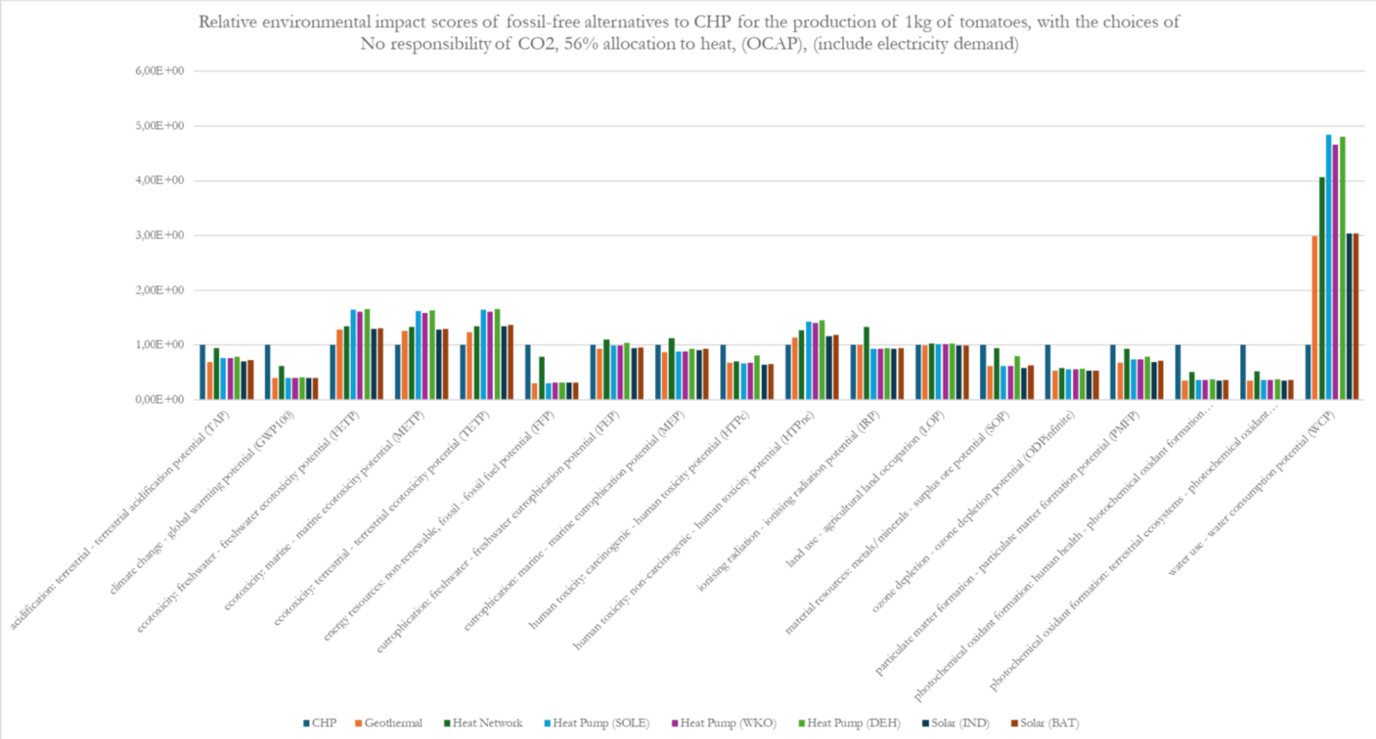
Stakeholder discussions have also revealed differing views on responsibility. Some growers argue that they should not be held accountable for the emissions associated with OCAP-supplied CO_2, since the gas originates from Shell and Alco. This sensitivity perspective treats the CO_2 as a waste stream, with the environmental burden fully belonging to the suppliers (Shell & Alco) rather than the growers. In practice Shell and Alco would likely argue the opposite, meaning the emissions will be unaccounted for since neither party will want to be held responsible.

In the baseline model, the environmental burden of OCAP-supplied CO_2 is allocated economically: 67% to the grower and 33% to the supplier, reflecting the shared responsibility for capture, purification, and distribution. Importantly, the emissions from the original production of the CO_2 are not included, as the gas is treated as a waste which is recycled into a new good. Only the material and energy demands for its recycling (so the capture, purification, use, and release) are accounted for.

To reflect the growers' perspective, an alternative sensitivity scenario was modelled in which 100% of the environmental burden is allocated to the supplier. This effectively treats the CO_2 as an environmentally burden-free product for the grower. Chapter 9. Discussion discusses in more detail on the justifiability of this perspective. The resulting environmental scores, shown in Figure 28 and Table 9. It demonstrates how attribution assumptions can significantly alter the perceived sustainability of CO_2 enrichment strategies.

Figure 28

Characterised LCA results of Fossil-Free Systems vs CHP (Excluding OCAP CO_2 Attribution).



Note. This figure presents the characterised life cycle assessment (LCA) results of fossil-free tomato production systems relative to the CHP baseline, under the assumption that CO_2 feedstock purchased from OCAP is not attributed to the tomato production system.

Table 9

Percentage Increase in Characterised Scores Compared to CHP System (Excluding OCAP CO_2 Attribution).

Impact categories	Unit	CHP	Geothermal (%)	Heat Network (%)	Heat Pump (SOLE) (%)	Heat Pump (WKO) (%)	Heat Pump (DEH) (%)	Solar (IND) (%)	Solar (BAT) (%)
acidification: terrestrial - terrestrial acidification potential **(TAP)**	kg SO2-Eq	2,37E-03	-30,9	-5,7	-23,9	-24,4	-21,1	-29,6	-28,1
climate change - global warming potential **(GWP100)**	kg CO2-Eq	1,41E+00	-60,9	-38,1	-60,3	-60,1	-58,7	-60,4	-60,0
ecotoxicity: freshwater - freshwater ecotoxicity potential **(FETP)**	kg 1,4-DCB-Eq	6,51E-02	16,7	20,6	39,0	36,9	39,8	17,4	18,5
ecotoxicity: marine - marine ecotoxicity potential **(METP)**	kg 1,4-DCB-Eq	8,27E-02	15,9	20,0	37,9	35,9	38,9	16,8	17,9
ecotoxicity: terrestrial - terrestrial ecotoxicity potential **(TETP)**	kg 1,4-DCB-Eq	3,03E+00	14,0	20,5	38,9	36,5	39,8	20,6	21,8
energy resources: non-renewable, fossil - fossil fuel potential **(FFP)**	kg oil-Eq	4,89E-01	-69,8	-21,3	-69,6	-69,4	-68,5	-69,4	-69,1
eutrophication: freshwater - freshwater eutrophication potential **(FEP)**	kg P-Eq	2,24E-04	-6,8	9,2	-0,4	-0,5	3,2	-5,4	-4,2
eutrophication: marine - marine eutrophication potential **(MEP)**	kg N-Eq	1,96E-05	-12,1	11,0	-10,6	-10,3	-6,5	-8,0	-6,4
human toxicity: carcinogenic - human toxicity potential **(HTPc)**	kg 1,4-DCB-Eq	1,04E-01	-32,9	-29,6	-33,3	-32,7	-19,2	-36,0	-35,4
human toxicity: non-carcinogenic - human toxicity potential **(HTPnc)**	kg 1,4-DCB-Eq	7,01E-01	9,5	18,7	29,3	27,6	30,8	10,9	12,7
ionising radiation - ionising radiation potential **(IRP)**	kBq Co-60-Eq	5,29E-02	0,2	24,5	-5,6	-5,2	-4,4	-5,1	-4,6
land use - agricultural land occupation **(LOP)**	m2*a crop-Eq	3,63E-02	-1,2	2,7	1,4	1,3	2,3	-1,4	-1,1
material resources: metals/minerals - surplus ore potential **(SOP)**	kg Cu-Eq	2,96E-02	-38,5	-6,2	-39,2	-38,4	-20,7	-42,0	-37,0
ozone depletion - ozone depletion potential **(ODPinfinite)**	kg CFC-11-Eq	1,68E-06	-47,1	-42,4	-44,2	-44,4	-44,0	-47,0	-46,9
particulate matter formation - particulate matter formation potential **(PMFP)**	kg PM2.5-Eq	8,40E-04	-32,7	-7,3	-26,2	-26,6	-21,6	-30,9	-29,1
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans **(HOFP)**	kg NOx-Eq	2,85E-03	-65,5	-49,2	-64,3	-64,2	-62,3	-64,9	-64,4
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems **(EOFP)**	kg NOx-Eq	2,95E-03	-65,6	-48,6	-64,3	-64,3	-62,3	-64,9	-64,4
water use - water consumption potential **(WCP)**	m3	5,55E-03	41,0	63,3	79,4	75,6	78,5	42,0	42,1

Note. This table shows the increase in characterised environmental impact scores for each fossil-free alternative relative to the CHP baseline, under the assumption that purchased CO_2 from OCAP is not attributed to tomato production.

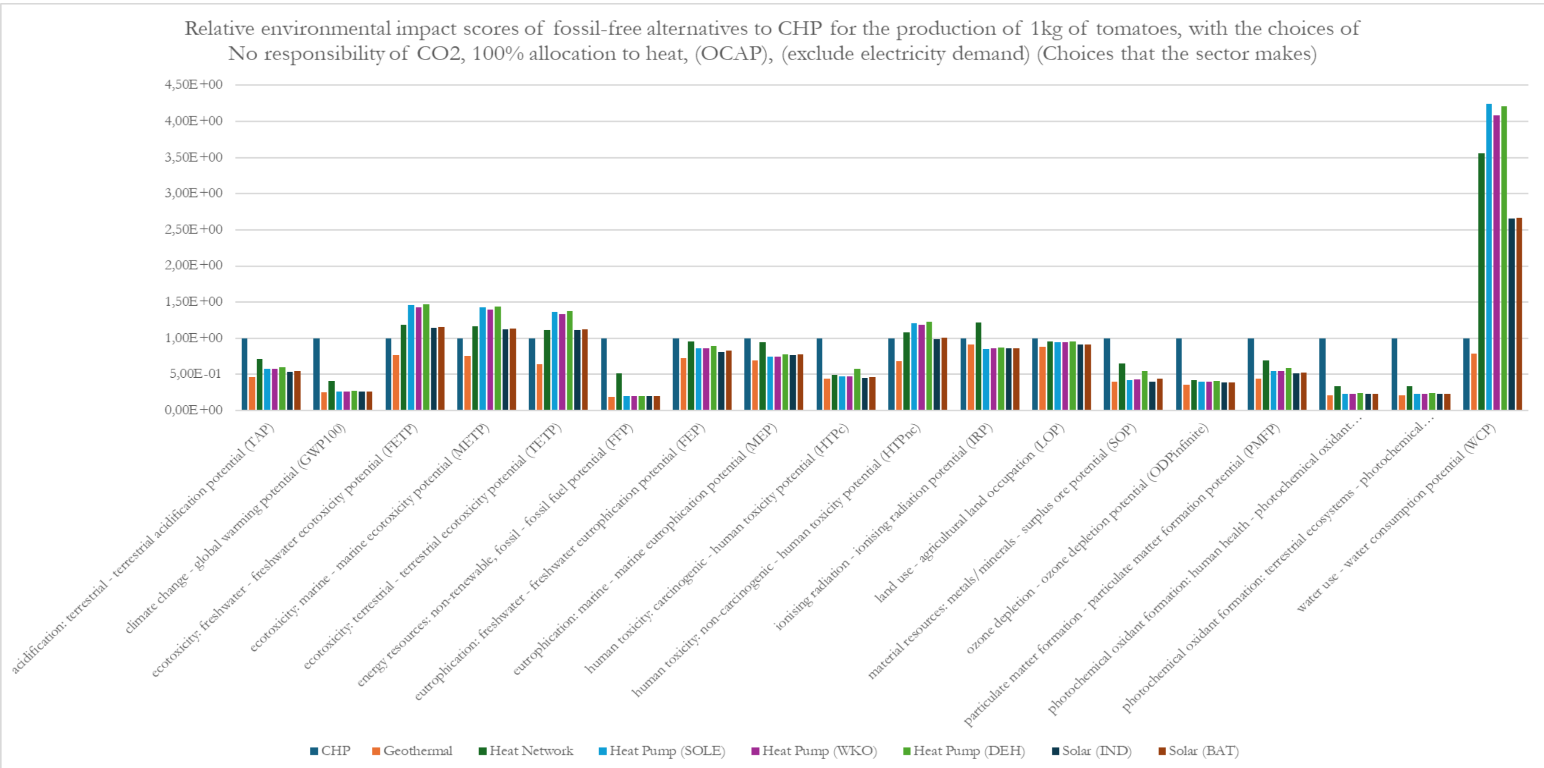
These changes are significant since the contribution analysis showed that the enrichment using OCAP is by and large the most important spot of CO2 equivalent production. This sensitivity analysis thus highlights how attributional choices can substantially influence the perceived climate benefits of fossil-free systems. By excluding the environmental burden of OCAP-supplied CO_2 from the tomato production system, the climate impact scores improve markedly. These results also potentially overstate the sustainability of the transition. While this perspective may align with certain stakeholder views, it risks creating blind spots in accountability.

7.4.3. No Allocation In CHP

To explore how alternative perspectives might influence environmental outcomes, an analysis was conducted in which 100% of the emissions were allocated to heat. This scenario reflects the viewpoint commonly held within the sector, where electricity and CO_2 are often treated as by-products with no associated environmental burden. The results of this scenario, shown in Figure 29. The CHP system now performs significantly worse across most environmental categories. This is due to the fact that some of the environmental emissions that were allocated away before, are now no longer moved outside of the growers responsibility.

Figure 29

Characterised LCA results of Fossil-Free Systems vs Unallocated CHP (Excluding OCAP CO_2).



Note. This figure presents the characterised life cycle assessment (LCA) results of fossil-free tomato production systems relative to the CHP baseline, under a scenario where CO_2 feedstock from OCAP is not attributed to tomato production and CHP coproducts are not allocated.

This figure combines two sensitivity assumptions: the exclusion of CO_2 enrichment emissions (i.e. also treating CO_2 as burden-free) and the full allocation of emissions caused by the burning of natural gas in CHP to heat. Together, these reflect the sector's preferred framing of CHP systems. From this perspective, the environmental case for transitioning to non-fossil energy sources becomes much stronger. It is of note, as can be seen in table 2, that these choices are not the recommended allocation choices for the sector to use to represent their environmental footprint. This is twofold since the fairness of this is debatable and that once regulation catches up these choices will likely not be accepted.

With the exception of water use and ecotoxicity, most categories show substantial improvements (see Table 10). This contrasts with the original assessment, where the benefits of alternative systems were less pronounced.

Table 10

Percentage Increase in Characterised Scores Compared to CHP System (Excluding OCAP CO_2 and CHP Coproduct Allocation).

Impact categories	Unit	CHP	Geothermal (%)	Heat Network (%)	Heat Pump (SOLE) (%)	Heat Pump (WKO) (%)	Heat Pump (DEH) (%)	Solar (IND) (%)	Solar (BAT) (%)
acidification: terrestrial - terrestrial acidification potential **(TAP)**	kg SO2-Eq	3,12E-03	-54,0	-28,4	-42,3	-42,7	-40,2	-46,6	-45,5
climate change - global warming potential **(GWP100)**	kg CO2-Eq	2,13E+00	-75,0	-59,1	-73,8	-73,7	-72,7	-73,9	-73,6
ecotoxicity: freshwater - freshwater ecotoxicity potential **(FETP)**	kg 1,4-DCB-Eq	7,34E-02	-16,0	12,9	31,3	29,2	32,2	9,8	10,8
ecotoxicity: marine - marine ecotoxicity potential **(METP)**	kg 1,4-DCB-Eq	9,38E-02	-17,2	11,7	29,7	27,6	30,7	8,6	9,7
ecotoxicity: terrestrial - terrestrial ecotoxicity potential **(TETP)**	kg 1,4-DCB-Eq	3,65E+00	-26,3	8,0	26,4	24,0	27,3	8,1	9,3
energy resources: non-renewable, fossil - fossil fuel potential **(FFP)**	kg oil-Eq	7,54E-01	-80,8	-49,0	-80,3	-80,2	-79,6	-80,2	-80,0
eutrophication: freshwater - freshwater eutrophication potential **(FEP)**	kg P-Eq	2,59E-04	-27,8	-4,8	-13,9	-14,0	-10,4	-18,6	-17,5
eutrophication: marine - marine eutrophication potential **(MEP)**	kg N-Eq	2,33E-05	-30,3	-5,3	-25,8	-25,5	-21,9	-23,3	-21,8
human toxicity: carcinogenic - human toxicity potential **(HTPc)**	kg 1,4-DCB-Eq	1,46E-01	-55,3	-50,0	-52,7	-52,3	-42,7	-54,6	-54,2
human toxicity: non-carcinogenic - human toxicity potential **(HTPnc)**	kg 1,4-DCB-Eq	8,24E-01	-25,4	6,6	17,2	15,5	18,7	-1,2	0,5
ionising radiation - ionising radiation potential **(IRP)**	kBq Co-60-Eq	5,75E-02	-7,5	18,0	-12,1	-11,7	-10,9	-11,6	-11,1
land use - agricultural land occupation **(LOP)**	m2*a crop-Eq	3,91E-02	-12,2	-4,6	-5,8	-5,9	-4,9	-8,5	-8,1
material resources: metals/minerals - surplus ore potential **(SOP)**	kg Cu-Eq	4,26E-02	-60,5	-34,9	-57,8	-57,2	-44,9	-59,8	-56,3
ozone depletion - ozone depletion potential **(ODPinfinite)**	kg CFC-11-Eq	2,32E-06	-64,1	-58,2	-59,5	-59,7	-59,4	-61,6	-61,5
particulate matter formation - particulate matter formation potential **(PMFP)**	kg PM2.5-Eq	1,13E-03	-56,1	-31,0	-45,0	-45,3	-41,6	-48,5	-47,2
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans **(HOFP)**	kg NOx-Eq	4,35E-03	-78,8	-66,7	-76,6	-76,6	-75,3	-77,0	-76,7
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems **(EOFP)**	kg NOx-Eq	4,52E-03	-78,8	-66,4	-76,7	-76,6	-75,3	-77,1	-76,7
water use - water consumption potential **(WCP)**	m3	6,35E-03	-5,0	60,3	76,4	72,6	75,6	39,0	39,2

Note. This table shows the increase in characterised environmental impact scores for each fossil-free alternative relative to the CHP system, under a conservative scenario where purchased CO_2 from OCAP is not attributed to tomato cultivation and CHP coproducts are not allocated.

This scenario highlights the stark contrast between allocation approaches. In the standard method, emissions are proportionally distributed across heat, electricity, and CO_2, reflecting their shared production. In the alternative framing, all emissions are attributed solely to heat, treating electricity and CO_2 as burden-free by-products. This shift dramatically alters the environmental profile. CHP systems appear significantly more polluting compared to fossil-free alternatives. Although this perspective aligns with certain sector narratives, it diverges from established LCA methodology. Nonetheless, it reinforces the argument that transitioning to non-fossil energy sources is crucial for reducing greenhouse gas emissions. Table 11 compares the outcomes of these allocation strategies, showing how the heat-only attribution inflates impact scores across all environmental categories.

Table 11

Comparison of Life Cycle Outcomes Across CHP Allocation Scenarios

Impact category	Unit	CHP with 53% allocation to heating	CHP with 100% allocation	100% allocation scores worse by
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0,002400696	0,003120774	30%
climate change - global warming potential (GWP100)	kg CO2-Eq	1,459649381	2,133125316	46%
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	0,065942325	0,073440299	11%
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	0,083797951	0,093827304	12%
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	3,100302451	3,654520579	18%
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	0,492884003	0,754109049	53%
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0,000228345	0,000258973	13%
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	2,03284E-05	2,32555E-05	14%
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	0,113452716	0,146218477	29%
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	0,71269705	0,82387942	16%
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0,053277973	0,05746503	8%
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0,037254144	0,039085191	5%
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	0,031707996	0,04258071	34%
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1,67784E-06	2,31693E-06	38%
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0,000858622	0,001128121	31%
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0,002882741	0,004349698	51%
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0,002994468	0,004517851	51%
water use - water consumption potential (WCP)	m3	0,005654132	0,00634572	12%

Note. This table compares the characterised environmental impact scores resulting from different allocation approaches applied to the CHP system, using the ReCiPe method.

This scenario underscores how sector-preferred allocation choices can significantly alter the environmental narrative of CHP systems. By attributing all emissions to heat and excluding CO_2

enrichment impacts, fossil-free alternatives appear substantially more favourable. However, this framing diverges from established LCA principles and risks misrepresenting the true environmental footprint. As regulatory standards evolve, such allocation strategies may face increased scrutiny. Therefore, while this perspective may support the transition to non-fossil systems, it should be applied with caution and transparency to avoid misleading sustainability claims.

7.4.4. CHP CO_2 as a waste

An alternative option on CO_2 produced by CHP systems is to treat it not as a co-product, but as a waste stream. In this sense, the CO_2 is not intentionally produced for enrichment but is instead a byproduct of energy generation that must be managed. From this viewpoint, the tomato production system is responsible for cleaning up the CO_2, rather than benefiting from it.

Despite this shift in interpretation, modelling CO_2 as a waste rather than a product does not lead to a measurable change in environmental impact scores. As shown in Table 12, the emissions attributed to the grower remain effectively unchanged. This is because, regardless of classification, the grower is still accountable for the eventual release of CO_2 into the atmosphere following enrichment. The environmental burden therefore remains with the greenhouse operation.

Table 12

Effect of CO_2 Classification on Environmental Scores in Tomato Production.

Impact category	Unit	CO2 as Good	CO2 as Waste	Waste emits less by
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	2,40E-03	2,39E-03	-1%
climate change - global warming potential (GWP100)	kg CO2-Eq	1,46E+00	1,46E+00	0%
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	6,59E-02	6,57E-02	0%
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	8,38E-02	8,35E-02	0%
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	3,10E+00	3,09E+00	0%
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	4,93E-01	4,90E-01	-1%
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	2,28E-04	2,27E-04	0%
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	2,03E-05	2,02E-05	0%
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	1,13E-01	1,13E-01	-1%
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	7,13E-01	7,10E-01	0%
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	5,33E-02	5,31E-02	0%
land use - agricultural land occupation (LOP)	m2*a crop-Eq	3,73E-02	3,71E-02	0%
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	3,17E-02	3,15E-02	-1%
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1,68E-06	1,67E-06	-1%
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	8,59E-04	8,54E-04	-1%
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	2,88E-03	2,86E-03	-1%
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	2,99E-03	2,97E-03	-1%
water use - water consumption potential (WCP)	m3	5,65E-03	5,63E-03	0%

Note. This table compares the life cycle impact assessment results for tomato production systems based on whether CO_2 generated from natural gas combustion is modelled as a valuable product or as a waste emission.

In practical terms, this means that the climate change impact of CO_2 from CHP systems is largely insensitive to whether the gas is treated as a co-product or a waste stream. While the framing may influence stakeholder perceptions, it does not materially affect the life cycle assessment results.

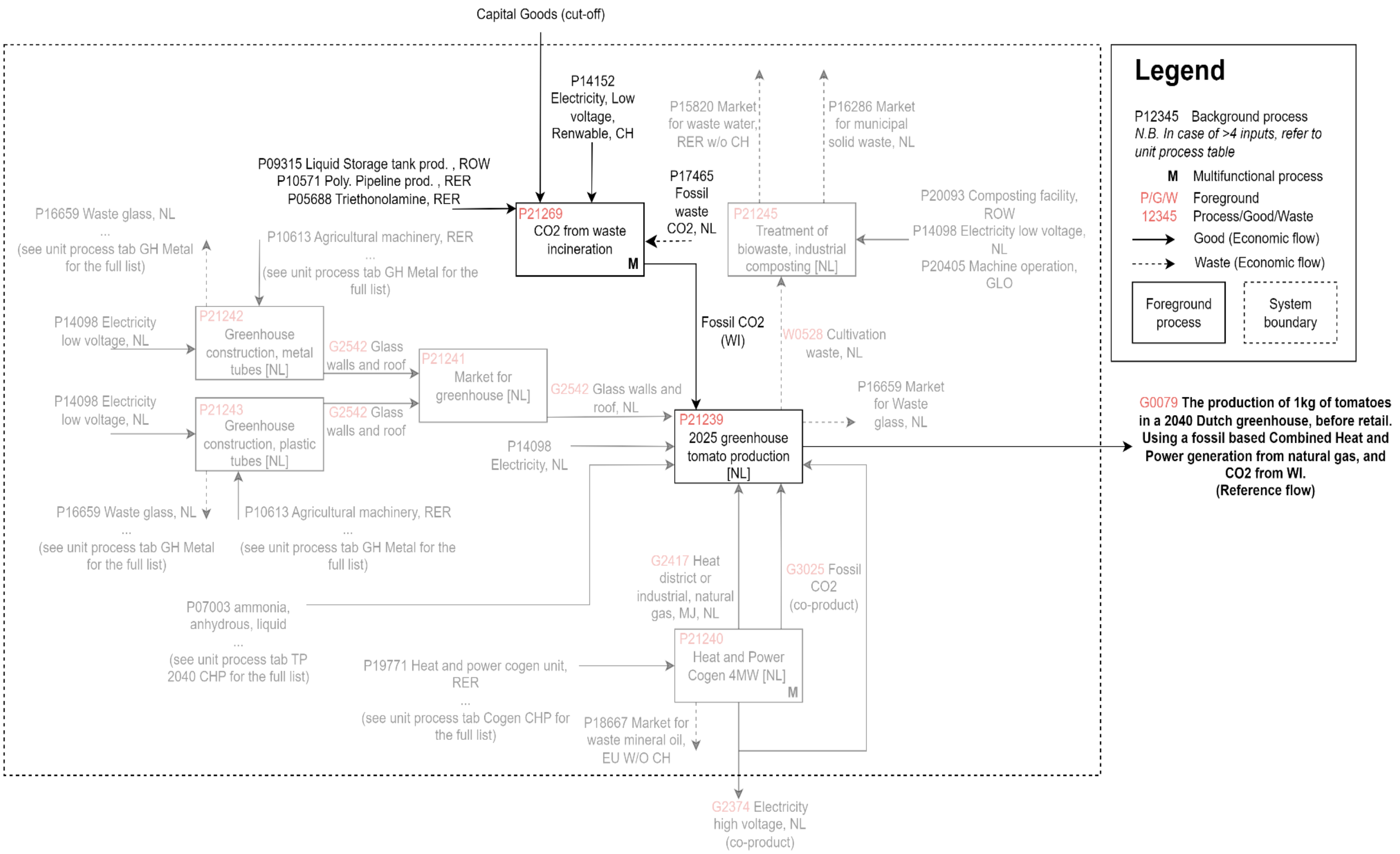
7.4.5. CO_2 From Waste Incineration

Several alternative methods of CO_2 delivery have been proposed to the sector. One such option, outlined in a 2023 report by Glastuinbouw Nederland, involves capturing and purifying CO_2 from municipal waste incineration facilities for use in greenhouse cultivation (Glastuinbouw Nederland, 2023).

This scenario has been modelled to assess its environmental implications. Figure 30 presents the modified system flowchart for tomato production, where CO_2 is sourced from waste incineration rather than the OCAP network. While the overall system structure remains largely unchanged, the environmental performance differs.

Figure 30

LCA Flowchart: Tomato Production Using CHP and Waste Incineration sourced CO_2 .



Figures 31 and 32 show the characterised life cycle assessment (LCA) results for fossil-free tomato systems under two CO_2 enrichment levels (high and low) using waste-derived CO_2. Compared to the OCAP-based scenario, the waste incineration route results in slightly elevated environmental scores across most impact categories. This is likely due to the additional energy and purification requirements associated with capturing CO_2 from incineration processes.

Figure 31

Characterised LCA Results for Fossil-Free Tomato Systems Relative to CHP (With High CO_2 Demand Sourced From Waste Incineration).

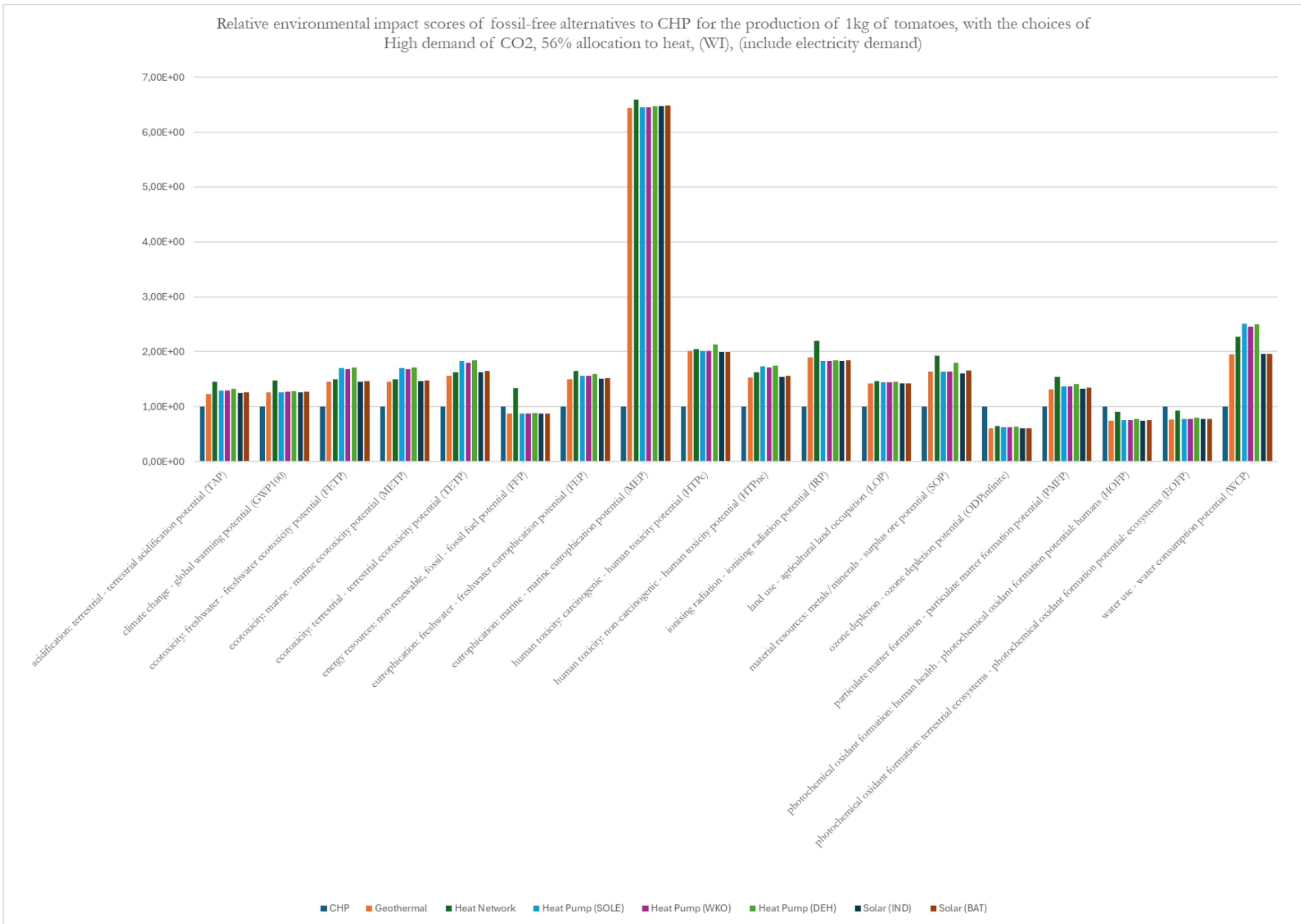
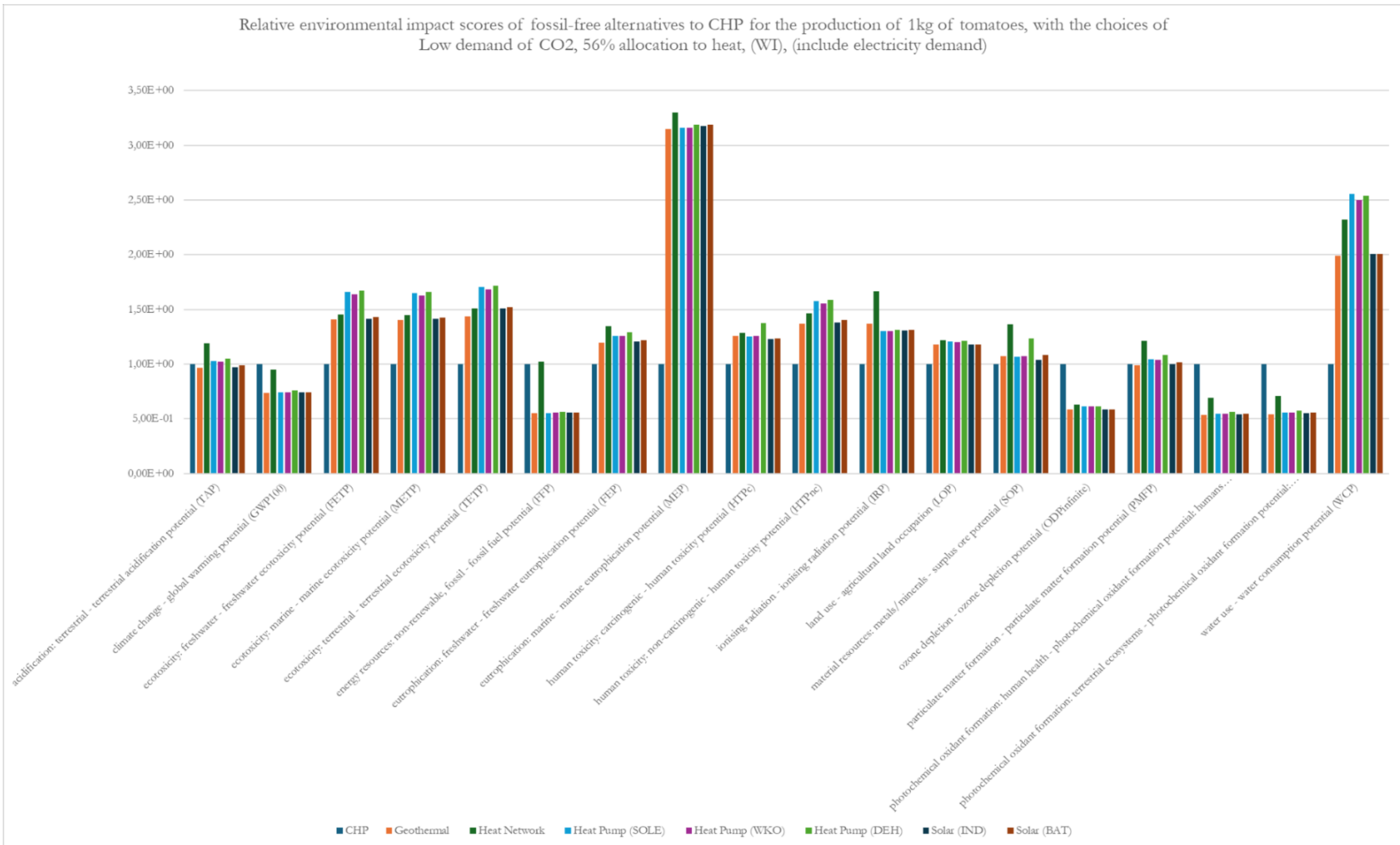


Figure 32

Characterised LCA Results for Fossil-Free Tomato Systems Relative to CHP (With Low CO_2 Demand Sourced From Waste Incineration).



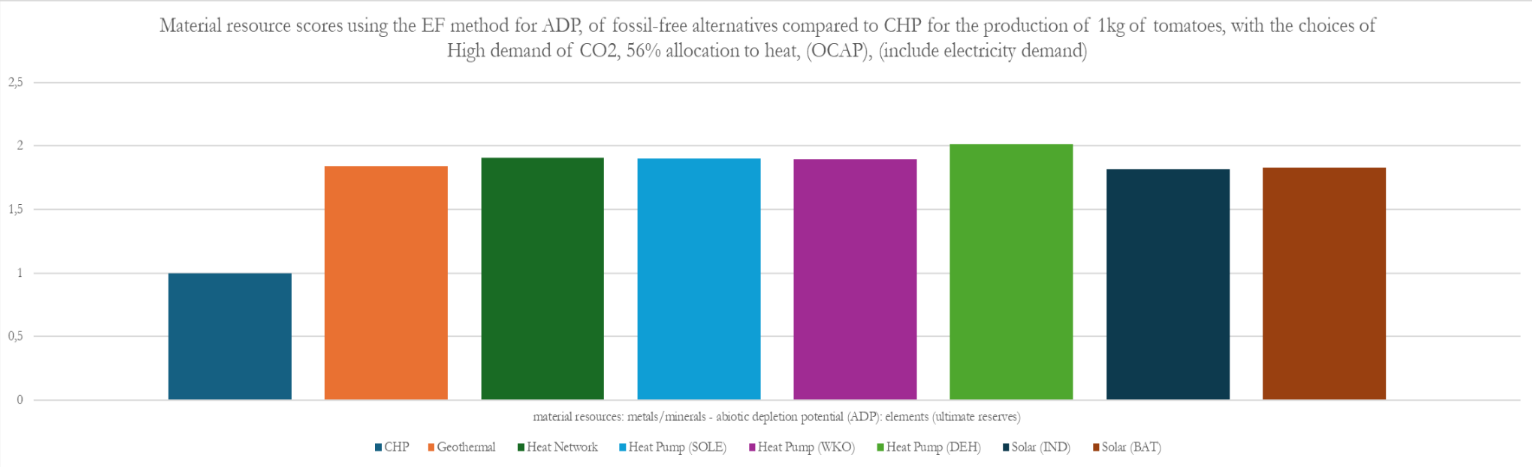
Although waste incineration offers a viable alternative for CO_2 supply, its environmental performance is marginally less favourable than OCAP-sourced CO_2. The differences are not dramatic, but they highlight the importance of evaluating not just the availability of CO_2 sources, but also their life cycle impacts.

7.4.6. EF Impact Family

Resource demand has been a central concern in evaluating fossil-free greenhouse systems, particularly due to the increased material requirements associated with electrification. Figure 33 presents the results for abiotic depletion potential (ADP) from the Environmental Footprint (EF) method, comparing fossil-free tomato systems to the CHP baseline.

Figure 33

Material Resource Use of Fossil-Free Tomato Systems Relative to CHP (EF Method).



Note. This figure compares the material resource use of fossil-free tomato production systems to the CHP-based reference system, using the Environmental Footprint (EF) life cycle impact assessment method.

The material resource scores of the fossil free alternatives almost consistently double that of CHP. Meanwhile table 13 highlights a notable divergence between two resource indicators: ADP and secondary material use (SOP). While SOP suggests that the material impacts of electrification are relatively modest, ADP indicates a more substantial burden. This discrepancy is especially pronounced in scenarios involving heat pumps powered by purchased renewable electricity. These systems require greater quantities of metals such as copper, nickel, and rare earth elements, which are materials critical to electrical infrastructure and energy storage systems.

Table 13

Relative Increase in Material Resource Scores of Fossil-Free Alternatives Compared to CHP.

Impact category	Unit	CHP	Geothermal (%)	Heat Network (%)	Heat Pump (SOLE) (%)	Heat Pump (WKO) (%)	Heat Pump (DEH) (%)	Solar (IND) (%)	Solar (BAT) (%)
material resources: metals/minerals - abiotic depletion potential **(ADP)**	kg Sb-Eq	7,03E-06	41,1	64,0	81,0	77,2	81,1	48,1	53,5
material resources: metals/minerals - surplus ore potential **(SOP)**	kg Cu-Eq	3,17E-02	31,2	47,1	30,8	31,2	39,9	29,4	31,9

Note. This table shows the increase in material resource impact scores for fossil-free CO_2 supply alternatives relative to the combined heat and power (CHP) system, using both the ReCiPe and EF impact assessment families.

The contrast between ADP and SOP underscores the importance of indicator selection in life cycle assessment. Depending on the chosen metric, the perceived material sustainability of electrified systems can vary

7.4.7. Electricity Purchase

When CHP systems are phased out, this self-generated electricity must be replaced with electricity purchased. This introduces an additional environmental burden. Although renewable electricity has a lower carbon footprint than fossil-based alternatives, it is arguably not impact-free. Its production still involves emissions and resource use across the life cycle, including material extraction, manufacturing, and infrastructure development (IEA, 2025a)

Some stakeholders argue that externally sourced electricity lies outside the grower's responsibility. Others maintain that certified renewable electricity should be considered environmentally neutral, particularly under scope 2 accounting frameworks (IEA, 2022). These views, while relevant for understanding sectoral perceptions, diverge from LCA conventions. Life cycle assessment attributes upstream impacts to the system regardless of ownership or accounting boundaries, meaning that purchased electricity carries environmental consequences, renewable or not.

Table 14 presents the contribution of electricity purchase to various impact categories. Notably, in the category of water use, renewable electricity accounts for a substantial share of the total impact. This suggests that if the sector aims to reduce its water footprint, it must also consider the upstream water demands of renewable energy systems.

Table 14

Impact of Renewable Energy on Water Use Scores Across Fossil-Free CO_2 Options.

Impact category	Unit	Impact of renewable electricity purchase per kWh	Contribution % Geothermal	Contribution % Heat Networks	Contribution % Heat Pump (SOLE)	Contribution % Heat Pump (WKO)	Contribution % Heat Pump (DEH)	Contribution % Solar (IND)	Contribution % Solar (BAT)
water use - water consumption potential **(WCP)**	m3	1,51E-02	64%	48%	41%	42%	41%	63%	63%

Note. This table quantifies the share of the total water use impact score that is attributable to renewable energy inputs in each fossil-free CO_2 supply alternative. The table displaying the contribution of renewable electricity to each ReCiPe impact category can be found in Appendix G

8

Decision-Support Tool

The tool was developed to help decision-makers and growers understand how environmental impact scores shift depending on operational and allocational choices. Its purpose is to make trade-offs visible, especially those that are less intuitive. While transitioning to fossil-free energy systems is often framed as progress toward climate neutrality, this shift introduces new upstream environmental burdens. Fossil fuel use, climate change, material resource use, and water use are impact categories that tend to absorb a significant portion of the problem shifting when fossil-based systems are replaced.

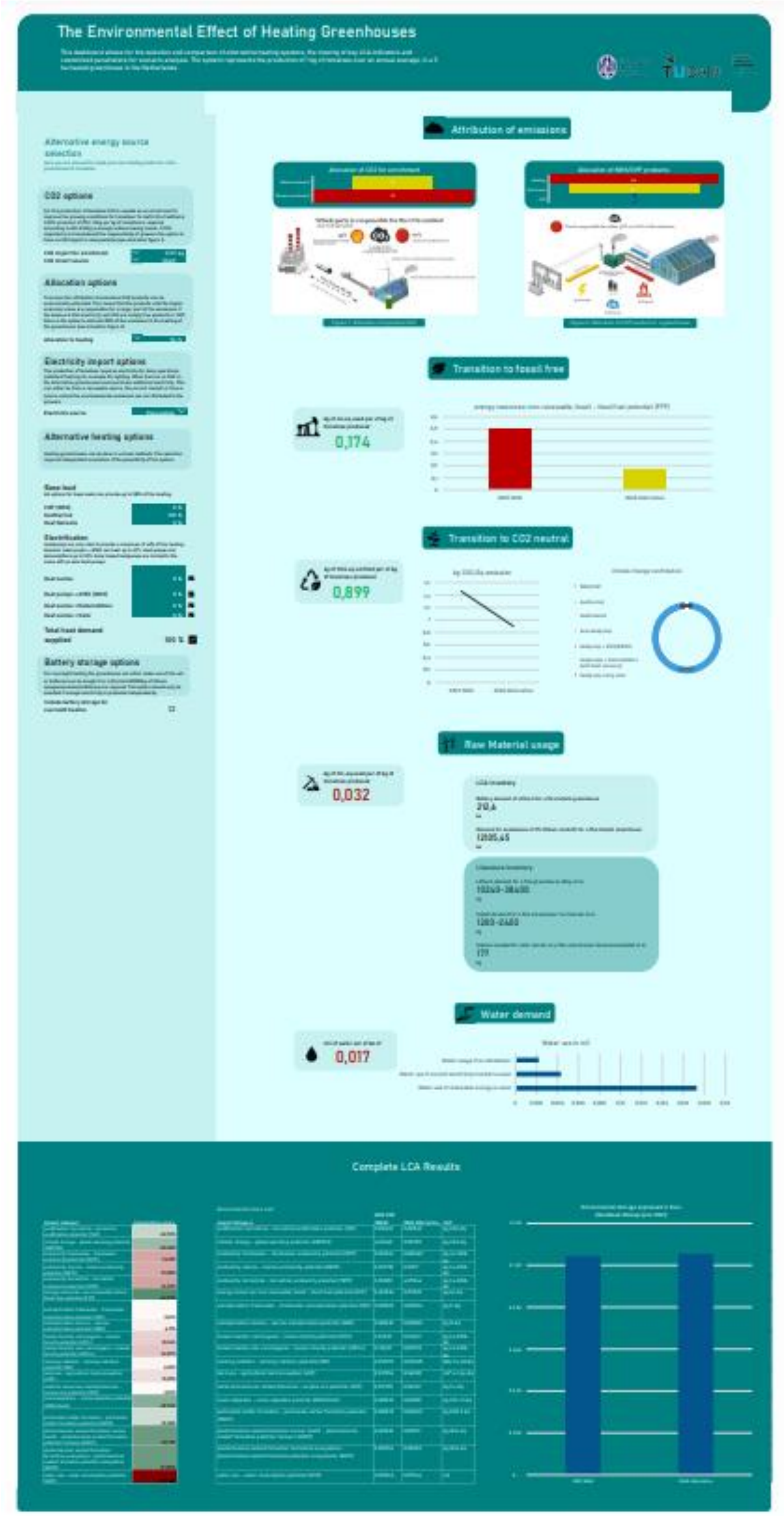
The motivation to make LCA results more legible emerged from collaboration within the LDE Thesis Lab. It became clear that the energy transition cannot be evaluated through environmental metrics alone. Financial, social, and technical aspects are equally relevant to the sector's broader sustainability goals. However, specialists outside the environmental sciences often find LCA results difficult to interpret. To address this, the tool was designed to be accessible and intuitive for users who are less familiar with LCA methodology.

This approach is not entirely new. Similar tools exist, such as the CO_2 calculator developed by Gibbs, which simplifies emissions data for broader audiences (Gibbs, 2024). What distinguishes this tool is its inclusion of multiple impact categories, allowing users to explore trade-offs beyond carbon emissions.

The interface of the tool is shown in Figure 34. It was developed in Excel and integrates results from OpenLCA. The dataset has been limited to prevent reverse calculation of the original values. After a brief welcome tab, users are directed to the main dashboard. On the left side, users can select allocation preferences. These options were developed in consultation with stakeholders and reflect configurations that are both valid and feasible within the sector, as outlined in Table 2 (See figure 35).

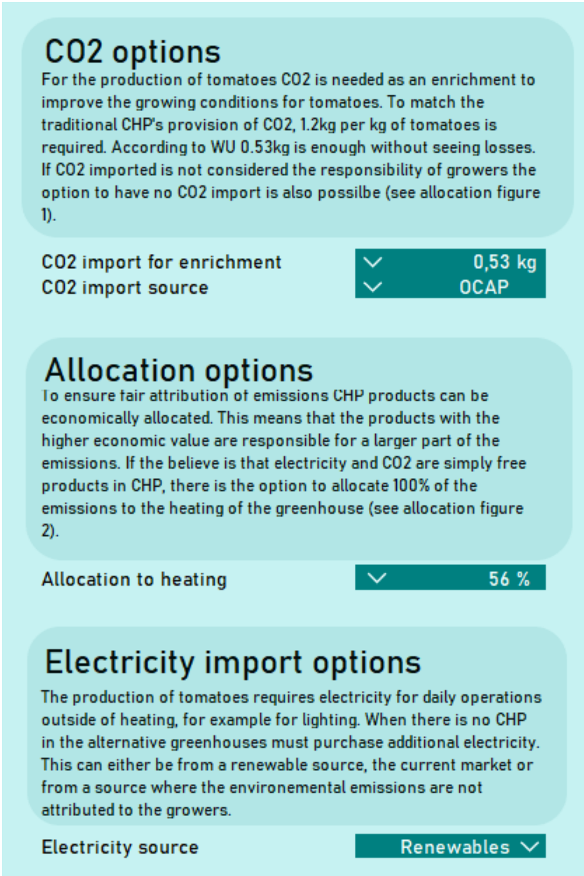
Figure 34

Dashboard of Tomato LCA Decision-Support Tool.



Note. This figure displays the full dashboard tab of the decision-support tool developed for the life cycle assessment of 1 kg of tomatoes produced in Dutch horticulture. The tool provides an accessible interface for exploring environmental impact results and can be found in Appendix I.

Figure 35
Allocation Choices in the Decision-Support Tool.



Note. This figure illustrates the allocation choices presented within the tool to communicate environmental impact scores and associated trade-offs to stakeholders in the sector. While not all options adhere to the strictest LCA standards, each represents a valid methodological approach that reflects the environmental effects of tomato production.

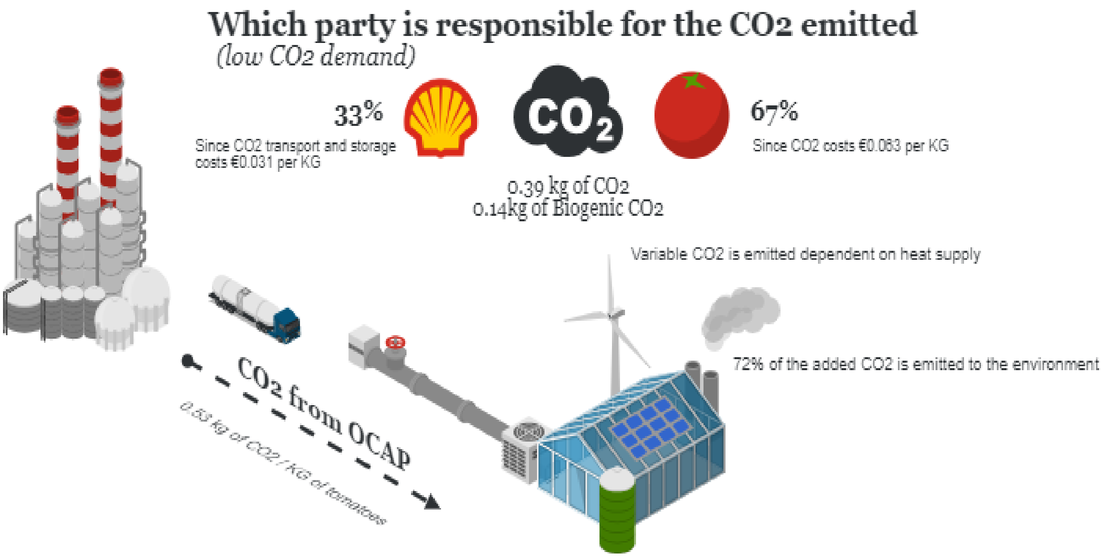
Once allocation choices are made, users can define their envisioned future energy system. Based on these selections, the tool displays four key impact categories on the right. At the bottom of the dashboard, the full environmental impact score is presented using the ReCiPe impact assessment method. These scores can also be translated into economic indicators using the Handboek Milieuprijzen 2023, to reflect the welfare loss (de Bruyn et al., 2025). However, these monetary values are intended only as illustrative aids and should not be used as definitive metrics for environmental decision-making.

8.1. Thesis lab implications

Figure 36 presents the allocation of CO_2 emissions developed for the Thesis Lab. The visualization shows that the sector is not solely responsible for all emissions. Nevertheless, the adoption of a more frugal enrichment strategy results in lower fossil CO_2 emissions, regardless of how responsibility is assigned. This finding underscores the importance of making fair allocation choices, but also raises the question of how fairness should be defined in environmental assessments.

Figure 36

Allocational Consequences of Decision-Support Tool Choices.



Note. This figure provides an overview of the allocation of emitted CO_2 as modelled for the Thesis Lab. Fossil CO_2 emissions are partially attributed to Shell & Alco. However, these emissions are lower thanks to a relatively higher biogenic CO_2 uptake, resulting from improved enrichment strategies.

The tool reveals that there is no shared understanding of what constitutes fair allocation, and that this ambiguity requires further discussion. Additionally, the results indicate that other environmental impacts, such as water use and material depletion, are currently underrepresented. The benefits of transitioning to fossil-free systems may be overstated, while the burdens shifted to other impact categories are not sufficiently acknowledged. While the Decision Support Tool offers a structured way to explore environmental trade-offs within Dutch tomato production systems, its applicability is intentionally narrow. The tool is built on crop-specific data, greenhouse-specific assumptions, and allocation choices that reflect the unique characteristics of tomato cultivation.

9
Discussion

This chapter firstly reflects on the central goal, uncovering the environmental and resource-risk trade-offs of shifting Dutch tomato horticulture toward climate-neutral energy systems and the questions that need to be answered. It then critically examines the study's main limitations, before closing with broader observations and concrete recommendations for future research and sectoral implementation.

9.1. Sub Research Questions

Sub RQ 1 Climate Neutrality

Stakeholder interpretations of "climate neutrality" often focus on eliminating fossil fuel use. However, this narrow framing overlooks broader life cycle emissions and environmental trade-offs. While electrification and alternative heating systems reduce direct emissions from fossil use, they still cause GHG emissions further upstream. Additionally, impact categories that are lower on the priority list might also increase in fossil free systems. Meaning problem shifting can occur on two occasions when the goal of climate neutrality is not clearly and fairly defined.

This ambiguity could have further practical consequences. In the absence of a unified and inclusive definition, decision-makers often default to what is easiest to quantify. That is fossil fuel usage, while overlooking less tangible CO_2 emissions. To guide effective policy and investment, the sector should adopt a shared definition of climate neutrality that includes life cycle impacts. However, this broader scope should remain focused on the most relevant indicators to avoid unnecessary complexity and ensure that assessments remain actionable.

Sub RQ 2 Energy Transition Paths

The transition away from Combined Heat and Power (CHP) systems requires a diversified energy mix, including geothermal, residual heat, and electrification. Each alternative presents unique trade-offs. For instance, while geothermal systems reduce fossil fuel use, they may involve higher water consumption than CHP. Meanwhile, electrified systems with solar and battery integration reduce emissions yet increase dependency on critical raw materials (CRMs).

In this thesis, eight alternative heating configurations were modelled to reflect a broad range of plausible sector pathways. Some emerging technologies (e.g., hydrogen, nuclear, and bio-based fuels) were excluded due to data limitations, but the selected alternatives sufficiently capture the key environmental trade-offs and inform the study's broader conclusions.

Seasonal heating demand further complicates this transition. Life Cycle Assessment (LCA) models typically assume steady-state conditions, which may not reflect real-world peak loads. This limitation should be addressed in future modelling efforts.

Part of the energy mix used for renewable electricity also holds an important limitation. The energy mix used as a proxy is that of Switzerland. This mix is in part supplied by hydropower, which will not be the case for the Netherlands if the renewable energy is locally produced. As a result the water demand caused by renewable electricity is likely exaggerated in the results for the alternatives that heavily rely on them.

Sub RQ 3 CO_2 Enrichment Strategies

CO_2 enrichment emerged as a key driver of environmental impact. When enrichment levels match current CHP output (1.2 kg CO_2/kg tomato), the climate benefits of alternative systems are largely negated due to high venting losses. Reducing enrichment to 0.53 kg CO_2/kg tomato significantly improves environmental performance.

This inefficiency highlights the need to integrate agronomic best practices, such as more precise CO_2 dosing. This is to reduce vented emissions and maximize uptake efficiency. While further reductions in enrichment might yield additional gains, they may also cause slight yield reductions beyond the fixed 1 kg reference flow.

Sourcing decisions also shape outcomes. CO_2 from waste incineration performs worse than OCAP in several impact categories, notably marine eutrophication, demonstrating that low-carbon options are not always low-impact. Moreover, the evolving role of OCAP in light of North Sea CCS projects (e.g., Porthos) may transform OCAP-supplied CO_2 from an emission-avoiding benefit into a re-emitted burden, underscoring the need to update system boundaries as policy and infrastructure evolve.

Stakeholder perspectives on CO_2 attribution vary. Some growers argue that emissions from OCAP-supplied CO_2 should be attributed to the supplier, not the user. Ultimately the CO2 is a waste product turned into a good and purchased by tomato growers, which makes them responsible for what happens with it. Thus an economic allocation approach is adopted, with the sensitivity scenarios included to reflect alternative viewpoints.

Sub RQ 4 System Flowcharts

While some environmental flows are missing due to data limitations, particularly in capital goods and infrastructure, the omissions are applied consistently across all alternatives. As a result, while the absolute impact values may be underestimated, the relative differences between systems remain meaningful.

For the sake of the hotspot analysis the inventory is as complete as possible. However, the goal was not to provide a perfectly accurate environmental footprint, but rather to offer a comparative assessment. While the modelled systems have some gaps in regards to the fertilizers and auxiliary equipment, the alternatives are sufficiently similar in scope and structure to allow for a fair comparison.

Sub RQ 5 Hotspots

The hotspot analysis identified CO_2 enrichment, electricity sourcing, and material use as dominant contributors to environmental impact. These categories were selected based on normalized LCA scores and stakeholder priorities. While climate change remains central, other indicators, particularly freshwater eutrophication and water consumption, warrant greater attention in future planning. While they are currently lower-priority, they may become critical as resource constraints and policy shifts evolve.

A key finding is that most impacts originate upstream in the supply chain rather than from in-greenhouse operations. The notable exception is climate change, where on-site CO_2 emissions from CHP dominate under baseline conditions. In alternative energy configurations, however, inefficiencies in CO_2 enrichment become the primary driver of GHG impacts, underscoring the need for more precise and frugal dosing practices.

As expected, fossil fuel consumption declines sharply in scenarios that move away from natural gas. However, residual fossil inputs persist due to indirect processes, such as diesel use in geothermal drilling or fossil-based hydrogen in heat networks.

Electrified systems show increased reliance on metals and minerals, particularly in configurations involving batteries and solar panels. This reflects a trade-off between reducing direct emissions and increasing dependency on critical raw materials.

Renewable electricity systems are significantly more water-intensive than CHP-based systems. Under LCA, renewable electricity causes a high life cycle water use score. This is in large part due to the use of the proxy of renewable electricity from Switzerland. This proxy gets a portion of its electricity generated via hydropower, which has a large water use footprint. This does not reflect a likely Dutch renewable energy system. That is unless a large quantity is bought from neighbouring countries that do generate electricity via hydropower. To account for this a contribution analysis of the renewable electricity process is performed. The results show that around half of the water use is caused by the renewable electricity in fossil-free systems. This means that the water use scores are over inflated in the LCA results. However, when the impact from renewable electricity is removed the fossil-free systems still score significantly higher than the CHP system. So while this may not pose a major issue in the Netherlands today nor is it as big as the LCA results might suggest, it could still become problematic under future climate scenarios.

Freshwater eutrophication increases modestly in alternative energy scenarios, primarily due to landfill treatment of waste materials. Although these emissions occur outside the greenhouse, they are linked to material choices and disposal practices within the sector.

Toxicity and land use were not explored in depth, but may warrant further investigation. For now, the focus remains on those categories with the highest normalized impacts and the clearest relevance to the sector's transition goals.

Sub RQ 6 Allocation

Allocation methods significantly influence LCA outcomes. This economic allocation (default) is compared with heat-only allocation (common in sector practice). Economic allocation distributes burdens based on the relative market value of heat, electricity, and CO_2, whereas heat-only allocation assigns 100 % of emissions from natural-gas combustion to heat.

Under heat-only allocation, part of the system (electricity and CO_2) appears burden-free even though its production emits greenhouse gases. This means tomato growers that rely on CHP, are held responsible for all natural-gas emissions, including those linked to electricity use by other parties.

The recommended allocation methods are not universally correct, nor are any allocation methods. Transparency in methodological choices are essential. Therefore the Excel tool lets users toggle between allocation schemes, enabling side-by-side comparisons and context-specific interpretations.

To reflect real-world sector perspectives, the sensitivity analysis also incorporates unconventional allocation scenarios derived from stakeholder dialogues. These viewpoints treat electricity and CO_2 as emissionless by-products of heat generation, which makes investments in renewables look more attractive and de-emphasizes CO_2 enrichment reduction. These are not recommended for rigorous foot printing. They are included to explore why certain practices may persist.

For example the heavy investment into renewables can be in part explained by the view that electricity and CO2 are emissionless byproducts from heat production in CHP. In other words, the heat production for tomatoes is responsible for all of the CO2 produced by burning natural gas. Making the current system seem more environmentally polluting since the allocation is missing.

9.2. Main Research Questions

Main RQ 1 Most Important Emissions

Focusing solely on greenhouse gas emissions risks overlooking other critical environmental pressures. Impact categories such as land use, biodiversity loss, and particulate matter formation were excluded from the core analysis due to data gaps or lower stakeholder relevance. Yet as the sector adopts land-intensive technologies or novel agricultural practices, these impacts could gain prominence.

Although land use, biodiversity loss, and particulate matter formation were not part of the core analysis due to data gaps and lower priority among stakeholders, they could become significant as the sector adopts land-intensive systems. Any shift toward expanded outdoor propagation, substrate-based systems, or more extensive infrastructure may amplify these impacts.

Toxicity-related categories, notably human toxicity and ecotoxicity, do appear in the results yet carry substantial uncertainty from incomplete emission data and broad characterisation models (Rosenbaum et al., 2008). Despite this volatility, the fact that processes like battery manufacturing, waste treatment, and chemical-dependent infrastructure register in toxicity scoring signals latent health and ecosystem risks. Future studies should therefore refine toxicity pathway modelling and, where possible, incorporate site-specific impact assessments to capture these dimensions more reliably.

Ultimately, there is no one-size-fits-all answer to which emission is "most important." Priorities vary across stakeholders and evolve over time. The sector's current emphasis on reducing fossil fuel use and carbon emissions is well justified, these categories score high in environmental impact scores and align with clear, measurable targets. However, the analysis also shows that eutrophication and water use should not be ignored.

The optimal system configuration depends on which impacts are prioritized, and those priorities may shift. Integrating a broader suite of environmental metrics into decision-support tools will help the sector navigate these trade-offs as it decarbonizes and diversifies.

Main Rq 2 Resource Risks

The shift toward electrification introduces new dependencies on critical raw materials (CRMs) such as lithium, cobalt, and rare earth elements. These materials are often sourced from geopolitically sensitive regions, raising concerns about supply chain stability and ethical sourcing. Cobalt, for instance, is overwhelmingly sourced from the Democratic Republic of Congo, where persistent political instability and reports of poor labour practices pose ethical dilemmas and heighten the likelihood of production shocks (Deberedt, 2024). Lithium likewise originates mainly from Australia, Chile, and China, each with its own mix of export controls, environmental regulations, and market interventions. Such reliance makes the upstream supply especially prone to geopolitical disruptions, trade embargoes, or sudden price swings (Hailes, 2022).

The extraction and processing of these raw materials impose heavy environmental burdens largely borne by exporting countries. This offshoring of impacts severs the link between the Netherlands' sustainability gains and the real-world costs in producer regions. Such disconnect underscores the need to address equity and ethical sourcing in any transition to low-carbon technologies.

Beyond geopolitical and environmental concentration, escalating demand for critical raw materials across transportation, energy storage, and electronics sectors intensifies competition for finite reserves. This mounting pressure can create bottlenecks in the manufacture and deployment of renewables-enabling technologies. For Dutch tomato growers, even a strong willingness to invest in electrified, CO_2-recapture systems may be hindered by delays or unexpected cost increases driven by material shortages (Mahnoor et al., 2025). Smaller producers are particularly exposed, as they might lack the purchasing power and long-term contracts that larger agribusinesses can use to secure access to scarce resources (Eso et al., 2010).

Resource risk is assessed using GeoPolRisk, SOP, and ADP indicators. Each of which underlines a different problem within resources. CRM used in GeoPolRisk captures short-term supply vulnerabilities driven by geopolitical tensions and market concentration (Santillán-Saldivar et al., 2022). SOP used in the ReCiPe method reflects the additional effort and environmental damage required to extract lower-quality ores as high-grade deposits are depleted (Vieira et al., 2017). ADP used in the EF method assesses, long term, reduced availability of resources in the lithosphere, due to present use, mainly based on physical constraints (van Oers et al., 2020).

In applying the GeoPolRisk characterisation, a notable gap was identified. Spodumene, which is a primary lithium-bearing mineral used in battery manufacture, is not included. This causes lithium-related risks to be systematically undervalued. The SOP metric, by including spodumene, highlights this inconsistency between resource-risk frameworks. To bridge the divide, materials flagged as high-risk by their CFs and Herfindahl-Hirschman Index scores were manually cross-checked against LCI data and relevant literature. This revealed that several critical metals, most prominently lithium compounds, appear underrepresented in the LCI. This is likely a consequence of outdated databases or simplified modelling assumptions.

The resource risk assessment results underscore the necessity of employing multiple metrics to capture both depletion dynamics and geopolitical vulnerability. Future iterations of the decision-support tool could integrate GeoPolRisk, SOP, and ADP dashboards to enable users to visualise trade-offs between immediate supply risks and long-term resource depletion.

Resource Use Concerns

While the per-kilogram material demand for greenhouse tomatoes appears modest, scaling these inputs to the Dutch sector's annual output (around 1.2 million tonnes) uncovers significant strategic vulnerabilities.

Similarly CO_2 feedstock sourcing will shift from on-site combustion to external provision as growers decarbonize heating. Exact demand depends on crop variety and season, however projections would show requirements far exceeding current outputs from suppliers like Shell and Alco (Ros et al., 2014). Thus alternative CO_2 streams warrant detailed lifecycle and supply-chain assessment.

Additionally, integrating critical raw material (CRM) risk into decision-support tools, and circular economy strategies will be needed to mitigate dependency. To ensure stable access to both materials and CO_2 feedstock, proactive, sector-wide collaboration between horticulture, energy providers, equipment manufacturers, and recycling networks will be needed. Future research should also look into the circularity of resources and examine potential industrial symbiosis.

Main RQ 3 Sensitivity

Given the complexity of greenhouse horticulture systems and the uncertainty surrounding future energy and CO_2 sourcing strategies, sensitivity testing plays a crucial role in validating the comparative conclusions drawn from the Life Cycle Assessment (LCA).

The most influential variable was the level of CO_2 enrichment. In the baseline scenario, enrichment demand was matched to the CO_2 output of CHP systems. However, this assumption leads to disproportionately high emissions in alternative energy scenarios, since most of the added CO_2 was vented rather than absorbed.

Several additional sensitivity scenarios were identified but not modelled due to constraints. These include intra-annual variations in heating and solar availability, degradation of battery efficiency over time, and the embodied emissions of capital goods such as solar panels. Yield-related trade-offs, such as the potential 4 % loss if enrichment is reduced to 0.25 kg CO_2/kg tomato, were noted but excluded to maintain a fixed functional unit.

The inclusion of allocation choices in the Excel decision-support tool ultimately ensures that growers or decision makers can explore how each assumption influences environmental outcomes. By tailoring scenarios to their own operational realities and priorities, users can identify robustness thresholds, uncover hidden trade-offs, and make more informed decisions on both technological upgrades and agronomic practices.

Tool Creation

The Excel-based decision-support tool developed in this thesis enables stakeholders to explore trade-offs across greenhouse energy configurations. It translates the static LCA model into an interactive format. The tool includes toggles for:

- CO_2 enrichment levels
- CO_2 sourcing
- Electricity sourcing
- Allocation method
- Battery inclusion

While the tool is designed for flexibility, it is based on a static LCA model and does not account for seasonal variation, dynamic pricing, or economic performance. To broaden applicability and decision relevance, future versions could incorporate time-series data for heating, lighting, and CO_2 demand to capture seasonal swings. Alternatively links with real-time electricity tariffs or peer-to-peer trading platforms could improve the assessment of cost-emissions trade-offs.

To improve clarity and stakeholder engagement, the tool converts environmental impacts into euro values using the Dutch government's 2023 environmental price handbook. However, these economic values are inherently normative and may skew priorities. High costs assigned to greenhouse gases and nitrogen reflect current Dutch policy, while water use is undervalued despite looming scarcity (Erbach & Dewulf, 2024; Toreti et al., 2022). Toxicity valuations are especially volatile, since uncertainties in characterization factors can cause large swings in scores. Moreover, aggregating impacts into one number can hide important trade-offs across categories (Mantovani, 2018). Thus, monetized results should complement and not replace traditional impact scores. Future updates could introduce dynamic pricing, regional adjustments, stakeholder weighting, and links to resource-risk indicators

9.3. Generalisability

The current findings derive from a case study on tomatoes grown in a 5 ha greenhouse in the western Netherlands. While the comparative insights between energy pathways are internally consistent, applying these results to other crops, greenhouse scales, or regions without adjustments risks misleading conclusions.

Contextual factors that influence transferability encompass crop-specific traits such as physiological demands, yield potential, and seasonal growth cycles. Next to that greenhouse scale and design considerations including heat loss dynamics, lighting layouts, automation levels, and structural materials, play an important role. Additionally, regional conditions covering local climate variables, grid electricity mixes, and technology choices ranging from heating and cooling systems to greenhouse materials are all additional reasons as to why crop specific modelling is crucial for accurate environmental reporting.

To enhance generalisability, future research should adopt a modular life cycle assessment framework guided by clearly defined assumptions. Such a framework would allow users to mix and match modules for different crops, climate zones, structural designs, and technology options.

9.4. Comparison to earlier or other studies

This thesis builds upon and extends a growing body of literature on the environmental performance of greenhouse horticulture, particularly in the context of energy use and climate change mitigation. Earlier studies such as those by Pluimers et al. (2000, 2001), Vermeulen (2010), and more recently Ali et al. (2023), have primarily focused on the carbon footprint of tomato production, often comparing produce grown using conventional systems with Combined Heat and Power (CHP) to produce grown using unheated polytunnels or produce that is grown in fields and transported over from other countries.

While valuable, they typically focus on current or near-term scenarios and emphasize greenhouse gas emissions as the primary metric. In contrast, this thesis adopts a future-oriented perspective, incorporates a broader range of environmental indicators and introduces resource risk assessment. Moreover, the inclusion of stakeholder perspectives and the development of an interactive decision-support tool further distinguish this work from earlier research, making it more applicable to real-world decision-making.

While previous studies have laid the groundwork for understanding the environmental impacts of greenhouse horticulture, this thesis contributes a more nuanced, forward-looking, and stakeholder-responsive analysis that is better aligned with the sector's evolving sustainability goals.

9.5. Limitations

While this thesis provides a detailed comparative Life Cycle Assessment (LCA) of energy transition pathways in Dutch tomato horticulture, several limitations must be acknowledged. These limitations pertain to the modelling framework, data availability, system boundaries, and methodological assumptions. Recognizing these constraints is essential for interpreting the results responsibly and identifying directions for future research.

1. Attributional Scope
An attributional LCA approach is employed to quantify the environmental burdens per 1 kg of tomatoes under different energy configurations. While this method is well-suited for comparing static systems, it does not account for broader market dynamics or indirect effects, such as changes in electricity demand, shifts in CO_2 sourcing infrastructure, or feedback loops in material supply chains. For example, increased demand for renewable electricity in horticulture could influence grid pricing, and these effects are not captured in the model. A consequential LCA could complement this work by modelling system-wide changes and exploring how decisions in the horticulture sector might affect the greater system.

2. Seasonality and Temporal Resolution
All energy use, CO_2 enrichment, and impact results are based on annualized averages. Yet greenhouse operations exhibit pronounced seasonal swings. Winter heating demand can double compared to annual means, while summer solar gains and plant CO_2 uptake fluctuate daily and monthly. This temporal mismatch may lead to overestimation of system performance, particularly for technologies like geothermal wells or solar panels. For example a geothermal well can provide for five 5ha tomato greenhouses if the demand is consistent, however if the winter demand is high the well might only be able to prove three 5ha greenhouses with their demand. While the Excel tool includes feasibility checks for electrification limits, the tool does not fully account for all inconsistent demand.

3. Data Gaps and Proxy Use

Several key processes in the model such as geothermal well construction, battery production, and CO_2 capture, were modelled using proxies or scaled datasets. This was due to the absence of detailed, region-specific data in the Ecoinvent database. For example, geothermal wells were modelled based on deep electricity-generating installations, even though the actual systems used in Dutch horticulture are shallower and heat-only. Similarly, battery systems were approximated using electric vehicle battery data. While these proxies were selected carefully, they introduce uncertainty into the results. Additionally, some capital goods and auxiliary systems (e.g., dehumidifiers, water pumps, control systems) were simplified or excluded due to data limitations, which may affect the completeness of the environmental inventory. Future research should aim to secure more primary data from Dutch horticultural operators.

4. Functional Unit and Crop Specificity

The functional unit used in this study is the production of 1 kg of tomatoes in a 5-hectare Dutch greenhouse. While this provides a consistent basis for comparison, it limits the generalisability of the results. Different tomato varieties may have different yields, growth cycles, and environmental requirements. Moreover, crops such as cucumbers, peppers, or leafy greens, may have entirely different heating and CO_2 enrichment needs. The results of this study should therefore not be extrapolated to other crops or production systems without careful adjustment. Future research could expand the model to include multiple crop types and greenhouse configurations to improve its applicability across the sector.

5. Uncharacterized and Missing Flows

Despite using comprehensive impact assessment methods (ReCiPe and PEF), some environmental flows could not be characterized due to missing characterization factors (CFs) in the Ecoinvent 3.9.1 database. This is particularly relevant for emerging technologies and trace materials used in batteries, solar panels, and CO_2 capture systems. For example, certain rare earth elements and specialty chemicals may contribute to toxicity or resource depletion but are not fully accounted for in the impact assessment. These gaps may lead to underestimation of certain impact categories, particularly human and ecotoxicity, and underscore the need for ongoing updates to LCA characterization factors.

6. Simplified Economic and Yield Modelling

The focus is on environmental impacts and does not include economic performance metrics or yield variability across scenarios. While the environmental impacts are modelled per kilogram of tomatoes, the economic feasibility and productivity of each energy system may differ significantly. For example, systems with higher capital costs or lower reliability may be less attractive to growers, even if they perform better environmentally. Similarly, additional reduction in CO_2 enrichment levels could have been considered, however any further reduction would have affected the yield. These omissions limit the ability to assess trade-offs between environmental and financial performance, an important consideration for real-world decision-making.

7. Infrastructure and Grid Constraints

The model assumes that infrastructure such as electricity grids, heat networks, and CO_2 pipelines, are available and scalable. In practice, grid congestion, spatial limitations, and permitting challenges may constrain the feasibility of certain energy mixes. For example, full electrification of greenhouses may not be possible in regions with limited grid capacity, and not all growers have access to geothermal wells or OCAP pipelines. These infrastructural realities are acknowledged, however they are not explicitly modelled. As a result, some scenarios may be technically feasible on paper but difficult to implement in practice. Integrating spatial-infrastructure and network-capacity analyses would improve the practical feasibility assessment of future scenarios.

9.6. Methodological Strengths

The scenario-based design stands out as a key advantage. By modelling eight distinct energy configurations and incorporating sensitivity toggles for CO_2 sourcing, enrichment levels, electricity mix, and allocation methods, the framework accommodates real-world variability. Stakeholders can explore specific trade-offs under diverse operational conditions, enhancing the relevance of the results for decision-makers. Sector viewpoints are embedded and further enriches the analysis by not imposing a single normative lens.

The tool bridges theory and practice. Translating cradle-to-gate LCA insights into actionable guidance aligns academic rigor with growers' and policymakers' needs, while the integration of resource risk indicators exemplifies systems thinking and resource criticality assessment. This holistic method can be replicated in other agricultural and industrial contexts.

10
Conclusion

This thesis explored the question: "How do 2040 fossil-free energy transition pathways in Dutch tomato horticulture influence cradle-to-gate environmental impacts and resource risks, and how are environmental scores shaped by sectoral practices of enrichment and attribution?"

Using attributional LCA, seven alternative energy configurations were compared to the current CHP system, focusing on cradle-to-gate impacts. The analysis was enhanced with GeoPolRisk-based resource risk assessment and the development of an Excel-based decision-support tool for growers and policymakers.

Conducted within the interdisciplinary Thesis Lab "The Future of Energy in the Horticulture Sector," the research emphasized applied, stakeholder-informed methods. The findings reveal that cradle-to-gate environmental impacts are highly sensitive to CO_2 enrichment levels, allocation methods, and material sourcing. Crucially, the analysis shows that without improving enrichment efficiency, the environmental benefits of transitioning to renewable energy systems are significantly diminished. Therefore, achieving climate-neutral tomato production depends not only on energy system transitions but also on minimizing CO_2 venting.

In terms of resource risks, electrified systems (e.g. heat pumps, geothermal) reduce fossil fuel dependency but introduce exposure to critical raw materials such as lithium, cobalt, and rare earth elements. These risks are often overlooked in sectoral decision-making but pose long-term vulnerabilities, especially under geopolitical instability.

The study also reveals deeper misalignments in the sector. The term climate neutrality itself lacks a consistent operational definition, complicating comparisons across systems and policies. Similarly, what constitutes fair allocation remains contested. Economic allocation offers a balanced view, but no method is universally correct. These conceptual gaps limit the clarity and comparability of sustainability claims, and might slow down the sector's transition.

Ultimately, achieving climate neutrality in Dutch tomato horticulture by 2040 requires more than adopting fossil-free energy, it demands a systemic shift in how environmental performance is defined, measured, and managed. This thesis provides a foundation for that shift and invites further interdisciplinary collaboration to guide sustainable transitions in agriculture.

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A

Main LCA Results Tables

Table A1

Characterised Results of the LCA for the Production of Tomatoes.

Impact categories	Unit	CHP	Geothermal	Heat Network	Heat Pump (SOLE)	Heat Pump (WKO)	Heat Pump (DEH)	Solar (IND)	Solar (BAT)
acidification: terrestrial - terrestrial acidification potential **(TAP)**	kg SO2-Eq	2,40E-03	2,14E-03	2,74E-03	2,31E-03	2,30E-03	2,37E-03	2,17E-03	2,21E-03
climate change - global warming potential **(GWP100)**	kg CO2-Eq	1,46E+00	1,46E+00	1,79E+00	1,47E+00	1,48E+00	1,50E+00	1,47E+00	1,48E+00
ecotoxicity: freshwater - freshwater ecotoxicity potential **(FETP)**	kg 1,4-DCB-Eq	6,59E-02	9,51E-02	9,94E-02	1,19E-01	1,17E-01	1,20E-01	9,60E-02	9,71E-02
ecotoxicity: marine - marine ecotoxicity potential **(METP)**	kg 1,4-DCB-Eq	8,38E-02	1,21E-01	1,26E-01	1,51E-01	1,48E-01	1,52E-01	1,22E-01	1,24E-01
ecotoxicity: terrestrial - terrestrial ecotoxicity potential **(TETP)**	kg 1,4-DCB-Eq	3,10E+00	4,83E+00	5,16E+00	6,08E+00	5,97E+00	6,13E+00	5,16E+00	5,22E+00
energy resources: non-renewable, fossil - fossil fuel potential **(FFP)**	kg oil-Eq	4,93E-01	2,07E-01	4,44E-01	2,08E-01	2,09E-01	2,13E-01	2,09E-01	2,10E-01
eutrophication: freshwater - freshwater eutrophication potential **(FEP)**	kg P-Eq	2,28E-04	2,69E-04	3,08E-04	2,85E-04	2,84E-04	2,94E-04	2,72E-04	2,75E-04
eutrophication: marine - marine eutrophication potential **(MEP)**	kg N-Eq	2,03E-05	2,75E-05	3,26E-05	2,78E-05	2,79E-05	2,87E-05	2,84E-05	2,88E-05
human toxicity: carcinogenic - human toxicity potential **(HTPc)**	kg 1,4-DCB-Eq	1,13E-01	2,16E-01	2,19E-01	2,15E-01	2,16E-01	2,30E-01	2,12E-01	2,13E-01
human toxicity: non-carcinogenic - human toxicity potential **(HTPnc)**	kg 1,4-DCB-Eq	7,13E-01	9,74E-01	1,07E+00	1,18E+00	1,16E+00	1,19E+00	9,89E-01	1,01E+00
ionising radiation - ionising radiation potential **(IRP)**	kBq Co-60-Eq	5,33E-02	5,84E-02	7,54E-02	5,43E-02	5,46E-02	5,52E-02	5,47E-02	5,50E-02

land use - agricultural land occupation **(LOP)**	m2*a crop-Eq	3,73E-02	5,02E-02	5,16E-02	5,12E-02	5,11E-02	5,15E-02	5,01E-02	5,02E-02
material resources: metals/minerals - surplus ore potential **(SOP)**	kg Cu-Eq	3,17E-02	5,04E-02	5,99E-02	5,02E-02	5,04E-02	5,56E-02	4,93E-02	5,08E-02
ozone depletion - ozone depletion potential **(ODPinfinite)**	kg CFC-11-Eq	1,68E-06	9,30E-07	1,01E-06	9,79E-07	9,76E-07	9,82E-07	9,32E-07	9,34E-07
particulate matter formation - particulate matter formation potential **(PMFP)**	kg PM2.5-Eq	8,59E-04	8,52E-04	1,06E-03	9,06E-04	9,03E-04	9,45E-04	8,67E-04	8,82E-04
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans **(HOFP)**	kg NOx-Eq	2,88E-03	1,52E-03	1,99E-03	1,56E-03	1,56E-03	1,61E-03	1,54E-03	1,55E-03
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems **(EOFP)**	kg NOx-Eq	2,99E-03	1,62E-03	2,13E-03	1,66E-03	1,66E-03	1,72E-03	1,64E-03	1,66E-03
water use - water consumption potential **(WCP)**	m3	5,65E-03	1,81E-02	2,41E-02	2,84E-02	2,74E-02	2,82E-02	1,84E-02	1,84E-02

Table A2

Normalized Results of the LCA for the Production of Tomatoes.

Impact categories	Unit	CHP	Geothermal	Heat Network	Heat Pump (SOLE)	Heat Pump (WKO)	Heat Pump (DEH)	Solar (IND)	Solar (BAT)
acidification: terrestrial - terrestrial acidification potential **(TAP)**	kg SO2-Eq	5,86E-05	5,23E-05	6,68E-05	5,63E-05	5,60E-05	5,79E-05	5,30E-05	5,39E-05
climate change - global warming potential **(GWP100)**	kg CO2-Eq	1,84E-04	1,84E-04	2,25E-04	1,86E-04	1,86E-04	1,88E-04	1,85E-04	1,86E-04
ecotoxicity: freshwater - freshwater ecotoxicity potential **(FETP)**	kg 1,4-DCB-Eq	5,37E-02	7,75E-02	8,10E-02	9,72E-02	9,54E-02	9,80E-02	7,82E-02	7,91E-02
ecotoxicity: marine - marine ecotoxicity potential **(METP)**	kg 1,4-DCB-Eq	8,12E-02	1,17E-01	1,22E-01	1,46E-01	1,43E-01	1,47E-01	1,18E-01	1,20E-01
ecotoxicity: terrestrial - terrestrial ecotoxicity potential **(TETP)**	kg 1,4-DCB-Eq	2,99E-03	4,66E-03	4,98E-03	5,87E-03	5,76E-03	5,92E-03	4,98E-03	5,04E-03
energy resources: non-renewable, fossil - fossil fuel potential **(FFP)**	kg oil-Eq	5,03E-04	2,11E-04	4,53E-04	2,12E-04	2,13E-04	2,17E-04	2,13E-04	2,14E-04
eutrophication: freshwater - freshwater eutrophication potential **(FEP)**	kg P-Eq	3,52E-04	4,14E-04	4,75E-04	4,39E-04	4,38E-04	4,52E-04	4,20E-04	4,24E-04
eutrophication: marine - marine eutrophication potential **(MEP)**	kg N-Eq	4,41E-06	5,97E-06	7,07E-06	6,04E-06	6,06E-06	6,24E-06	6,17E-06	6,24E-06
human toxicity: carcinogenic - human toxicity potential **(HTPc)**	kg 1,4-DCB-Eq	4,10E-02	7,79E-02	7,91E-02	7,77E-02	7,79E-02	8,30E-02	7,67E-02	7,69E-02
human toxicity: non-carcinogenic - human toxicity potential **(HTPnc)**	kg 1,4-DCB-Eq	4,78E-03	6,54E-03	7,16E-03	7,88E-03	7,77E-03	7,99E-03	6,63E-03	6,75E-03
ionising radiation - ionising radiation potential **(IRP)**	kBq Co-60-Eq	1,11E-04	1,21E-04	1,57E-04	1,13E-04	1,14E-04	1,15E-04	1,14E-04	1,14E-04
land use - agricultural land occupation **(LOP)**	m2*a crop-Eq	6,04E-06	8,13E-06	8,37E-06	8,29E-06	8,28E-06	8,35E-06	8,12E-06	8,14E-06
material resources: metals/minerals - surplus ore potential **(SOP)**	kg Cu-Eq	2,64E-07	4,20E-07	4,99E-07	4,18E-07	4,20E-07	4,64E-07	4,11E-07	4,23E-07

ozone depletion - ozone depletion potential **(ODPinfinite)**	kg CFC-11-Eq	2,80E-05	1,55E-05	1,69E-05	1,64E-05	1,63E-05	1,64E-05	1,56E-05	1,56E-05
particulate matter formation - particulate matter formation potential **(PMFP)**	kg PM2.5-Eq	3,36E-05	3,33E-05	4,16E-05	3,54E-05	3,53E-05	3,69E-05	3,39E-05	3,45E-05
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans **(HOFP)**	kg NOx-Eq	1,40E-04	7,39E-05	9,65E-05	7,56E-05	7,57E-05	7,84E-05	7,47E-05	7,55E-05
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems **(EOFP)**	kg NOx-Eq	1,69E-04	9,15E-05	1,20E-04	9,35E-05	9,36E-05	9,69E-05	9,26E-05	9,34E-05
water use - water consumption potential **(WCP)**	m3	2,12E-05	6,79E-05	9,04E-05	1,07E-04	1,03E-04	1,06E-04	6,89E-05	6,90E-05

B

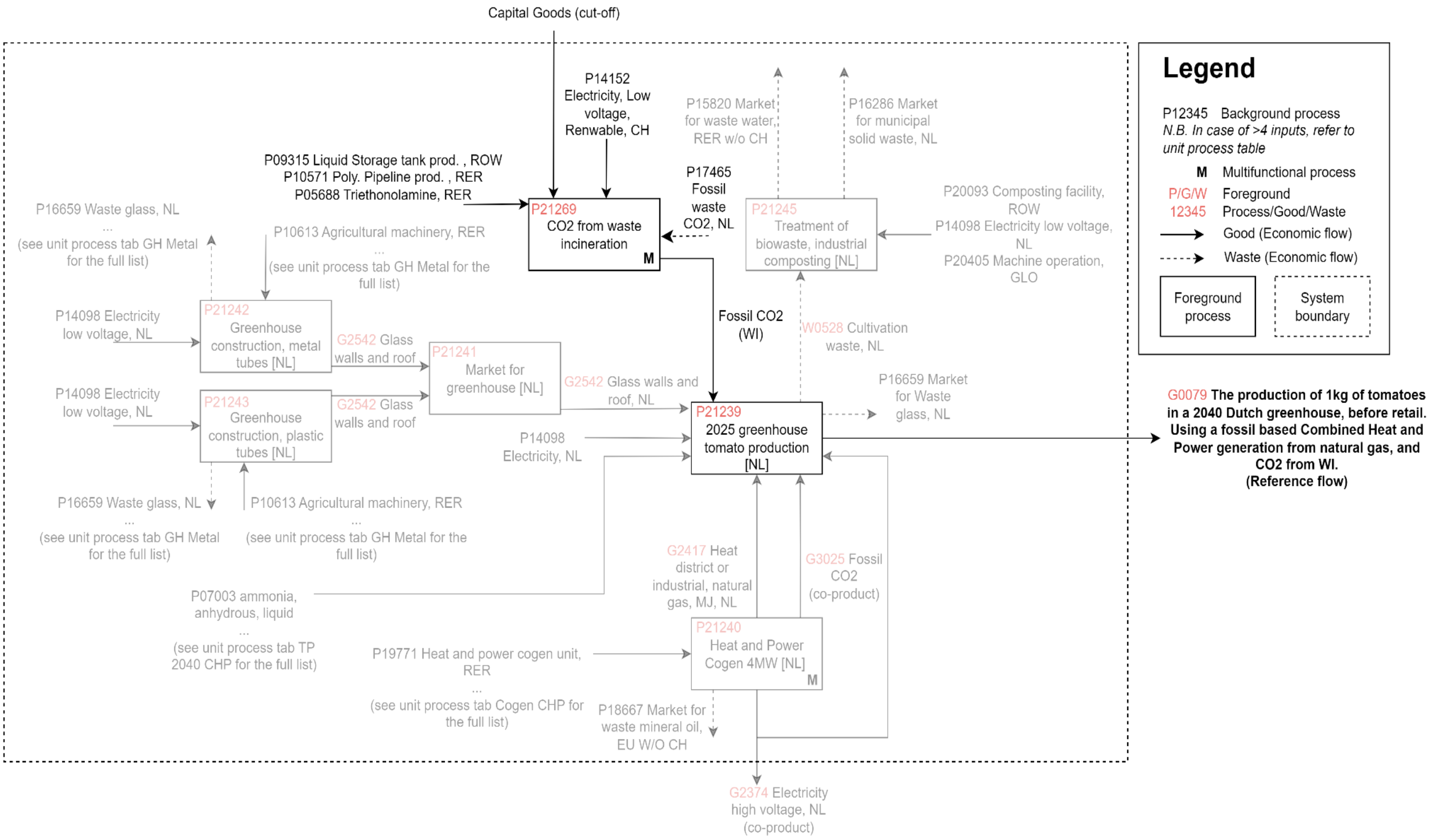
Sensitivity Flowcharts

Flowchart 1B: The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using a fossil based Combined Heat and Power generation from natural gas. (With CO2 sourced from Waste Incineration)

Opposed to the production of tomatoes using OCAP sourced CO2, the small amount of CO2 needed when a CHP generator is used, the CO2 can also be sourced from Waste Incineration. The difference in effect is little since the demand of CO2 per kg of tomatoes is in both cases too little to make a significant change. The parts that are faded out in the flowchart are the same as flowchart 1.

Figure B1

LCA Flowchart: Tomato Production Using CHP and Waste Incineration sourced CO_2.

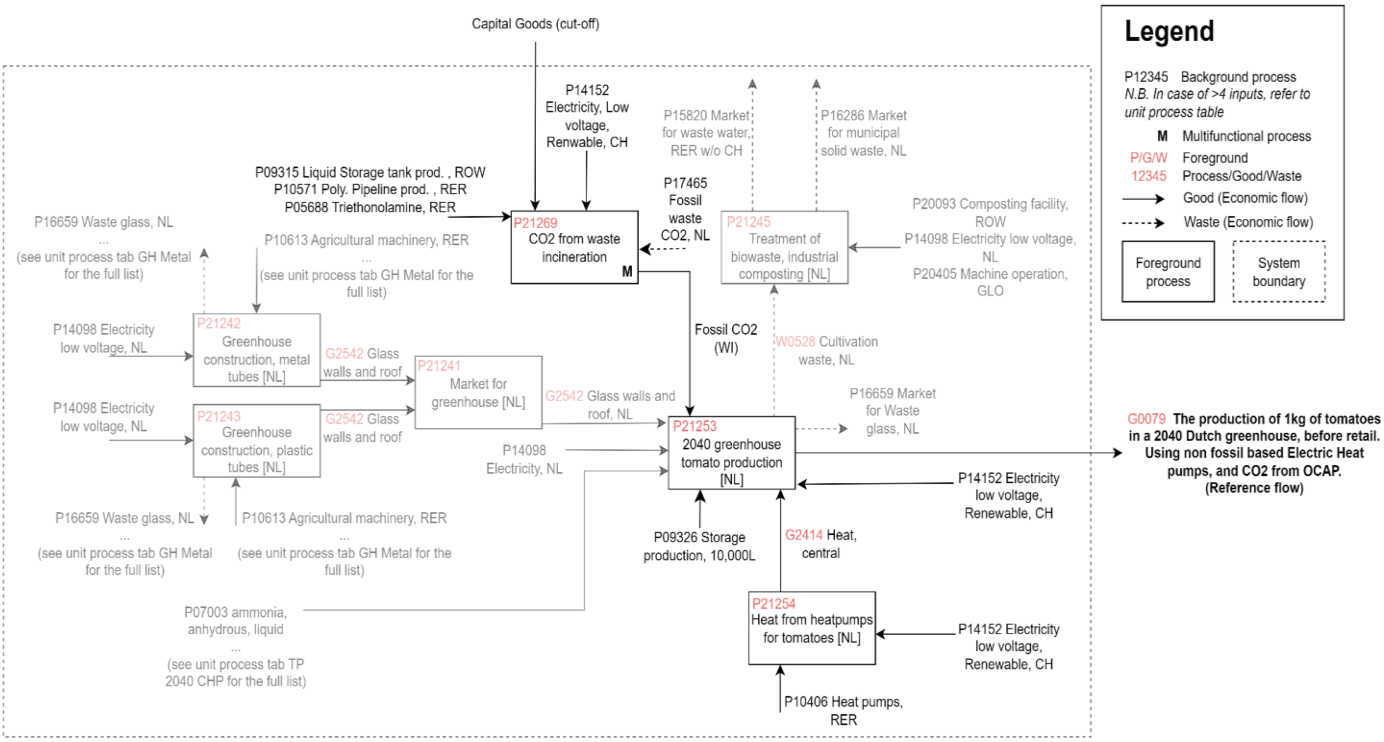


Flowchart 4B: The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using non fossil based Electric Heat pumps. (With CO2 sourced from Waste incineration)

The chart is in principle the same as 4A, the difference is only in the CO2 provision. rather than getting 1.2kg of CO2 from OCAP the CO2 is sourced from Waste incineration.

Figure B2

LCA Flowchart: Tomato Production Using Heat Pump and Waste Incineration sourced CO_2.



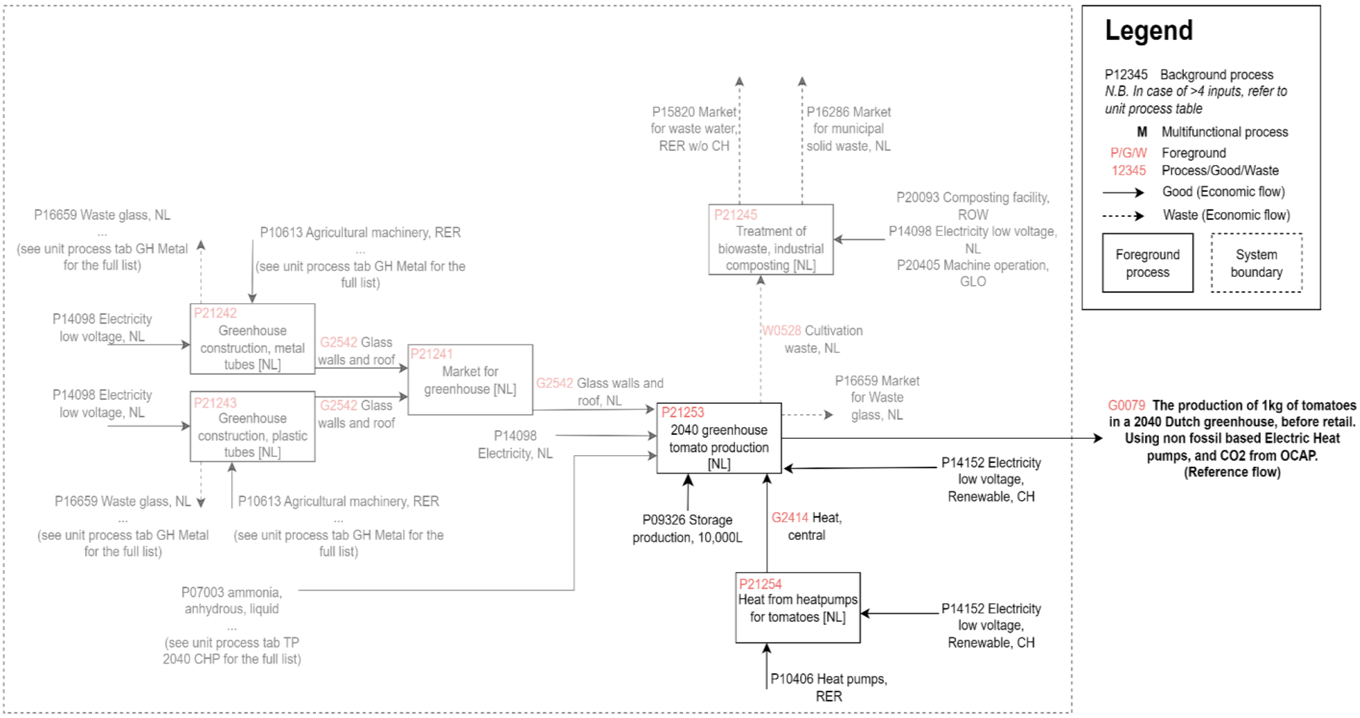
Flowchart 4C: The production of 1kg of tomatoes in a 2040 Dutch greenhouse, before retail. Using non fossil based Electric Heat pumps. (With no CO2 sourced)

The growers also do not have to enrich their crops with CO2. This does have a potentially significant effect on their yield however the trade-off between the two is outside of the scope of this study. Rather the option to do so exists and is therefore modelled. It also serves as a baseline for the flowcharts 4A and 4B. The difference between the two and the baseline indicates the emissions that purely the CO2 enrichment is responsible for. This difference can be applied to the other scenarios, reducing the amount of LCA's results that have to be manually quantified.

Figure 4A and 4C are the same, and the difference can only be found in the quantity of CO2 supplied by OCAP. In 4 A this value is 1.2kg and in 4C this value is 0. Effectively removing the CO2 supply.

Figure B3

LCA Flowchart: Tomato Production Using Heat Pump and No CO_2.



C
Assumptions and Modelling Choices

System 1 CHP

The baseline scenario models 2040 tomato production as unchanged from 2025: natural-gas CHP heating with a small amount of OCAP-sourced CO_2 enrichment. It serves as the reference point. Each alternative scenario swaps in geothermal networks, residual heat from hydrogen production, or electric heat pumps, while keeping CO_2 enrichment at 1.2 kg per kg of tomatoes, mirroring CHP emissions. This assumes plants absorb roughly 12.5% of the CO_2 supplied, with the remaining 87.5% vented back into the atmosphere.

System 2 Geothermal Network

This scenario mirrors the 2040 baseline for tomato production, 1 kg of tomatoes in a Dutch greenhouse. The exception is that all heat comes from a non-fossil geothermal network and CO_2 is sourced externally.

CO_2 enrichment is fixed at 1.2 kg per kilogram of tomatoes, matching the emissions that would result from natural-gas CHP. In reality, plants absorb only about 12–15 % of the CO_2 supplied; the remaining 85–88 % is vented back into the atmosphere.

Following Ecoinvent conventions, the CO_2 taken up by the plants is treated as biogenic and carries no climate-change impact, on the grounds that fixed carbon is ultimately re-emitted. Some stakeholders argue for a negative factor to reward temporary storage in biomass, while others insist that every kilogram of CO_2 should incur a positive factor. We retain the neutral approach and attribute only the unassimilated CO_2—roughly 85 %—as a direct emission from the grower.

To reflect differing perspectives, the accompanying model includes a toggle that lets users assign responsibility for vented CO_2 either to the grower (default) or to the external CO_2 supplier. This flexibility ensures transparency and adaptability as sector norms and regulations evolve.

System 3 Heat Network

This scenario replaces on-site CHP with residual heat drawn from an industrial district heating system, modelled on the WarmtelinQ pipeline linking the Rotterdam port to greenhouse clusters. The thermal energy originates as waste heat from hydrogen production rather than natural-gas combustion.

We proxy hydrogen production using liquefaction, which runs at roughly 30–40 % efficiency. The discarded 60–70 % of input energy becomes waste heat, about 4 MJ per kilogram of H_2. Meeting the 10.7 MJ needed to grow 1 kg of tomatoes thus requires around 2.7 kg of H_2. Emissions are allocated economically: since heat is the lower-value byproduct, nearly all environmental burden falls on the hydrogen itself, leaving the heat supply with a modest footprint (though this allocation carries market-based uncertainty).

Pipeline infrastructure is represented by a 5 km DN700 segment with a 40-year lifespan, prorated so that our greenhouse bears 1/1,000 of the network's embodied impacts, reflecting service to roughly 5,000 ha of greenhouses.

CO_2 enrichment stays at 1.2 kg per kilogram of tomatoes via the OCAP network. As elsewhere, we treat the 12.5% of CO_2 fixed by the plants as biogenic (climate-neutral) and assign the remaining 87.5% vented CO_2 to the grower.

While tapping industrial waste heat offers a low-carbon alternative, its practicality hinges on waste-heat availability, the economics of pipeline build-out, and grower willingness to join centralized networks.

System 4 Electric Heat Pumps

This scenario models the production of 1 kg of tomatoes in a 2040 Dutch greenhouse heated exclusively by electric heat pumps, with CO_2 enrichment supplied via the OCAP network. It assumes full electrification, despite real-world limits of around 42 % heat-pump coverage for consistent comparison across all scenarios. The Excel tool flags feasibility issues when users push beyond practical bounds.

Electricity demand for heating is set at 0.71 kWh per kilogram of tomatoes (equivalent to about 10.7 MJ), based on a 5 ha greenhouse consuming 3.36 GWh annually. A bank of eight 160 kW heat pumps, each with a 20-year lifespan, is scaled to meet this load. To smooth hourly and seasonal peaks, we include a 1,500 m^3 water-based thermal buffer, modelled by scaling up a 10 m^3 reference tank and assuming a 40-year service life.

All electricity is drawn from the projected Dutch renewable grid mix, recognizing that actual 2040 grid composition may differ. Upstream impacts from renewable power, particularly water use and mineral extraction become significant in this fully electrified system.

CO_2 enrichment remains at 1.2 kg per kilogram of tomatoes (matching CHP emissions), with 12.5% uptake treated as biogenic (impact-neutral) and the remaining 87.5% vented and assigned to the grower. The CO_2 itself is considered a waste-stream from industrial suppliers, and only the capture, purification, and transport infrastructure carries an environmental burden.

By eliminating on-site fossil combustion, this scenario cuts direct greenhouse-gas emissions but raises new dependencies on electricity infrastructure and critical materials. It also maintains a link to fossil-based processes through OCAP CO_2. Users can toggle assumptions, such as lower enrichment rates or alternative burden allocations, to test how these choices shift environmental outcomes.

System 5 Electric Heat Pumps with ATES (WKO).

This scenario models 1 kg of tomatoes in a 2040 Dutch greenhouse heated by electric heat pumps coupled with Aquifer Thermal Energy Storage (ATES), with CO_2 enrichment supplied via OCAP. By adding ATES, heat pumps can cover roughly 47 % of annual heating demand (Kas als Energiebron), but for apples-to-apples comparison we scale to 100 % electrification—Excel-tool feasibility checks prevent unrealistic configurations.

Thanks to ATES boosting the heat-pump COP to 5.1, electricity use for heating drops to about 0.64 kWh/kg (10.7 MJ/kg). We model four 160 kW heat pumps (20-year life) instead of eight, and include a 1 500 m^3 water buffer, scaled from a 10 m^3 reference tank, with a 40-year lifespan to smooth hourly and seasonal peaks.

The ATES system uses two 200 m deep wells and a circulation pump, each amortized over 30 years. Drilling and pump impacts are spread across total tomato output; circulation energy is folded into the heat-pump electricity demand.

All power is drawn from the projected Dutch renewable grid mix, making upstream impacts, water use and material extraction, more significant than in other scenarios.

CO_2 enrichment stays at 1.2 kg per kg of tomatoes, with 12.5% uptake treated as biogenic (impact-neutral) and the remaining 87.5% vented and attributed to the grower. The environmental burden of OCAP CO_2 lies in capture, purification, and transport infrastructure, not the gas itself.

This hybrid electrification strategy lowers required heat-pump capacity and enhances seasonal flexibility, but real-world rollout hinges on site geology, permitting processes, and long-term maintenance—issues explored further in the policy discussion.

System 6 Electric Heat Pumps with Dehumidifiers

This scenario models 1 kg of tomatoes in a 2040 Dutch greenhouse heated by electric heat pumps paired with dehumidifiers that recover latent heat, with CO_2 enrichment via the OCAP network. It represents an advanced electrification approach that boosts the share of heating met by electricity through heat-recovery technology.

To maintain comparability, we scale the system to 100 % electrification, despite real-world limits of around 52 % heat-pump coverage with dehumidifiers and build in Excel-tool checks to flag impractical configurations.

Electricity demand for heating is set at 0.66 kWh per kilogram of tomatoes (10.7 MJ/kg), assuming a COP of 5.1. We model seven 160 kW heat pumps (20-year lifespan) to meet this load, reflecting the combined demands of space heating and moisture control.

Dehumidification is handled by two 12 kW condensers (approximated with air-water heat-pump proxies), continuously extracting moisture at about 20 L/hour and consuming roughly 87,600 kWh annually on a 5 ha greenhouse. Heat released during condensation feeds back into the heating loop.

A 750 m^3 water-based thermal buffer, half the size of the standard 1,500 m^3 tank, smooths out hourly and seasonal peaks. It's modelled by non-linearly scaling a 10 m^3 Ecoinvent reference tank and carries a 40-year lifespan.

All electricity is drawn from the projected Dutch renewable grid mix, making upstream water use and critical-material extraction more prominent. CO_2 enrichment remains at 1.2 kg per kilogram of tomatoes, with 12.5% uptake treated as biogenic and the remaining 87.5% vented and attributed to the grower.

By capturing latent heat from dehumidification, this configuration lowers net heating demand and raises electrification potential, but it also drives up total electricity use and adds complexity via extra condensers and buffer tanks. Its real-world viability hinges on reliable power supply, seamless integration of dehumidifiers, and growers' operational practices.

System 7 Electric Heat Pumps with Solar Panels

This scenario heats a 2040 Dutch greenhouse via electric heat pumps powered by an on-site solar PV array, with CO_2 enrichment from the OCAP network. It builds on the standalone heat-pump model but swaps grid electricity for solar power. Drawing on the Solarkas Velden benchmark, we assume panels cover one-sixth of the 5 ha greenhouse, generating roughly 20 GWh per year. This is about six times the heat-pump demand.

Heating demand stays at 0.71 kWh per kg of tomatoes (10.7 MJ/kg), met by eight 160 kW heat pumps (20-year life) and buffered by a 1 500 m^3 water tank (40-year life). The PV system follows the

Ecoinvent multi-Si wafer profile, scaled to match Velden's panel density, with a 30-year lifespan and impacts amortized over its total electricity output.

Solar generation is fed into the grid and repurchased as needed, effectively using the grid as a virtual battery. This avoids modelling on-site storage but doesn't capture potential grid congestion challenges in intensive greenhouse regions.

CO_2 enrichment remains at 1.2 kg per kg of tomatoes; 12.5% is fixed and treated as biogenic (impact-neutral), while the remaining 87.5% is vented and attributed to the grower. The environmental burden of OCAP CO_2 lies in capture, purification, and transport infrastructure.

On-site solar cuts dependence on external electricity and reduces operational emissions, but it shifts impacts to PV manufacturing and introduces the complexity of matching intermittent solar supply with continuous heating demand.

The model lets users vary panel coverage, virtual storage approaches, and enrichment settings to explore trade-offs between energy autonomy, environmental impact, and grid interaction.

System 8 Electric Heat Pumps with Solar Panels and Batteries.
This scenario heats 1 kg of tomatoes in a 2040 Dutch greenhouse using electric heat pumps powered by on-site solar PV, with battery storage sized to cover overnight demand. CO_2 enrichment comes from the OCAP network. It represents a fully electrified, energy-autonomous setup that minimizes reliance on the grid and tackles congestion issues.

To meet the 10.7 MJ (0.71 kWh) of heat per kilogram, we assume 70 % of daily demand must be supplied from stored electricity. That translates to roughly 6 400 kWh of storage per day for a 5 ha greenhouse. Modelling draws on EV battery pack proxies (32 kWh each), requiring about 200 units (56 000 kg total) with a 20-year lifespan—equating to ~0.00059 kg of batteries per kilogram of tomatoes.

Solar panels cover one-sixth of the greenhouse roof, mirroring the Solarkas Velden density and generating ~20 GWh annually—ample to power heat pumps and charge batteries. PV modules follow a 30-year multi-Si wafer profile. A 1 500 m^3 water buffer (40-year life) smooths thermal peaks, modelled by scaling a 10 m^3 reference tank.

CO_2 enrichment remains at 1.2 kg per kilogram of tomatoes, with 12.5% uptake treated as biogenic (impact-neutral) and the remaining 87.5% vented and attributed to the grower. The model treats OCAP CO_2 as a waste stream, carrying only the capture, purification, and transport burdens.

This configuration eliminates direct fossil use and slashes grid draws after dark but shifts environmental impacts to battery production—amplifying critical-material demand and associated ethical risks. Users can adjust battery capacity, PV coverage, and enrichment levels in the Excel tool to explore trade-offs between autonomy, emissions, and resource constraints.

D
Unit Processes

See additional documentation:
tomato-documentation (unitprocess).xlsx

E
Inventory Results

See additional documentation:
tomato-contribution-table and LCI.xlsx

Tabs:
LCI Results

F
Contribution Results

See additional documentation:
tomato-contribution-table and LCI.xlsx

Tabs:
FFP
SOP
Water
EU fresh
GWP

G
Contribution by Renewable Electricity

Table G1

Entire Impact of Renewable Energy on Water Use Scores Across Fossil-Free CO_2 Options.

Impact category	Unit	Impact of renewable electricity purchase per kWh	Contribution % Geothermal	Contributio n % Heat Networks	Contributio n % Heat Pump (SOLE)	Contributio n % Heat Pump (WKO)	Contributio n % Heat Pump (DEH)	Contributio n % Solar (IND)	Contributio n % Solar (BAT)
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	2,60E-04	9%	7%	9%	9%	8%	9%	9%
climate change - global warming potential (GWP100)	kg CO2-Eq	2,22E-02	1%	1%	1%	1%	1%	1%	1%
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	3,52E-02	28%	27%	23%	23%	23%	28%	28%
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	4,36E-02	28%	27%	22%	23%	22%	28%	27%
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	1,82E+00	29%	27%	23%	23%	23%	27%	27%
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	3,87E-03	1%	1%	1%	1%	1%	1%	1%
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	2,63E-05	8%	7%	7%	7%	7%	7%	7%
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	9,98E-07	3%	2%	3%	3%	3%	3%	3%
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	5,57E-03	2%	2%	2%	2%	2%	2%	2%
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	3,00E-01	24%	22%	20%	20%	19%	23%	23%
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1,08E-03	1%	1%	2%	2%	2%	2%	2%

land use - agricultural land occupation (LOP)	m2*a crop-Eq	1,99E-03	3%	3%	3%	3%	3%	3%	3%
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	1,76E-03	3%	2%	3%	3%	2%	3%	3%
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	7,40E-08	6%	6%	6%	6%	6%	6%	6%
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	9,19E-05	8%	7%	8%	8%	7%	8%	8%
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	7,58E-05	4%	3%	4%	4%	4%	4%	4%
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	7,86E-05	4%	3%	4%	4%	4%	4%	4%
water use - water consumption potential (WCP)	m3	1,51E-02	64%	48%	41%	42%	41%	63%	63%

H
Supporting Figures and Tables

Table H1

Explained Assessment of Attribution Choices in the Decision-Support Tool for the Production of Tomatoes.

Choices made for the LCA	Valid	Choices made for the thesis lab	Valid	Choices that the sector makes	Valid	Validity explanation
High CO2 enrichment (1.2kg)	**Yes**	Low CO2 enrichment (0.53kg)	**Yes**	No CO2 enrichment responsibility	**No**	Lower CO2 enrichment is possible, without loss of yield by systematic dosing. Burden free co2 dosing is however not considered fair.
CO2 from OCAP	**Yes**	CO2 from OCAP	**Yes**	CO2 from OCAP	**Yes**	CO2 can also be imported from waste incineration, as an alternative for places outside of the reach of OCAP.
Economic heating allocation (56%)	**Yes**	Economic heating allocation (56%)	**Yes**	Complete allocation to heating (100%)	**No**	No allocation to electricity is not considered a valid choice, since CO2 part of the electricity is used for growing tomatoes and since it is an economic product with value.
Renewable electricity (with emissions)	**Yes**	Renewable electricity (with emissions)	**Yes**	Renewable electricity (with no responsibility for emissions)	**No**	The sentiment that renewable electricity is climate neutral is possible, however in reality it does not mean no harm to the environment is done.

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Decision-Support Tool

See additional documentation:
Dashboard_for_tomato_LCA_TL_V4.xlsx