BlueTerra
Energy Experts

Final report

Comparison of low-grade biomass conversion routes for energy applications: techno-economic and GHG performance

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Nyasha Grecu	5273528
Sander Heshusius	6235069
Sam Klap	6282997
Inge Ossentjuk	6145795
Jeroen Wegh	5980569

Utrecht University

Client

Organization	BlueTerra Energy Experts	
Contacts	Jeroen Larrivee	jeroen.larrivee@blueterra.nl
	Pim van Dijk	pim.vandijk@blueterra.nl

Address

Lunet 5
3905 NW
Veenendaal, The Netherlands

Project group members	Nyasha Grecu	n.d.grecu@students.uu.nl
	Sander Hehusius	s.heshusius@students.uu.nl
	Sam Klap	s.klap@students.uu.nl
	Inge Ossentjuk	i.m.ossentjuk@students.uu.nl
	Jeroen Wegh	j.b.wegh@students.uu.nl
Supervisor	Dr. Elena Fumagalli	e.m.fumagalli@uu.nl

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Executive summary

Biomass can provide sustainable alternatives to fossil-based chemicals, food and feed, materials, and energy and heat production. It can therefore play an important role in the Dutch government's goal of reducing carbon dioxide (CO_2) emissions by 95% by 2050 compared to 1990. The government strategy is to use biomass for the highest value applications possible first and then cascade down to lower value applications. Currently low-grade biomass waste streams are either not utilised or used for low-value applications such as low-quality compost. It is difficult to use these waste streams for the highest value applications due to their chemical and physical properties. Still, they might have potential to be used for applications with higher value than their current use. This includes energy production and might be able to contribute to the Dutch climate targets.

Accordingly, this study aimed to provide insight into the potential of low-grade biomass waste streams for energy applications in the Netherlands. This was achieved by carrying out a techno-economic and environmental analysis of selected waste streams and conversion routes. Specifically, the study was organized in three phases:

In the **first phase**, literature review and expert interviews were used to create a detailed inventory of biomass waste streams and technological conversion routes. This inventory informed the selection of waste streams and conversion routes to be analysed. Waste streams were selected based on their availability (quantity and current use) and quality (physical and chemical properties and suitability for energy production). Subsequently, a spatial analysis was conducted to study the spatial distribution of waste production and potential transport distances. Finally, technological conversion routes (consisting of pre-processing and conversion steps) compatible with the selected waste streams were researched and identified.

In the **second phase**, a Microsoft Excel model was built to perform the techno-economic and environmental analysis of the chosen conversion routes. To model the technological performance of each route, an energy and mass balance was modelled, and energy and mass efficiencies were calculated. Economic performance was modelled through the calculation of net present value (NPV), payback period (PBP), and levelized cost of energy (LCOE). Environmental performance was measured by the GHG avoidance potential.

In **the third phase** a comparative analysis of the indicators calculated, combined with a sensitivity analysis, informed a discussion of the conversion routes analysed and led to final recommendations.

The waste streams identified as most suitable for energy applications were verge grass, greenhouse tomato waste, and greenhouse bell pepper waste. The spatial distribution of verge grass is dispersed but highest in Noord-Brabant, while that of bell pepper and tomato waste is more concentrated and highest in Zuid-Holland. These waste streams were combined with various pre-processing steps and torrefaction, pyrolysis, gasification, or anaerobic digestion as conversion processes, resulting in a total of eleven conversion routes analysed.

Results indicated that the conversion routes that performed well in terms of dry mass and energy efficiencies were the routes that combined ensiling, washing, and pressing with anaerobic digestion. Verge grass with drying, shredding, pelletising and gasification had a high dry mass efficiency but a low energy efficiency. However, these routes were not economically viable (negative NPVs). The routes that performed best economically were those with torrefaction or pyrolysis as the conversion technology albeit only having moderate efficiencies. This indicates a trade-off between technical and economic performance. The GHG avoidance potential of the conversion routes was mainly associated with the final products' substitution of fossil fuel alternatives and ranged from 0.20 - 0.57 kg CO_2-eq/kg biomass for the different routes.

Based on these findings it is recommended that the torrefaction and pyrolysis routes be further investigated due to their economic viability, and moderate technical and good environmental performance. Moreover, it is recommended that feedstock prices be set at a fixed value in supply contracts due to high sensitivity of NPV and LCOE to changes in feedstock prices. Additionally, due to concentrated production in Zuid-Holland and transport costs constituting a relatively small portion of LCOE, a single large installation is recommendable for processing bell pepper or tomato waste. Due to its dispersed production, multiple dispersed installations could be considered for verge grass processing.

It is important to note that the findings of this study are subject to uncertainty of input parameters and assumptions within the model. Moreover, considerations outside the scope of this study are the seasonality (and storage) of biomass waste, mixing of feedstocks, varying supply chain set-ups, effect of scaling factors, and the combination of multiple conversion technologies in a single conversion route. All these present opportunities for future research.

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CAPEX	Capital expenditure
CBS	Statistics Netherlands
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
GHG	Greenhouse gas
GWP	Global warming potential
IRR	Internal rate of return
KPI	Key performance indicator
LCOE	Levelized cost of energy
LHV	Lower heating value
N_2O	Nitrous oxide
NPV	Net present value
O&M	Operation and maintenance costs
PBP	Payback period

Conversion routes

1-TomTor	1: drying, shredding, and torrefaction of greenhouse tomato waste
2-PepTor	2: drying, shredding, and torrefaction of greenhouse bell pepper waste
3-VerTor	3: washing and pressing, drying, and torrefaction of verge grass
4-TomPyr	4: drying, shredding, and pyrolysis of greenhouse tomato waste
5-PepPyr	5: drying, shredding, and pyrolysis of greenhouse bell pepper waste
6-VerGas	6: drying, shredding, pressing, and gasification of verge grass
7-VerAna	7: ensilage, washing and pressing, and anaerobic digestion of verge grass
8-TomAna1	8: ensilage, washing and pressing, and anaerobic digestion of greenhouse tomato waste
9-PepAna1	9: ensilage, washing and pressing, and anaerobic digestion of greenhouse bell pepper waste
10-TomAna2	10: shredding and anaerobic digestion of greenhouse tomato waste
11-PepAna2	11: shredding and anaerobic digestion of greenhouse bell pepper waste

1 Introduction

The Dutch government set out to reduce greenhouse emissions by 95% compared to 1990 and to make circularity a precondition in buildings, logistics, and industry by 2050 (Klimaatakkoord, 2019). The government has recognised the importance of the use of sustainable[1] biomass to reach these emission and circularity targets (Veldhoven & Wiebes, 2020). The strategy of the Dutch government is to use biomass for the highest-value applications possible (cosmetics, chemicals, aviation biofuels) first and subsequently cascade down to lower-value applications (compost, low-temperature heat, or electricity generation; Figure 1).[2] Biomass can be categorised as high-grade and low-grade, depending on the physical and chemical properties of the material. High-grade biomass refers to high quality biomass which can relatively easily be converted to high-value applications (Figure 1). Low-grade biomass refers to lower quality biomass, which could be due to contamination or unfavourable physical and/or chemical properties, making conversion challenging. These low-grade biomass streams (also called “waste streams" in this report) include verge grass, reed, manure, and contaminated biomass. Since it is especially challenging to use low-grade biomass for high-value applications, it is currently often disposed of using low-grade conversion routes. An example of the latter is composting, which loses carbon dioxide (CO_2) and energy that was stored inside the biomass directly to the atmosphere, and emits methane (CH_4) and nitrous oxide (N_2O) (Groenestijn et al., 2019).

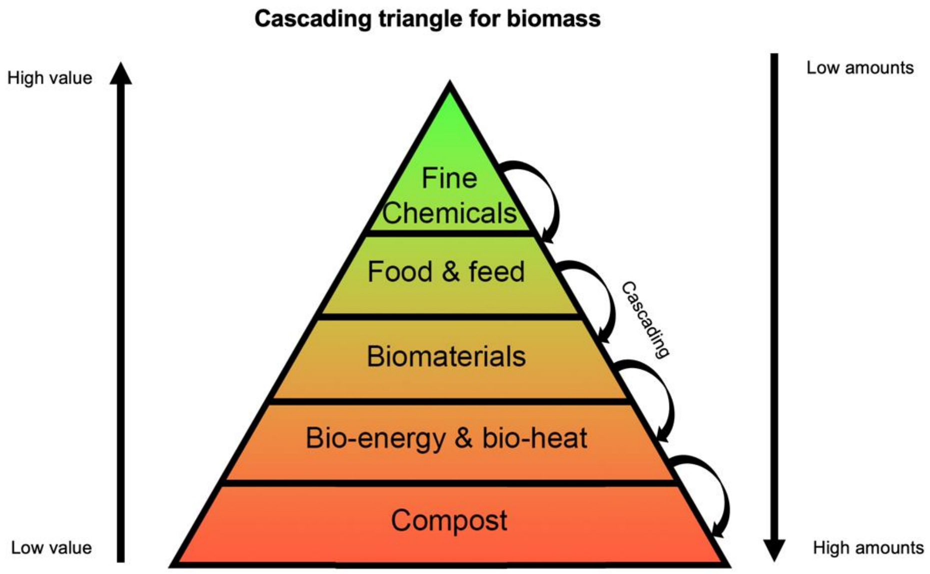

Figure 1. Cascading triangle for application hierarchy of biomass. Adapted from Lange et al. (2012).

Optimal use of waste streams could further enhance the contribution of biomass to the Dutch climate targets and circularity. The program *Kas als Energiebron* (“*Greenhouse as Energy*

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[1] i.e. complying with the national ‘sustainability framework biomass’.

[2] For a more detailed overview of this vision, see the report from the Social Economic Council (2020).

Source"), was set up by *Glastuinbouw Nederland* and the Dutch ministry of Agriculture, Nature, and Food Quality, to bring innovation to the Dutch horticulture sector. Part of the research for the *Kas als Energiebron* program is performed by BlueTerra Energy Experts, who are supervising this study. The horticulture sector, responsible for 3.7% of Dutch CO_2 emissions, could potentially deliver around 130 kilotonne (dry basis) of low-grade biomass waste streams (Smit & van der Velden, 2021; Schulze et al., 2017). Knowledge gained during the *Kas als Energiebron* project could therefore contribute to Dutch sustainability targets in two ways. First, circularity can be stimulated by improving the application of low-grade biomass. This is relevant since the Dutch government aims to develop a fully circular economy, being a system where no finite resources are exhausted and waste streams are reused (Klimaatakkoord, 2019). Second, applying low-grade biomass in inventive ways could contribute to reducing CO_2-emissions by replacing fossil energy use.

There might be potential for low-grade biomass that is currently not utilised or utilised for the lowest value applications (i.e., compost) to be used for higher-value applications. This includes it being used for energy applications, thereby substituting fossil energy use. Although conversion of low-grade biomass to a higher value is challenging, several ideas have been developed. For **nutritional and pharmaceutical use**, there are initiatives to use low-grade biomass as feed for insects to biotransform it into more high-value applications such as chitin, enriched compost, feed proteins, and feed lipids (Millibeter, 2018; BioflyTech, 2020). Other high-grade conversions are biopesticide production from tomato plant waste (Kalogeropoulos et al., 2012), pectin production for food coating (Valdés et al., 2015), and production of natural aromas for the food sector (Edris & Fadel, 2002). For **material use**, there are several initiatives as well. In the Netherlands, a company called The Greenery initiated the production of cardboard boxes from tomato stem fibres (BioBoost, n.d.). Biochar made from pyrolysis of biomass may be an interesting soil quality enhancer for the nursery, agriculture, and horticulture sectors (Trupiano et al., 2017). However, these are either in experimental phase or the scale is limited compared to the amount of organic waste streams available in the Netherlands.

For **energy applications**, the literature reports various examples of projects where low-grade biomass is used for energy applications. Thomsen et al. (2014) investigated various low-grade biomass types for low-temperature gasification for use in CHP plants. Further, converting low-grade biomass to a mix of biohydrogen and biomethane through fermentation might be promising (Liu et al., 2018). Abelha et al. (2018) investigated the upgrading of low-grade biomass (verge grass, miscanthus, wheat straw, and spruce bark) through washing and torrefaction. Some efforts have been made to use low-grade biomass to produce energy through bio-fuel cells (Tong et al., 2013; Verma et al., 2021). Finally, in the Netherlands, several pilot projects have been developed or are under development that can process low-grade biomass streams into energy using various combinations of pre-processing and conversion methods (Table 1). Conversion methods that might be suitable for the conversion of biomass to energy include anaerobic digestion, fermentation, torrefaction, pyrolysis, hydrothermal liquefaction, and gasification (see Section 2). However, problems remain that prevent the large-scale implementation of these ideas. Limitations related to the low-grade feedstock are high salt content, high ash content, high moisture content, and contamination (Larrivee & van Dijk, 2022).

Table 1. Overview of current (planned) projects for different biomass conversion methods in the Netherlands. Adapted from Larrivee & van Dijk (2022).

	Location	Method	Realization	(Projected) scale input [tonne/yr]
WABICO (HoSt)[3]	Waalwijk	Anaerobic digestion + gas upgrading	2015	60,000
Wagro	Waddinxveen	Fermentation + anaerobic digestion (labscale)	2021	1,000
Vidras	Middenmeer	Anaerobic digestion + gasification	Planned 2022	70,000
Perpetual Next/Torrcoal	Nieuwveen	Torrefaction + gasification	Planned 2022	1,000
Perpetual Next	Delfzijl	Torrefaction + gasification	Planned 2023	100,000
SCW Systems	Alkmaar	Supercritical gasification	Planned 2023	20,000

Despite developments in low-grade biomass conversion, a critical and structured overview of potential conversion routes for different types of low-grade biomass produced in the Netherlands is still lacking. This study aims to fill this research gap by gaining insight into the technological and economic challenges related to the feedstocks and conversion routes. This can contribute to the *Kas als Energiebron* project and studies performed by BlueTerra and can be used to guide policy and investment decisions.

The overarching goal of this study is *to gain insight into the potential of low-grade biomass waste streams, produced in The Netherlands, for energy applications.*

This is achieved by analysing the techno-economic and greenhouse gas (GHG) performance of different pre-processing and conversion technologies in combination with several low-grade biomass waste streams. Specifically, this study will be organised in three steps:

1. Select potentially promising biomass waste streams and conversion routes based on:
    a. A mapped-out inventory of low-grade biomass waste streams produced in the Netherlands that could be suitable for energy purposes (where suitable means in adequate quantity and of adequate quality);
    b. A classification of the high-value conversion routes for these biomass waste streams based on their short-term potential (i.e., their technology readiness level).
2. Perform a techno-economic and environmental analysis of the selected routes.
3. Perform a comparative analysis of the selected biomass conversion routes for energy applications.

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[3] HoSt BioEnergy Systems develops and delivers a variety of biomass conversion technologies for large- and small-scale energy conversion, including anaerobic digestion, fermentation, and gasification (*HoSt*, n.d.).

Based on this work, recommendations will be provided regarding preferable treatments for low-grade biomass waste streams in the Netherlands.

2 Theoretical background

A preliminary literature review identified various established high-value conversion technologies suitable for low-grade biomass. These include fermentation, anaerobic digestion, pyrolysis, torrefaction, hydrothermal liquefaction, and gasification (Pant & Mohanty, 2014). The technologies are briefly introduced below, and their specifications are shown in Table 2.

Fermentation of biomass is a process in which micro-organisms convert organic matter into a product containing alcohol, acids, and hydrogen. Fermentation is suitable for carbohydrates, such as glucose, sucrose, and starch (Baeyens et al., 2020). Waste products that contain these carbohydrates, such as crop residues, can be used for this process, though pre-treatment might be necessary to liberate the carbohydrates. Fermentation can be divided into photo-fermentation or dark-fermentation, depending on the availability of light during the process (Osman et al., 2021).

Anaerobic digestion is a form of fermentation where biomass is decomposed anaerobically under controlled conditions in the presence of bacterial consortia, resulting in the production of bio-gas and a digestate (Pham et al., 2015). The bio-gas consists of a mix of CH_4 and CO_2 and can be used for various energy applications. The digestate can be used as replacement for fertilizer. The digestion conditions must be carefully managed to obtain the highest possible yield. It has been shown as a proven technology for waste from food, agriculture, and water treatment facilities (Meegoda et al., 2018). A disadvantage of the process is the long treatment time (20-40 days).

Pyrolysis consists of the decomposition of biomass into bio-oil, bio-char, and bio-gas (Wang et al., 2020). The decomposition ratios depend on exact reaction conditions and feedstock type. The process takes place under high temperatures and oxygen-free conditions. The lower the moisture content of the input biomass, the higher the efficiency of the process will be (Safarian et al., 2019).

Torrefaction of biomass is used to increase the energy density of the biomass, after which it can be combusted or gasified (Bergman & Kiel, 2005). Torrefaction is a mild form of pyrolysis. The process takes place under high temperatures and oxygen-free conditions. It consists of a volatilisation, polymerisation and carbonisation step resulting in solid biomass and smaller amounts of bio-gas (Osman et al., 2021). Similarly to torrefaction, the lower the moisture content of the input biomass, the higher the efficiency of the process will be (Babinszki et al., 2020).

Hydrothermal liquefaction of biomass consists of three main components: depolymerisation, decomposition, and recombination (Gollakota et al., 2018). First the biomass is depolymerised and decomposed resulting in smaller, highly reactive particles. These particles will recombine and form mainly bio-oil with bio-gas and bio-char in smaller amounts. This process is suitable for dry and wet biomass feedstocks.

During **gasification**, biomass is converted into syngas at high temperatures in an oxygen-free environment (Kirubakaran et al., 2009). The biomass can have a moisture content between 5-35% before drying, and a maximum of 5% after drying (Safarian et al., 2019). Subsequently, the biomass goes into the pyrolysis step. The tar gases produced in this step undergo cracking in the gasification step, resulting in syngas.

All these conversion processes require various pre-processing steps of biomass to make it suitable for the conversion step and obtain the highest energy yield. Examples of pre-processing steps are drying, shredding, pressing, washing, and ensiling. These pre-processing steps can be applied to alter properties of the biomass such as moisture content, particle size, salt content, and pH.

Table 2. Conversion processes and their temperature, main products, and by-products. Adapted from: Gollakota et al. (2018); Osman et al. (2021); Pham et al. (2015); Safarian et al. (2019).

Conversion technology	Temperature (°C)	Main products	By-products
Anaerobic digestion	35-55	Gas (CH_4 and CO_2)	Digestate
Fermentation	30-35	Ethanol, CO_2	Fibres
Torrefaction	200-300	Solid biomass	Ash
Gasification	350-1800	Gas (CO, CH_4, N_2, H_2, CO_2)	Ash
Liquefaction	250–500	Bio crude	Gas and solids
Pyrolysis	200-500	Charcoal and bio-oil	Tar and gases

3 Methods

Figure 2 presents an overview of the methods applied in this study. The study was divided into three phases, corresponding to the three sub-objectives identified in Section 1. In the first phase, a literature review and expert interviews formed the basis for a detailed inventory of low-grade biomass waste streams and potential technological conversion routes. This informed the selection of waste streams and conversion routes to be analysed. In the second phase, a model was built in Excel to perform the techno-economic and environmental analysis of the chosen waste streams and literature-based conversion routes. In the third phase, a comparative analysis of the indicators calculated and a review of model limitations and sensitivity, led to final recommendations.

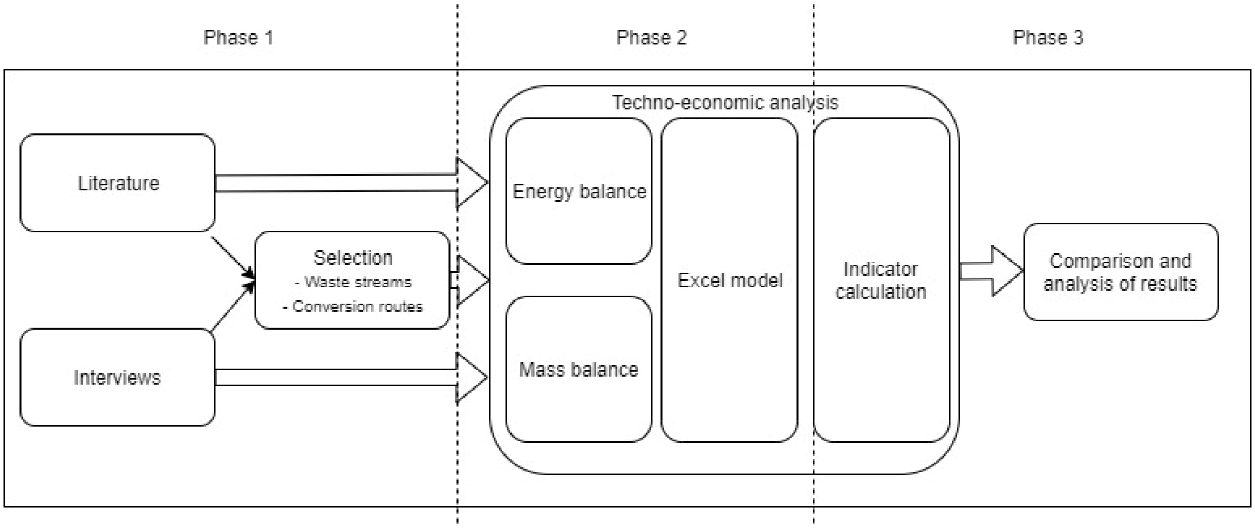


Figure 2. Visual representation of methodology used.

3.1 Phase 1: Selection of waste streams and conversion routes

A combination of literature review and expert interviews was used to identify and select low-grade biomass waste streams produced in the Netherlands and associated conversion routes. An overview of the experts interviewed can be found in Appendix A. These are representatives of companies and organisations that are working in the horticulture, biomass, and bio-energy sectors in the Netherlands.

3.1.1 Low-grade biomass waste stream inventory and selection

First, an inventory of low-grade biomass waste streams in the Netherlands was compiled. This inventory consisted of data on availability and quality. Availability refers to the waste stream quantities and its current use. Quality covers physical and chemical properties of the waste stream.

For **availability**, annual production of low-grade biomass waste streams was determined from literature. For the greenhouse horticulture sector, data on the annual biomass production was available, but data on the waste stream production was not. To still obtain data on horticulture waste stream availability, the Statistics Netherlands (CBS) data on current greenhouse horticulture area was used (CBS, 2021). This was combined with specific crop waste values from the company BioBoost (Appendix B; Table B.1) to arrive at total annual waste production (BioBoost, 2018). For this, a formula adapted from Pradhan et al. (2019) was utilised:

Equation 1

$$TW = A_i * W_i$$

Where:

$TW \ = \ total\ waste\ production\ [tonne]$
$A_i = \ horticulture\ area\ for\ a\ crop\ i\ [ha]$
$W_i = \ waste\ generated\ per\ crop\ area\ for\ crop\ i\ [tonne/ha]$

Current use of waste streams was also determined through literature review. Waste streams identified as being high-grade or fully utilised for higher-value applications than compost were excluded from further analysis. For remaining waste streams, estimates of the proportion of unused streams that could potentially be applied for energy were found in the literature. These were then multiplied with annual waste production to arrive at final values of waste stream quantities available for energy purposes. Subsequently, a threshold that empirically divided the waste streams based on quantity available was determined. Specifically, this threshold was 70,000 tonnes per year with the next available quantity being 36,229 tonnes per year and resulted in the selection of eight waste streams for further analysis.

For **quality**, the physical and chemical properties of these eight waste streams were inventoried through means of literature review. Biomass properties determine its potential applications and transportability (van Groenestijn et al., 2019). Properties investigated were moisture content, lower heating value (LHV), fixed carbon, ash content, and volatiles. The main parameters for applicability for energy purposes are LHV, moisture content, and ash content (Eneco, personal communication, May 25, 2022).

Subsequently, the streams suitable for further analysis were selected based on the inventory data. Dry weight and dry based LHV were taken as parameters for this selection because of their importance for energy applications. More dry weight is favourable because it represents the part of the biomass containing an energetic value. Dry based LHV reflects how much energy is contained within the biomass, on a mass basis containing zero moisture. When combining these two parameters, the energy contained within the fresh biomass can be determined while avoiding double-counting by overlapping content of the parameters. To evaluate the different biomass types based on these parameters, query values were standardised using linear standardisation on a [0,1] range, meaning the lowest and highest value for each criterion were zero and one respectively. Linear standardization was selected as method because it is a simple and effective means of standardization, enabling the comparison of the streams' properties (Sakai, 2016). The scores of both parameters were added per waste stream to come to the overall score. The waste streams with the highest overall score were regarded the most suitable for energy purposes. A threshold empirically dividing the final scores was identified at 1.5, with the next highest scoring value at 1.1. Thus, the three waste streams scoring higher than 1.5 were selected for analysis. These three streams – verge grass, greenhouse bell pepper waste, and greenhouse tomato waste – were used to further develop the methods.

3.1.1.1 Spatial analysis

After identification and quantification of suitable low-grade waste streams, a visualisation of the selected waste streams per province and existing waste treatment facilities in The Netherlands was composed. This allowed for an understanding of the spatial distribution of waste production and the calculation of possible transport distances. Transport costs can contribute significantly to the total costs for biomass conversion companies (DES B.V., personal communication, May 30, 2022). Thus, transport distances should be limited while ensuring sufficient feedstock flows for constant production.

For the greenhouse bell pepper and tomato waste, CBS spatial data was consulted for the number of bell pepper and tomato greenhouse hectares per province. This was combined with Equation 1 and the specific waste values per crop (Appendix B) to calculate waste generation per province. For verge grass, CBS data on the road type and length per province was applied to a verge grass quantification equation developed by de Jong (2019):

Equation 2

$$VG_d = \left[\left(\left(R_{M,sl} + R_{WA,sl} + R_{prov,t} + H_t\right) \cdot A_{MR}\right) + \left(\left(R_{M,jl} + R_{WA,jl}\right) \cdot A_{BR}\right)\right] * A_{VG}$$

Where:

$VG_d = Verge\ grass\ \left[tonne_{drymatter}/year\right]$
$R_{M,sl} = roads, municipal, separated\ lanes\ [km]$
$R_{WA,sl} = roads, water\ authority, separated\ lanes\ [km]$
$R_{prov,t} = roads, provincial, total\ [km]$
$H_t = highways, total\ [km]$
$A_{MR} = constant\ main\ roads = 1\ [ha\ verge/km\ road]$
$R_{M,jl} = roads, municipal, joint\ lanes\ [km]$
$R_{WA,jl} = roads, water\ authority, joint\ lanes\ [km]$
$A_{BR} = constant\ B\ roads = 0.4\ [ha\ verge/km\ road]$
$A_{VG} = constant\ verge\ grass = 3\ \left[tonne_{drymatter}/year/ha\ verge\right]$

The annual dry tonnes of verge grass per province were then converted to annual wet tonnes per year using Equation 3:

Equation 3

$$VG = \frac{VG_d}{dw_{VG}}$$

Where:

$VG = Verge\ grass\ \left[tonne_{fresh\ matter}/year\right]$
$VG_d = Verge\ grass\ \left[tonne_{dry\ matter}/year\right]$
$dw_{VG} = dry\ weight\ verge\ grass\ [0.4\ tonne_{dry\ matter}/tonne_{wet\ matter}\ ]$

The spatial analysis was performed in ArcGIS Pro. Data on waste stream production per province was compiled in a Microsoft Excel table and combined with a shapefile of Dutch provinces (obtained from the online database of ArcGIS Pro). The location of green waste disposal facilities was derived from the Dutch Association of Organic Waste Streams (BVOR, 2022). The location data points were exported from Google Earth Pro as a KMZ file to make it compatible with ArcGIS Pro. Spatial data on the location of greenhouses in the Netherlands was obtained from the National Georegister (RvO, 2020). A shapefile for Dutch municipalities was also obtained using the online database in ArcGIS Pro. Subsequently, green waste disposal facilities, municipality centres, and greenhouses were mapped using ArcGIS Pro.

To estimate transportation distances, the central point of the province with the greatest production of each waste stream was chosen as the destination point. This assumption was made to limit transport distance as much as possible. Subsequently, the average distance from waste production locations to this point was calculated using the '*near*' tool in ArcGIS Pro. For greenhouse and tomato waste, the production locations were assumed to be the locations of greenhouses in the Netherlands, as data on which greenhouses were specifically producing tomatoes or bell peppers was unavailable. For verge grass, it was assumed that the production locations are the centre points of municipalities in the Netherlands, as municipalities are responsible for collecting and processing verge grass.

3.1.2 Conversion route inventory and selection

As presented in the theoretical background, various conversion technologies are available. These technologies can be combined to form conversion routes, including pre-treatments and conversions that were specific to each type of biomass waste (Figure 3).

The selection of conversion routes was based on technological readiness level (TRL) and compatibility with the waste streams identified in the waste stream inventory. TRL is a tool to indicate the maturity level of a technology (Animah et al., 2018). This research only considered technologies that are well-established. Therefore, a TRL of 6 was taken as the minimum in this study, meaning that the technology has been demonstrated in its relevant environment. The identification of conversion routes and their compatibility with selected waste streams was based on a thorough literature review of studies analysing the conversion of verge grass, greenhouse bell pepper waste, and greenhouse tomato waste for energy applications, as well as on interviews conducted with experts in the field. The conversion technologies described in the theoretical background formed the basis for this selection. All conversion routes identified based on the above criteria were included in the final model.

3.2 Phase 2: Modelling the conversion routes

In the second phase of the research the different conversion routes were modelled in Microsoft Excel. The model calculates the mass/energy balance, GHG avoidance potential, and economic impact of each route from the point the waste is collected until the final energy product is produced. An overview of the model in- and outputs is visualised in Figure 3. On the left side of the figure, the inputs are shown, consisting of process data, economic data, and adjustable parameters for each step in the conversion route. This data, retrieved from the literature review and expert interviews from phase 1 of the research, was then fed into the Excel model. For each conversion route, a separate Excel sheet was built for the energy and mass balances, to customise the formulas to the data available. For the economic indicators, a separate Excel sheet was compiled using the formulas as explained later in this section. Afterwards, an interface was built for easy use, where the adjustable parameters can be filled in and the KPI results are given. The exact formulas and assumptions made are explained in the remainder of this section.

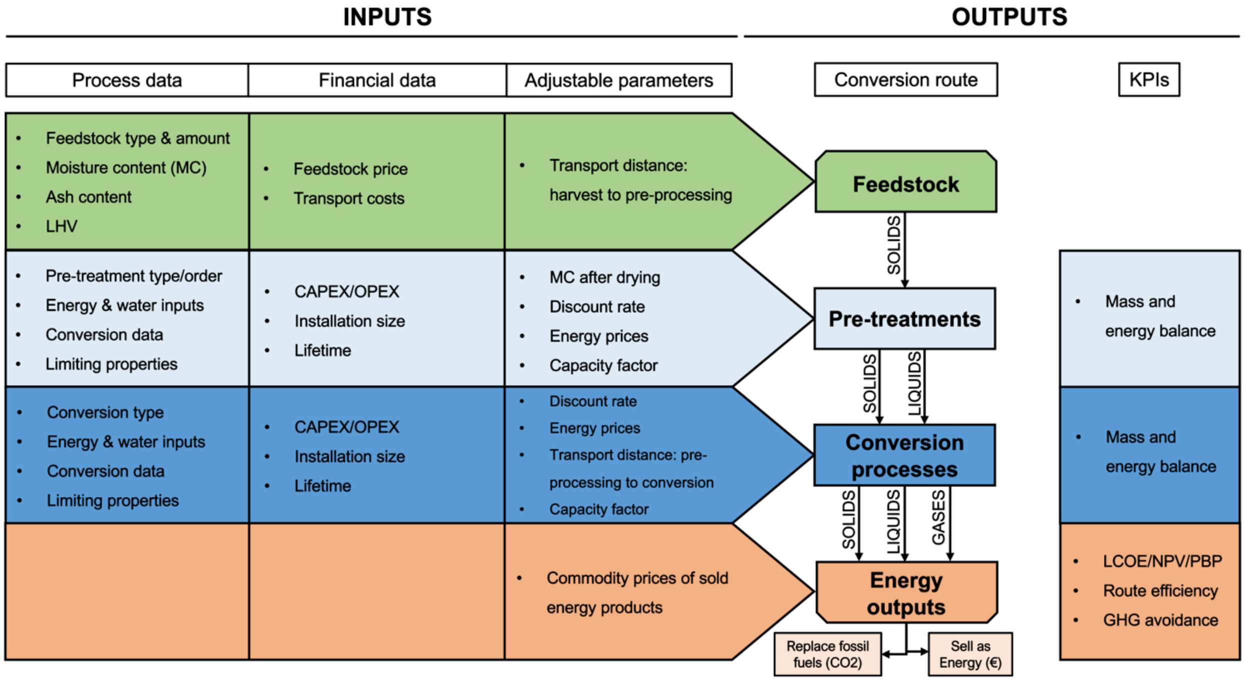


Figure 3. Set-up of the Excel model indicating inputs and outputs for a general biomass conversion route.

3.2.1 Pre-processing

From the inventory, the following pre-treatment processes were found to be used in biomass conversion: drying, shredding, pressing, washing, and ensiling. This section explains the model background for these processes.

For the **drying** process, the assumption is made that all energy inputs are used to heat the biomass and evaporate the water that is present in the biomass, except for an efficiency loss (Batidzirai et al., 2013). The only biomass property that changes due to drying is the moisture content. The amount of water that will be evaporated is calculated based on the difference between desired moisture content after drying and moisture content in the feedstock. Since the dry matter in the biomass also heats up, an average value for specific heat of biomass is used to model this process. The following equation is used to calculate the energy (heat) required for drying:

Equation 4

$$E = \frac{m_{water} * \left(c_{water} * \Delta T + h_{evaporation,water}\right) + m_{dry,biomass} * c_{dry,biomass} * \Delta T}{\eta}$$

Where:

$E = energy\ required\ for\ drying\ [kJ]$
$m_{water} = mass\ of\ water\ to\ be\ evaporated\ [kg]$
$c_{water} = specific\ heat\ of\ water\ [kJ/kgK]$
$h_{evaporation,water} = heat\ of\ evaporation\ of\ water\ [kJ/kg]$
$m_{dry,biomass} = mass\ of\ dry\ biomass\ [kg]$
$c_{biomass} = specific\ heat\ of\ biomass\ [kJ/kgK]$
$\eta = efficiency\ of\ the\ drying\ process\ [\%]$
$\Delta T = Temperature\ difference\ (K)$

The model includes self-consumption of the product to maintain the required temperature, meaning that part of the dried biomass is combusted (with an efficiency of 80%) to supply the heat for the process. The total dried biomass minus this self-consumption is then used as input for the next conversion step.

Shredding is a mechanical pre-treatment. It is modelled as a process requiring 32.4 kJ of electricity per one kg of dry biomass, based on a study from Ehlers (2013). Further, it is assumed that two percent of the dry biomass is lost in the process, leading to a small waste output.

Pressing is modelled in different ways, depending on the place in the pre-treatment process. If pressing is applied to wet biomass, the outflow consists of press cake and press juice. Depending on the conversion technology used after pressing, either the press cake or the press juice is the desired output. Thus, the preferred division of dry matter and water over the press cake and juice changes accordingly. This division can be adjusted by using different methods of pressing. For *anaerobic digestion*, the press juice is used as feedstock and it is assumed that the press juice contains 66% of the dry biomass and 84% of the water and the cake contains the remaining masses (Larrivee & van Dijk, 2021). For *gasification*, the press cake is used as feedstock. Then, it is assumed that 80% of the dry matter ends up in the press cake, while 20% is transferred to the press juice (Abelha et al., 2018b).

If the input for the pressing process is dried biomass, there is no transfer of dry matter to the water and 5% of the water in the biomass is pressed out (Chou et al., 2009; Cui et al., 2010). For clarity, this *dry pressing* is referred to as **pelletising** in this research. The energy required for all pressing processes is modelled to be 209 MJ/kg biomass (RUF briquetting systems, n.d.).

During **washing**, water is added to the biomass (per kg fresh biomass input, 3 kg of water is added) to remove salts and other contaminants. Of the dry biomass, 90% remains in the resulting substance, while the other 10% is assumed to leach into the washing water. In the outgoing flow the moisture content increases by 54% as a result of the washing (Abelha & Kiel, 2020).

Ensiling is a way of conserving biomass, while also breaking up bonds in the fibres of the material. Biomass is sealed airtight under a layer of plastic where it can be stored for months. The conservation overcomes the seasonality of the waste-stream production, making it possible to have a continuous and constant biomass supply. Due to chemical processes and leaching occurring in the process, the model assumes a 9% loss of dry biomass, water content and LHV (Redden et al., 2016).

3.2.2 Conversion technologies

The conversion technologies that were combined in literature with the selected waste streams and pre-treatment methods are: torrefaction, pyrolysis, gasification, and anaerobic digestion.

Torrefaction is a method of increasing the energy density of a material, requiring 0.52 MJ/kg biomass input (Kuzmina et al., 2016). It is assumed that the process leads to a mass loss of 30% and an energy loss of 10% (Tumuluru et al., 2021). The resulting useful products are biochar and gas (torrgas). This torrgas is said to be sufficient to sustain the torrefaction process, and thus it is assumed that no external energy inputs are needed and all torrgas is fed back into the process (PerpetualNext, 2022).

During **pyrolysis**, the biomass is converted to biochar, bio-oil and bio-gas. Of the total biomass input, respectively 21.8%, 41% and 37.3% of the weight is converted to these products for a reaction temperature of 600˚C (Encinar et al., 2008). The biochar consists of 87.6% dry matter and 3% moisture, the remainder being ash (Encinar et al., 2008). For the bio-oil, a LHV of 20.6 MJ/kg is taken (Björnsson et al., 2021). To convert the gas output to mass, a mol ratio at the same process temperature is taken from Encinar et al. (2008). The LHV of the gas is assumed to be a weighted average of the heating values of the main gas components with respect to their mass percentage. The energy required for pyrolysis is 11.15 MJ/kg solid product (Memici & Ekinci, 2020). It is assumed that all the bio-gas outputs are fed back to supply the process energy, while the remaining heat required is supplied by natural gas.

For **gasification,** the circulating fluidised bed (CFB) gasification technology was assumed to be used. CFB is often mentioned as the most suitable gasification technology for biomass, due to its relative insensitivity to differing particle shapes and sizes of the feedstock (Mirmoshtaghi, 2016).

It was assumed that 1.92 m^3 syngas and 11 g tar are produced per kg biomass input (Diken & Kayişoğlu, 2020; Faaij et al., 1997). The energy required is 4 MJ/kg biomass input (Hrabovsky, 2011), which is partially supplied by the produced tar. The remaining energy is supplied by natural gas.

Anaerobic digestion produces a bio-gas which is assumed to consist of 65% methane and 35% CO_2 (Caposciutti et al., 2020). The process has a methane yield of 0.39 m^3/kg dry, ash-free biomass input (Lehtomäki et al., 2008). Besides gas, a fibre-rich digestate is formed as non-energy by-product, which can be used as low-grade compost. The energy required for the process is 0.43 MJ/m^3 methane produced. This energy is assumed to be taken from the bio-gas output (self-consumption).

3.2.3 Techno-economic and environmental analysis

The model was used to perform a techno-economic and environmental analysis for various combinations of feedstocks and conversions. A techno-economic analysis is a methodological approach to analyse the technical and economic performance of a process, product, or product system (Mahmud et al., 2021). It can be used to identify the potential economic feasibility of technologies. To perform the techno economic and environmental, indicators were selected that represent the goal and scope of the research. These were categorised into technical, environmental, and economic indicators (Table 3).

Table 3. Key performance indicators (KPI) chosen for each field of analysis.

Performance field	KPI	Unit
Technical	Dry mass efficiency	%
	Energy efficiency	%
Environmental	GHG avoidance potential	tonne CO_2eq /tonne biomass
Economic	Net present value	€
	Payback period	Years
	LCOE	€/GJ

3.2.3.1 Technical indicators

To evaluate the technical performance of the technologies, the dry mass efficiency and energy efficiency of the conversion routes were computed. Dry mass efficiency was calculated as the percent of the input dry matter that is found in the final useful output (useful being defined as suitable for energy applications; Equation 5). This provides insight into the mass balance of the conversion route.

Equation 5

$$\eta_{dm} = \frac{m_{dry,useful\ out}}{m_{dry,in}} \cdot 100$$

Where:

$\eta_{dm} = dry\ mass\ efficiency\ [\%]$
$m_{dry,useful\ out} = useful\ output\ dry\ mass\ [kg]$
$m_{dry,in} = input\ dry\ mass\ [kg]$

Energy efficiency was calculated based on the energy content of the functional unit (output) divided by the energy flows entering the system boundaries (input) (Eq. 6). Thus, the indicator is based on the mass and energy balances of the different technologies within a conversion route.

Equation 6

$$\eta_E = \frac{E_{useful,out}}{E_{in}} \cdot 100$$

Where:

$\eta_E = energy\ efficiency\ [\%]$
$E = useful\ energy\ outputs\ [J]$
$E_{in} = energy\ inputs\ [J]$

The efficiencies of the routes are relevant indicators because they give information on their technical performance and allows comparison to other routes.

3.2.3.2 Environmental indicator

To assess the environmental performance of the conversion routes, GHG avoidance potential is taken as the indicator. The conversion route emissions are compared to the emissions of the reference scenario. For the conversion route emissions, the emissions from transport, natural gas use, and electricity use are considered. The reference scenario consists of two components: emissions related to the current disposal of the low-grade biomass, and emissions from fossil fuels used to supply energy.

For the first component, the reference scenario is composting, since this is the current end-of-life strategy of low-grade biomass waste streams in the Netherlands (van Groenestijn et al., 2019). Composting results in the emission of three main greenhouse gases: CO_2, CH_4 and N_2O. CO_2 emissions are not accounted for in this research, because biogenic CO_2 (originating from biomass) is assumed to have a net-zero effect on global warming, as is common in IPCC reporting (Muñoz & Schmidt, 2016). For the non-CO_2 emissions, the values for green waste composting are taken as: 850 g CH_4 and 72 g N_2O per tonne green waste (BVOR & IVAM, 2013). These are then converted to CO_2-equivalents using the global warming potential (GWP) over a period of 100 years (GWP100). For biogenic CH_4, a value proposed by Muñoz & Schmidt (2016) is used (27.75 kg CO2-eq/kg biogenic CH_4). For N_2O, the GWP100 is 273 kg CO_2-eq/kg N_2O.

For the second component, the fossil fuel used as reference is dependent on the final useful products of the conversion route analysed. For this, it is assumed that bio-char, bio-oil, bio-gas, syngas, press cake, and digestate are replacing coal, crude oil, natural gas, fossil syngas, natural gas and low-grade compost, respectively. Again, the biogenic carbon released during combustion of bio-based energy carriers is not taken into account, thus the emissions of the conversion routes only exist of the emissions due to fossil energy being supplied to the processes.

Appendix D shows the input parameters for the GHG reduction potential in the model.

3.2.3.3 Economic indicators

To estimate the economic feasibility, the net present value (NPV), payback period (PBP) and levelized cost of energy (LCOE) are used. The NPV is an indicator used to interpret future costs and benefits of a technology, while the PBP evaluates how long it takes for a project to earn back its investment (Blok & Nieuwlaar, 2016). LCOE is defined as the price of the energy output required for a plant to break even at the end of the lifetime (Papapetrou & Kosmadakis, 2022). Equations for these indicators are found below (Equation 7-9):

Equation 7

$$NPV\ [€] = -I + \sum_{i=1}^{n} \frac{B_i - C_i}{(1+r)^i}$$

Equation 8

$$PBP\ [yr] = \frac{I}{B - C}$$

Equation 9

$$LCOE\ \left[\frac{€}{GJ}\right] = \frac{I + \sum_{i=1}^{n} \frac{C_i}{(1+r)^i}}{\sum_{i=1}^{n} \frac{E_t}{(1+r)^i}}$$

Where for Equations 7-9:

$I\ =\ investment\ costs\ [€]$
$C\ =\ costs\ [€]$
$B\ =\ benefits\ [€]$
$r\ =\ discount\ rate\ [\%]$
$n\ =\ project\ lifetime\ [years]$
$E\ =\ energy\ generation\ [GJ]$

Appendix E shows the economic inputs used for this model. These inputs are based on the most recent literature that could be found. Since the costs involved were different for each project, sometimes averages of multiple values were taken. For some operation & maintenance (O&M)

input data no numbers could be found. In those cases, an assumption was made to have an O&M of 5% of the investment costs per year. Prices were adapted for inflation and exchange rates to convert to €$_{2022}$ using Inflationtool.

3.3 Phase 3: Result Analysis

Phase 3 consisted of performing a sensitivity analysis to identify the most sensitive parameters influencing the KPIs and to link these to model limitations. The sensitivity analysis was conducted on the influence of input parameters on the NPV and LCOE. An overview of these parameters can be found in Table 4. For the analysis of sensitivity of NPV for changes in discount rate, it should be noted that the value for the discount rate at which the NPV becomes positive is equal to the internal rate of return (IRR). Thus, this value was estimated from the sensitivity results and used for interpretation of the sensitivity, though it had not been calculated in the KPIs.

Table 4. Input parameters and value ranges analysed for sensitivity on NPV and LCOE. ver = verge grass; pep = greenhouse bell pepper waste; tom = greenhouse tomato waste. NB: the range in commodity prices and CAPEX is given in percentage change of the original value.

Input parameter	**Discount rate [%]**	**Feedstock prices [€/tonne]**	**Commodity prices [% change]**	**CAPEX [% change]**
Original value	6%	-20 (ver) -10 (pep, tom)	0%	0%
Range used for sensitivity	0%; 50%*	-40; 40	-50%; 200%	-50%; 50%

*The sensitivity of the discount rate is only performed on the NPV

Based on the results from Phases 1-3 (consisting of the biomass and conversion routes inventories, the spatial visualisation of biomass availability, the resulting KPIs, and the sensitivity results), a comparative analysis was carried out to analyse the different biomass conversion routes from the perspective of potential investors. This perspective was chosen because investors are key stakeholders needed for implementation. The outcomes of this analysis were used to propose recommendations for better use of low-grade biomass waste streams.

4 Results

4.1 Suitable waste streams

The results of the biomass waste stream inventory of the Netherlands are presented in this section. Based on the scope of this report, all waste streams that are currently utilised (for applications of higher value than compost) and/or are considered high grade were excluded from the research. An overview of these excluded waste streams is provided in Table 5.

Table 5. Biomass waste streams excluded from this research, with the rationale for exclusion.

Waste stream	Rational for Exclusion	Source
Wood residues/chips	Utilised and high grade	(Larrivee & van Dijk, 2022; van Dael et al., 2014)
Waste fats	High grade	(van Dael et al., 2014)
Primary biomass (grass, sugar beet, maize)	High grade	(Larrivee & van Dijk, 2022)
Sewage	Utilised	(Bastein et al., 2013)
Food industry waste (VGI)		
➢ Brewer’s grain	High grade	(van der Meer et al., 2012)
➢ Oil seed scrap	Utilised	(K. P. H. Meesters & Bos, 2013)
➢ Fish waste	Utilised	(van der Meer et al., 2012)
➢ Slaughter waste	Utilised	(Vijn, 2019)
➢ Sugar beet	Utilised (remaining part is unavailable)	(Schulze et al., 2017; Vijn, 2019)
➢ Used cooking oil	Utilised	(Smit & Janssens, 2016)
➢ Potato waste	Utilised (remaining part is unavailable)	(Smit & Janssens, 2016)
Sieve overflow/shreds	Utilised	(Larrivee & van Dijk, 2022)
GFT waste	Utilised	(Larrivee & van Dijk, 2022)

The waste streams that are low-grade and under-utilised were included in the study. These waste streams, as well as total quantity produced, estimated percentage available for energy purposes, and resulting unused available biomass are listed in Table 6. Estimates on availability from Dael et al. (2014) were used for cattle manure, pig manure, and verge grass and from Schulze et al. (2017) for open horticulture flower waste. For lack of other data, it was estimated that the same percentage of poultry manure was available for energy purposes as for other manure types. For mushroom compost, an availability of 95% was estimated based on current utilization. Namely, mushroom compost is used for the tree growing industry (5000 m^3 annually, which is around 2.75 tonnes; (Oei & Albert, 2008)), and in two installations that already use it for energy purposes. These are: Gemert Upcycling B.V. with a composting and heat recovery installation (roughly

20,000 tonnes/yr, with plans to double (Borgmeier, 2015)) and Champignonkwekerij ‘t Voske (Uden) that uses a combustion installation (roughly 6,000 tonnes/yr ((Gielen, n.d.)). For greenhouse production waste, it was assumed that 100% of the waste is available for energy purposes because this waste is currently composted.

Table 6. Availability of low-grade biomass waste streams in The Netherlands. For the horticulture production values, Equation 1 was used.

#	Biomass stream	Production [tonne/yr]	Availability [%]	Unused low-grade biomass [tonne/year]	Source
1	Cattle manure	60,200,000	5%	3,010,000	(van Bruggen & Gosseling, 2019; Van Dael et al., 2014)
2	Verge grass	1,722,000	100%	1,722,000	(Van Dael et al., 2014; van der Meer et al., 2012)
3	Mushroom compost	800,000	95%**	760,000	(Larrivee & van Dijk, 2022)
4	Open horticulture flower waste	840,000	70%	588,000	(Schulze et al., 2017)
5	Pig manure	9,800,000	5%	490,000	(van Bruggen & Gosseling, 2019; Van Dael et al., 2014)
6	Tomato waste*	80,125	100%**	80,125	(BioBoost, 2018; CBS, 2021)
7	Bell pepper waste*	75,545	100%**	75,545	(BioBoost, 2018; CBS, 2021)
8	Poultry manure	1,400,400	5%**	70,020	(Leenstra et al., 2014)
9	Cucumber waste*	36,229	100%**	36,229	(BioBoost, 2018; CBS, 2021)
10	Flower waste*	19,842	100%**	19,842	(BioBoost, 2018; CBS, 2021)
11	Reed	17,425	100%**	17,425	(RIVM, 2022)
12	Potplant waste*	14,664	100%**	14,664	(BioBoost, 2018; CBS, 2021)
13	Aubergine waste*	5,162	100%**	5,162	(BioBoost, 2018; CBS, 2021)
14	Strawberry waste*	796	100%**	796	(BioBoost, 2018; CBS, 2021)
15	Fruit waste*	164	100%**	164	(BioBoost, 2018; CBS, 2021)

* From Dutch greenhouse horticulture.

** Assumed value based on available data (see accompanying text).

As described in Section 3.1.1, the eight largest waste streams were analysed further based on their physical and chemical properties. Table 7 depicts dry weight per kilogram of fresh (wet) waste and LHV (dry basis) of these eight waste streams. Total dry weight availability can be found in Appendix B, Table B.2.

Table 7. Dry weight per kilogram fresh (wet) biomass and dry basis LHV per biomass type.

#	Biomass streams	Dry weight [kg_{dry} /kg_{wet}]	LHV [MJ/kg_{dry}]	Source
1	Cattle manure	0.243	14.55	(Font-Palma, 2019; TNO, 2022)
2	Verge grass	0.400	16.86	(TNO, 2022; Voinov et al., 2015)
3	Mushroom compost	0.479	10.96	(TNO, 2022; Oei & Albert, 2008)
4	Open horticulture waste	0.180	15.24	(TNO, 2022; Sharma et al., 2017)
5	Pig manure	0.297	15.87	(TNO, 2022; Zang et al., 2016)
6	Tomato waste	0.500	13.94	(Larrivee & van Dijk, 2022; TNO, 2022)
7	Bell pepper waste	0.500	14.35	(Larrivee & van Dijk, 2022; TNO, 2022)
8	Poultry manure	0.255	12.57	(TNO, 2022; Quiroga et al., 2010)

The standardised scores for dry weight and LHV, overall score, and resulting ranking are shown in Table 8. The three highest scoring, and thus most suitable, waste streams are verge grass, greenhouse bell pepper waste, and greenhouse tomato waste.

Table 8. Standardised scores and overall ranking of the eight waste streams with the highest availability. The subscript 'std' means the parameter is standardized.

#	Biomass type	Dry Weight_std	LHV_std	Total Score	Ranking
1	Cattle manure	0.20	0.61	0.81	6
2	Verge grass	0.69	1.00	1.69	1
3	Mushroom compost	0.93	0.00	0.93	5
4	Open horticulture waste	0.00	0.73	0.73	7
5	Pig manure	0.37	0.83	1.20	4
6	Tomato waste	1.00	0.51	1.51	3
7	Bell pepper waste	1.00	0.57	1.57	2
8	Poultry manure	0.23	0.27	0.51	8

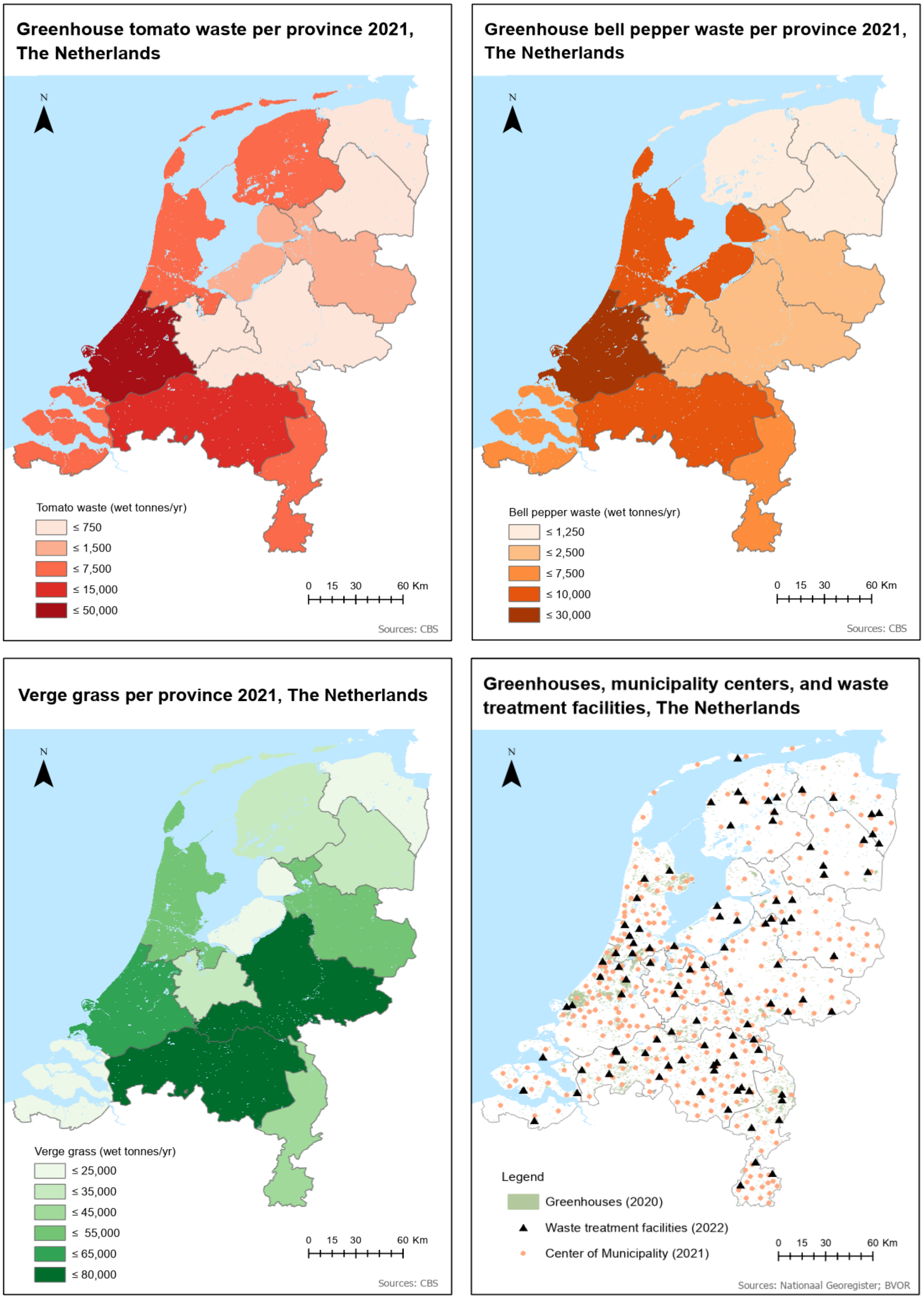
4.2 Spatial distribution of the waste streams

The results of the spatial analysis of the waste streams can be found in Figure 4, with exact numbers shown in Table 9. A larger sized map of greenhouses, waste treatment facilities, and municipality centers can be found in Appendix C. There is a clear uneven distribution visible of the waste streams across the Netherlands for bell pepper and tomato waste. These waste streams originate from the greenhouse horticulture sector, and are thus concentrated in areas with greenhouse clusters, especially Zuid-Holland. Specifically, 45,849 and 28,705 tonnes of tomato and bell pepper waste respectively are produced each year in Zuid Holland. For the verge grass, it becomes clear that the spatial distribution is less relevant and there is large availability everywhere. The greatest production of verge grass occurs in Noord-Brabant (79,179 tonnes/year) and Gelderland (73,410 tonnes/year).

The concentration of greenhouses in the west of the Netherlands and particularly in Zuid-Holland is also evident in Figure 4. Additionally, it is apparent that waste treatment facilities are concentrated in the west and middle regions of The Netherlands, in the provinces of Noord- and Zuid-Holland and Noord-Brabant. The average distance between greenhouses and the center of Zuid-Holland was calculated to be 64.68 km. The average distance between the center of municipalities and the center of Noord-Brabant was calculated to be 82.63 km. These values were assumed as transport distances for greenhouse tomato and bell pepper waste and verge grass, respectively.

Table 9. Greenhouse tomato and bell pepper waste, verge grass and number of waste treatment facilities per province in The Netherlands

Province	**Tomato waste [wet tonnes/ yr]**	**Bell pepper waste [wet tonnes/ yr]**	**Verge grass [wet tonnes/ yr]**	**Waste treatment facilities**
Groningen	5	3	24,242	6
Friesland	3,284	1,113	32,015	9
Drenthe	88	716	26,987	5
Overijssel	1,347	1,786	47,543	5
Flevoland	1,176	8,174	15,435	3
Gelderland	13	2,470	73,410	12
Utrecht	607	1,920	27,000	5
Noord-Holland	6,230	9,866	50,639	12
Zuid-Holland	45,849	28,705	60,102	7
Zeeland	3,133	5,207	24,855	5
Noord-Brabant	13,591	9,321	79,179	23
Limburg	4,801	6,264	39,966	7
Total	80,125	75,545	501,371	99



Greenhouse tomato waste per province 2021, The Netherlands

Sources: CBS

Greenhouse bell pepper waste per province 2021, The Netherlands

Sources: CBS

Verge grass per province 2021, The Netherlands

Sources: CBS

Greenhouses, municipality centers, and waste treatment facilities, The Netherlands

Sources: Nationaal Georegister; BVOR

Figure 4. Spatial distribution of bell pepper waste, tomato waste and verge grass across the Netherlands, and location of greenhouses, central points of municipalities and waste treatment facilities. NB: scaling differs per feedstock type.

4.3 Suitable conversion routes per waste stream

After the waste streams were selected, the literature review on suitable conversion technologies and routes was performed. An overview of the conversion routes found in the literature for the selected waste streams can be found in Figure 5.

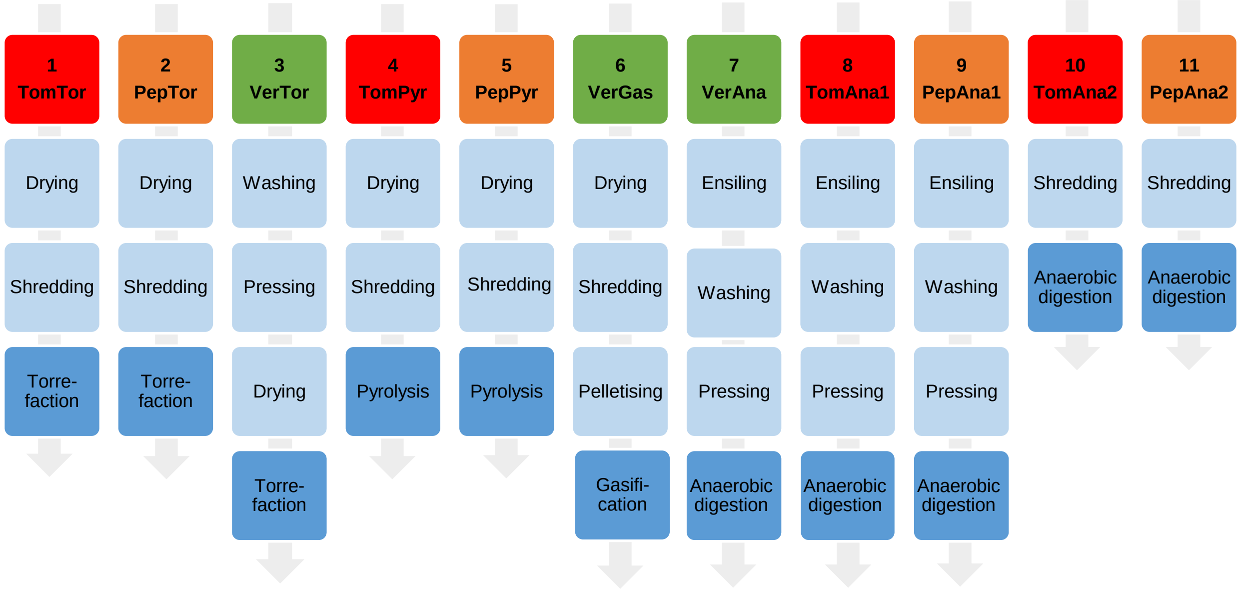


Figure 5. Overview of the conversion routes. In the highest row the colour represents the feedstock type: red is tomato, orange is bell pepper and green is verge gras. Withing the boxes the name of the conversion route is shown that will be used throughout the report. Light blue represents the pre-treatment and blue the corresponding conversion technologies for each route.

For **verge grass**, three main technologies were found in literature. Namely, ***torrefaction, gasification,*** and ***anaerobic digestion***. Several torrefaction methods are proposed in literature. For example, Joshi et al. (2015) looked at how of temperature and time affected the torrefaction process, and only used drying as pre-treatment method. However, Abelha & Kiel (2020) claim that washing is needed to overcome high salt contents in the feedstock that otherwise cause corrosion and other damages to the torrefaction plants. Therefore, their route, consisting of washing and pressing, drying, and thereafter torrefaction, is used for further analysis (route 3-VerTor). Hereby, it is assumed that pelletisation is part of the torrefaction step.

Though slightly outdated, multiple researchers have proven gasification of verge grass, either through modelling (Faaij et al., 1997) or through demonstration in a pilot plant (van der Drift et al., 2001). For gasification, pre-treatments are needed to avoid clogging of the feeding system and to adhere to a maximum moisture content of 15%. Therefore, shredding, drying, and pressing are proposed by van der Drift et al. (2001) – corresponding to route 6-VerGas. Finally, anaerobic digestion is posed often in literature and has been tested widely. Brown et al. (2020) found that verge grass can be used in farm-fed plants for co-digestion. Further, they found that contaminations are below levels of concern and that despite contaminations, the resulting digestate can still be used for agricultural purposes. Piepenschneider et al. (2016) propose a route that is similar to the Wagro pilot plant (Table 1), consisting of ensiling, washing, and pressing, combined with anaerobic digestion of the liquid and combustion of the solid products (Piepenschneider et al., 2016; route 7-VerAna). The washing is again seen as a means to minimize negative effects of high mineral contents, while the ensiling is both a storage method as a process to break chemical bonds in the feedstock allowing for easier conversion by bacteria in the digestor.

Greenhouse waste streams from **tomato and bell pepper** production are similar, and therefore have similar potential conversion routes (Figure 5). For both, the conversion routes analysed most often in the literature are ***pyrolysis*** and ***torrefaction*** (Font et al., 2009; Iáñez-Rodríguez et al., 2017; Memici & Ekinci, 2020; Mokrzycki et al., 2021). For example, Memici and Ekinci (2020) analysed the effect of temperature and holding time on the pyrolysis of tomato harvest waste, while Iáñez-Rodriguez et al. (2017) analysed torrefaction of greenhouse waste (mainly consisting of bell pepper waste) under different temperatures and with different amounts of plastic within the waste stream. Thus, (air) drying and shredding followed by torrefaction (routes 1-TomTor and 2-PepTor) or pyrolysis (routes 4-TomPyr and 5-PepPyr) were identified as the first conversion routes to be analysed for tomato and bell pepper waste. The third conversion selected is, similarly to verge grass, based on a pilot project conducted by Wagro where tomato stems and verge grass were ensiled, rinsed, and pressed. The resulting juice was used for ***anaerobic digestion*** and the press cake was used as substrate for crops or combusted (routes 8-TomAna1 and 9-PepAna1) (W. Lexmond, personal communication, June 6, 2022). Finally, various studies have investigated anaerobic digestion of fresh tomato harvest waste resulting in its selection as the fourth conversion route (routes 10-TomAna2 and 11-PepAna2) (Jagadabhi et al., 2011; Oleszek et al., 2016; Szilágyi et al., 2021).

As mentioned in the methods, only conversion technologies with a TRL greater than 6 were used in this study. Specifically, the TRLs of the conversion technologies chosen, taken from an overview by (WUR, n.d.), are shown in Table 10.

Table 10. Technological readiness level (TRL) of the analysed conversion technologies (WUR, n.d.).

Conversion route	**TRL**
Fluidised bed gasification	7
Torrefaction (moving bed reactor)	9
Anaerobic digestion	9
Pyrolysis	7

4.4 Model results

The model results consist of the energy and mass balances and the KPI values of each route in Figure 5. This section first discusses energy and mass balances, followed by environmental performance and finally economic performance.

4.4.1 Energy and mass balance

The input to the energy and mass balances was assumed to be 1000 kg of fresh material (verge grass, greenhouse tomato waste, or greenhouse bell pepper waste). In all drying processes included in the energy and mass balances, it was assumed that the material was dried to a moisture content of 15%.

Under conversion routes **1-TomTor** and **2-PepTor** the fresh matter is dried, shredded, and torrefied (Figure 6). The drying and shredding processes require energy as an input and produce water, and waste (feedstock losses), respectively. The drying process is fuelled by the dried tomato or bell pepper waste, while shredding is powered electrically. Torrefaction requires energy as an input and produces biochar, torrgas, as well as water and ash as waste products. The torrgas is used to fuel the torrefaction process.

As bell pepper waste has a higher LHV than tomato waste, less waste is needed for the drying process for the same amount of energy required. Shredding requires about 12 MJ and torrefaction about 230 MJ (greater for bell pepper waste due to the slightly larger quantity of waste being processed). Torrefaction outputs are slightly greater for bell pepper waste than tomato waste, both mass-wise and energetically, again due to the greater mass being processed. For tomato waste, 6970 MJ of energy are included in the 1000 kg fresh waste, 1547 MJ are required for the conversion route processes (1535 self-supplied, 12.4 external) and 3296 MJ are included in the final product. This results in an energy efficiency of 47%. Moreover, 53% of the initial dry mass is included in the final products. For bell pepper waste, 7175 MJ of energy are contained in the 1000 kg fresh waste, 1550 MJ are required for the conversion route processes (1537 self-supplied, 12.5 external) and 3423 MJ are produced: resulting in an energy efficiency of 48%. The dry mass efficiency is 53%.

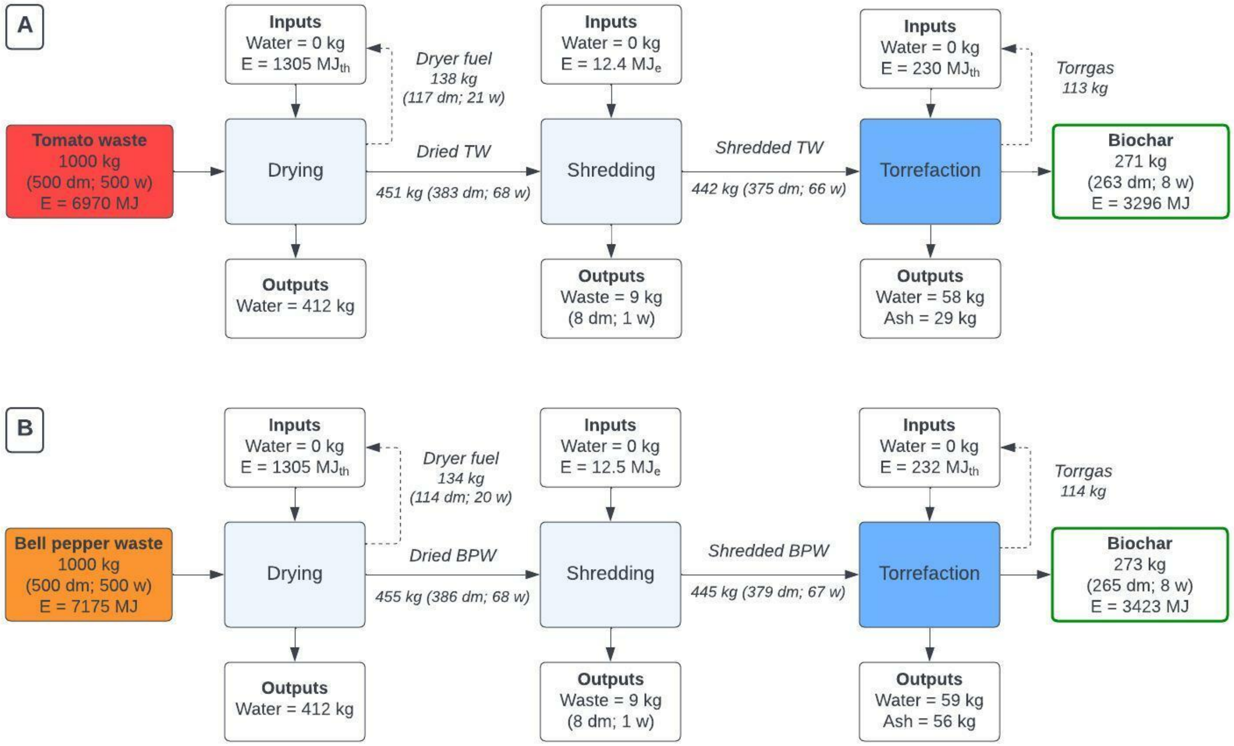


Figure 6. Energy and mass balance of conversion routes 1-TomTor (A) and 2-PepTor (B): drying, shredding, and torrefaction of greenhouse tomato and bell pepper waste respectively (TW = tomato waste, BPW= bell pepper waste, dm = dry matter, w = water).

Conversion route **3-VerTor** consists of washing and pressing, drying, and torrefaction (Figure 7). The washing and pressing process, requiring 3000 kg of water and 39 MJ of energy, produces press cake and press juice. The press cake is then dried, requiring 1155 MJ of energy and producing dried press cake, of which some is used to provide the energy needed for drying. A further 148 MJ of energy are required to torrefy the press cake and produce biochar. Waste products are water and ash. From the mass balance it becomes clear that the final product lost around 58% of its dry mass and 99% of its water mass. Ash is part of the dry mass. The total ash in the fresh verge grass equals 34 kg. After the washing and pressing process part of this ash is removed, with the ash content of the biochar being 16 kg. Of the 6744 MJ energy input, the final product has 2571 MJ and a total of 1342 MJ was required for all the processes (1303 self-supplied; 39 sourced externally). Therefore, the energy efficiency of this route equals 38%. The percent of the initial dry mass that is included in the biochar is 42%.

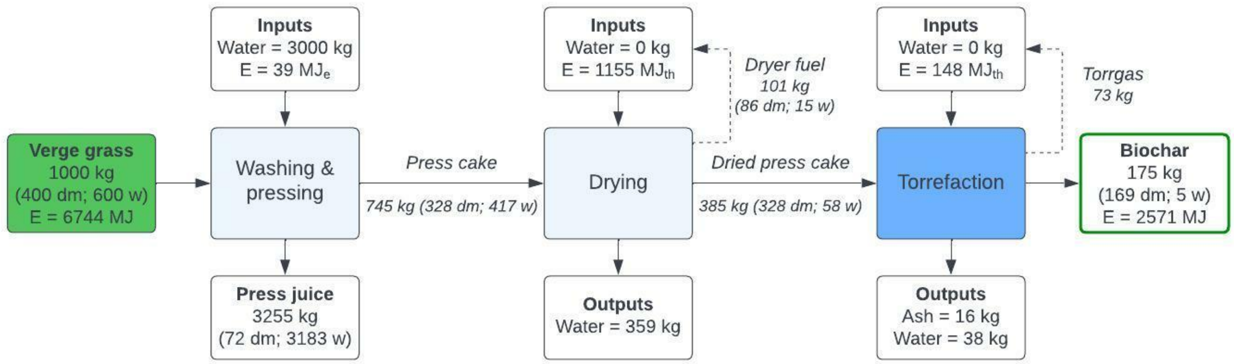


Figure 7. Energy and mass balance of conversion route 3-VerTor: washing, pressing, drying, and torrefaction of verge grass (VG = verge grass, dm = dry matter, w = water).

Conversion routes **4-TomPyr** and **5-PepPyr** consist of drying, shredding and pyrolysis (Figure 8). The drying and shredding processes are the same as in conversion routes 1-TomTor and 2-TomTor. Pyrolysis requires energy as an input and produces bio-gas, biochar, and pyrolysis oil. Ash is produced as a waste. The bio-gas is used to fuel the pyrolysis process along with some natural gas. The pyrolysis process requires more energy than torrefaction (around 1078 MJ), with more energy needed for bell pepper waste pyrolysis because of the greater amount being processed. The overall energy efficiency is 53% for both tomato and bell pepper waste. The dry mass efficiency is 41% for tomato waste and 43% for bell pepper waste.

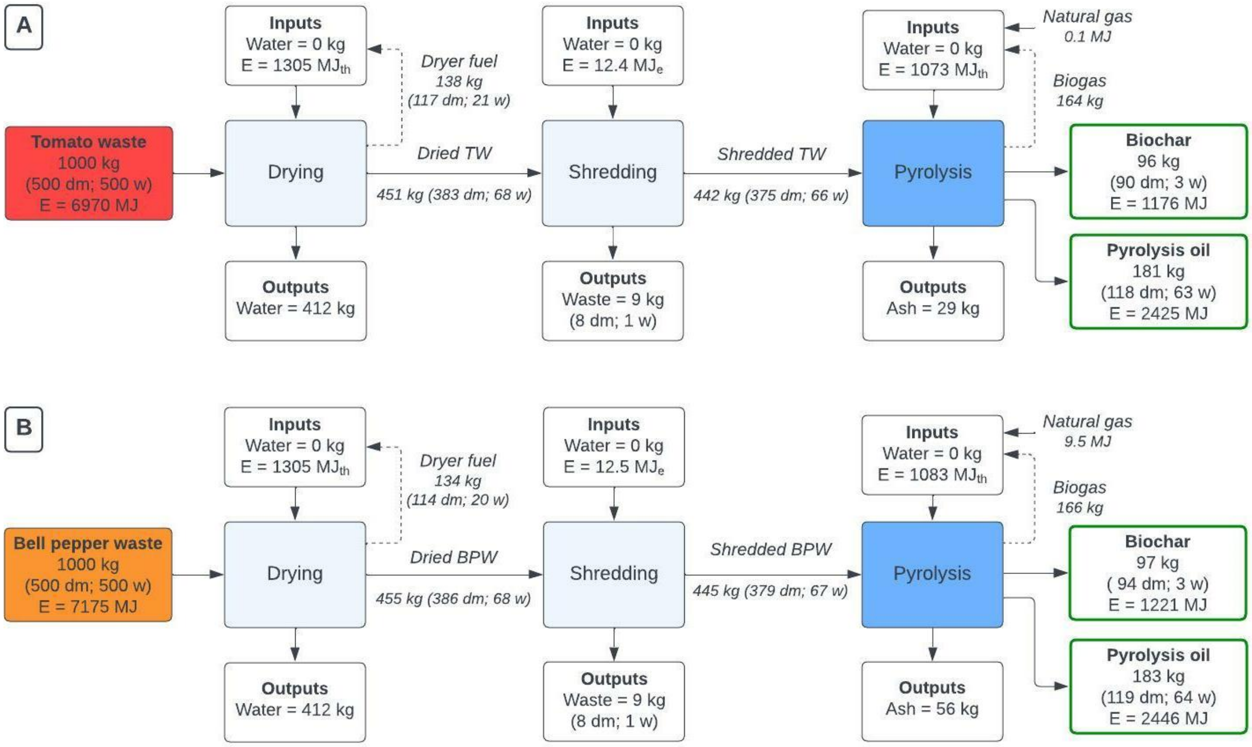


Figure 8. Energy and mass balance of conversion routes 4-TomPyr (A) and 5-PepPyr (B): drying, shredding, and pyrolysis of greenhouse tomato and bell pepper waste respectively (TW = tomato waste, BPW= bell pepper waste, dm = dry matter, w = water).

Under route **6-VerGas**, the fresh material is dried, shredded, and pressed before being gasified (Figure 9). All three pre-processes only require energy and their outputs are processed verge grass, waste matter and/or water, depending on the process. Gasification requires air and energy, and produces syngas (useful output), as well as ash and water (waste products). The initial energy contained in the fresh material is 6744 MJ and a total of 2937 MJ are required for the various processes. However, part of the dried verge grass is used as fuel for the drying process and the tar produced in gasification is also self-consumed. This accounts for 2861 MJ of the total energy demand, meaning only 76 MJ needs to be sourced externally. The syngas output has an energy content of 3212 MJ, resulting in an energy efficiency of about 39%. A total of 584 m^3 of syngas is produced, which contains 259 kg of the dry biomass matter (65% of the fresh material dry matter content).

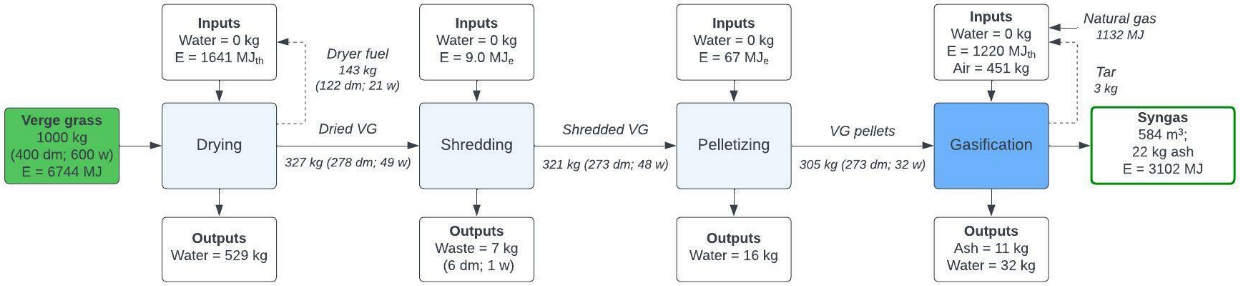


Figure 9. Energy and mass balance of conversion route 6-VerGas: drying, shredding, pressing, and gasification of verge grass (VG = verge grass, dm = dry matter, w = water).

In route **7-VerAna**, the fresh matter is first ensiled (Figure 10). This process requires no energy or water and produces verge grass ensilage, and some waste dry matter and water. Next, washing and pressing requires 2730 kg of water and 36 MJ of energy, resulting in a press cake and press juice. The press cake can be used for combustion and the press juice can be used to produced bio-gas or filtered/concentrated to obtain concentrated nutrients that could be used as fertilizer (BVOR, personal communication, May 15, 2022). In the model, the press juice is further processed through anaerobic digestion to produce bio-gas (requiring 112 MJ of energy, supplied by the bio-gas itself), and digestate and water as waste products. After conversion, 75% of the dry matter originally included in the biomass is in the bio-gas product. The 1000 kg of verge grass input contains 6744 MJ and an external energy input of 36 MJ results in a syngas output with 2584 MJ energy and a press cake containing 2457 MJ of energy. Thus, the energetic efficiency of the process is 72%.

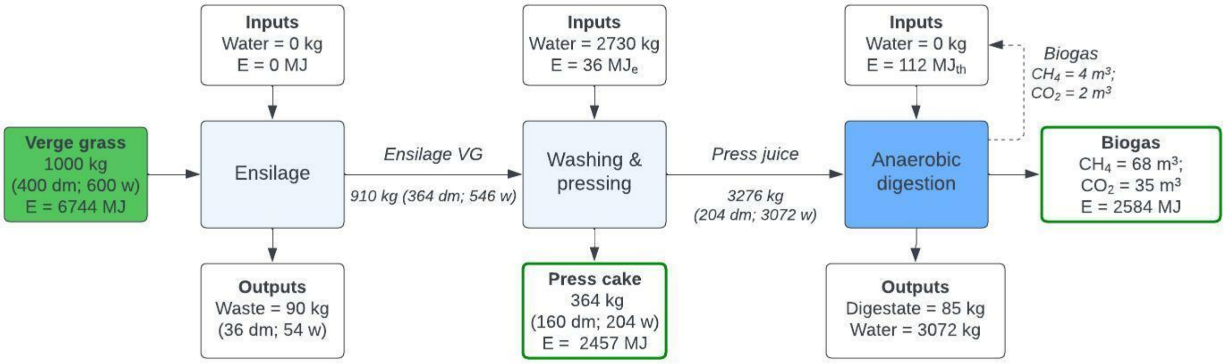


Figure 10. Energy and mass balance of conversion route 7-VerAna: ensilage, washing and pressing, and anaerobic digestion of verge grass (VG = verge grass, dm = dry matter, w = water).

In routes **8-TomAna1** and **9-PepAna1**, the fresh matter is ensiled, washed, and pressed before going through anaerobic digestion (Figure 11). Ensiling does not require energy or water, but some losses (wastes) occur in the production of the ensilage. Washing requires water and produces some waste matter and water in addition to the washed tomato or bell pepper waste. Finally, pressing requires energy, and produces press cake and press juice. The press juice then undergoes anaerobic digestion which requires energy input (provided by the bio-gas produced). This produces bio-gas, digestate, and water. Overall energy efficiency is 66% for tomato waste and 59% for bell pepper waste while dry mass efficiency is 65% for tomato waste and 60% for bell pepper waste.

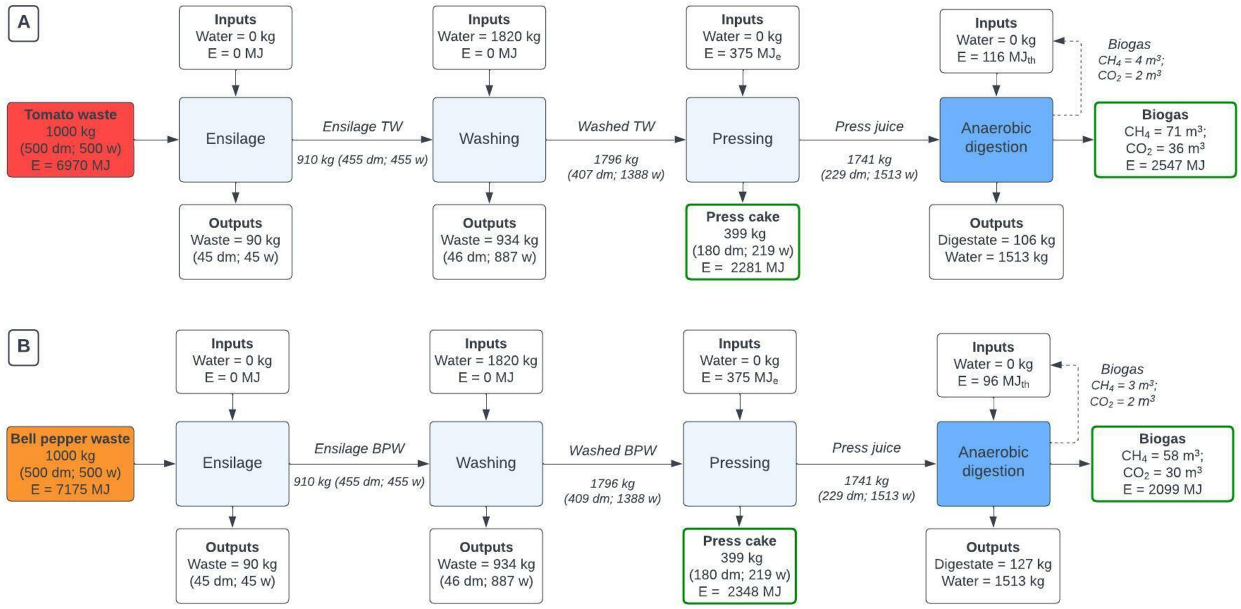


Figure 11. Energy and mass balance of conversion routes 8-TomAna1 (A) and 9-PepAna1 (B): ensilage, washing, pressing, and anaerobic digestion of greenhouse tomato and bell pepper waste respectively (TW = tomato waste, BPW= bell pepper waste, dm = dry matter, w = water).

Routes **10-TomAna2** and **11-PepAna2** consist of shredding and anaerobic digestion (Figure 12). Both processes require energy: shredding requires electricity, and anaerobic digestion requires heat to maintain the temperature at the desired level. The output from shredding is dry matter, and anaerobic digestion forms bio-gas, digestate and water. Part of this bio-gas is used to supply the energy required for the anaerobic digestion. Anaerobic digestion for bell pepper waste needs slightly less energy input than for tomato waste due to the higher heating value of bell pepper waste, however less bio-gas is produced because of the higher ash content of bell pepper waste compared to tomato waste. The energy efficiency of the conversion route is 49% for tomato waste and 42% for bell pepper waste, while the dry mass efficiency is 40% tomato waste and 35% for bell pepper waste.

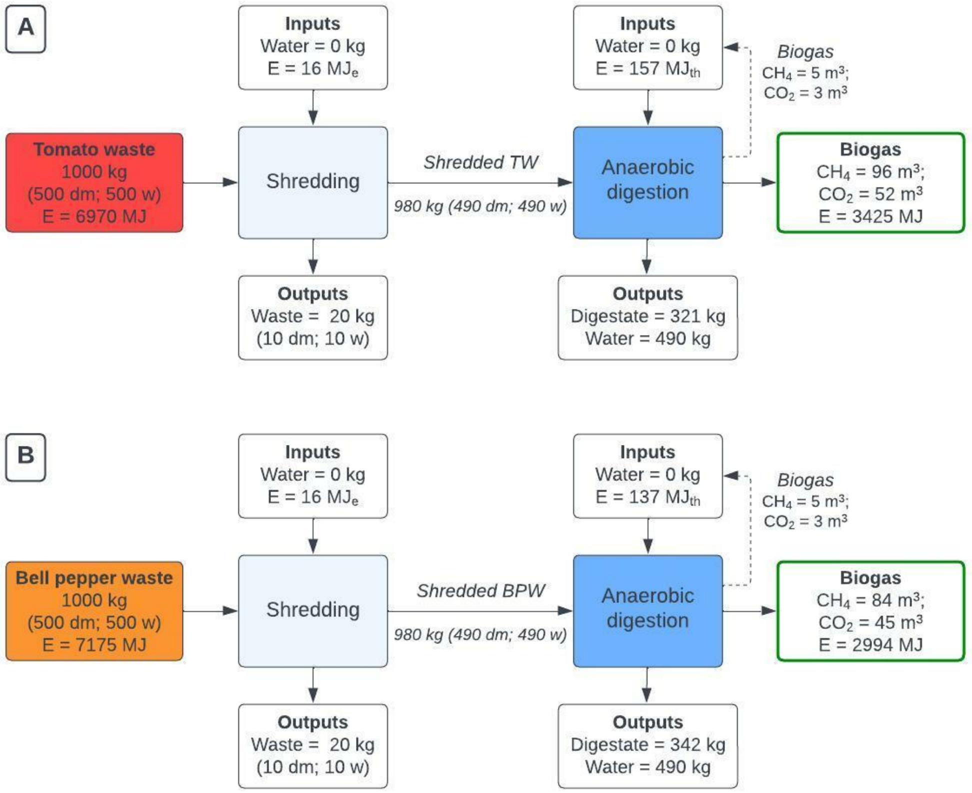


Figure 12. Energy and mass balance of conversion routes 10-TomAna2 (A) and 11-PepAna2 (B): shredding and anaerobic digestion of greenhouse tomato and bell pepper waste respectively (TW = tomato waste, BPW= bell pepper waste, dm = dry matter, w = water).

The dry mass and energy efficiency of each conversion route are summarised in Table 11.

Table 11. Mass efficiency and energy efficiency of the conversion routes analysed

Conversion route	Dry Mass Efficiency [%]	Energy Efficiency [%]
1-TomTor	53	47
2-PepTor	53	48
3-VerTor	42	38
4-TomPyr	41	53
5-PepPyr	43	53
6-VerGas	65	39
7-VerAna	75	72
8-TomAna1	65	66
9-PepAna1	60	59
10-TomAna2	40	49
11-PepAna2	35	42

4.4.2 GHG avoidance potential

Figure 13 shows the specific GHG avoidance potential of the various conversion routes. For each route, the offsetting of fossil fuel use had the biggest impact on the results. Note that the amount of GHG emissions that can be offset is dependent on the conversion efficiency of each route (the more products are formed, the more fossil fuels are replaced). The CH_4 and N_2O that would otherwise be emitted from composting had a relatively small, but significant effect on the net GHG avoidance potential. Natural gas use, electricity use, and transport had only a minor effect, the former being explained by a large share of self-consumption within the routes. The large GHG avoidance potential of Route 6-VerGas is caused by the fact that it offsets syngas made from gasified coal, which is an energy intensive and emission-heavy procedure. Route 11-PepAna has the lowest avoidance potential. This is explained by a relatively low energy output (compared to other anaerobic digestion because there is no pre-treatment) and the relatively low emission factor of the fossil fuel replaced (namely, natural gas).

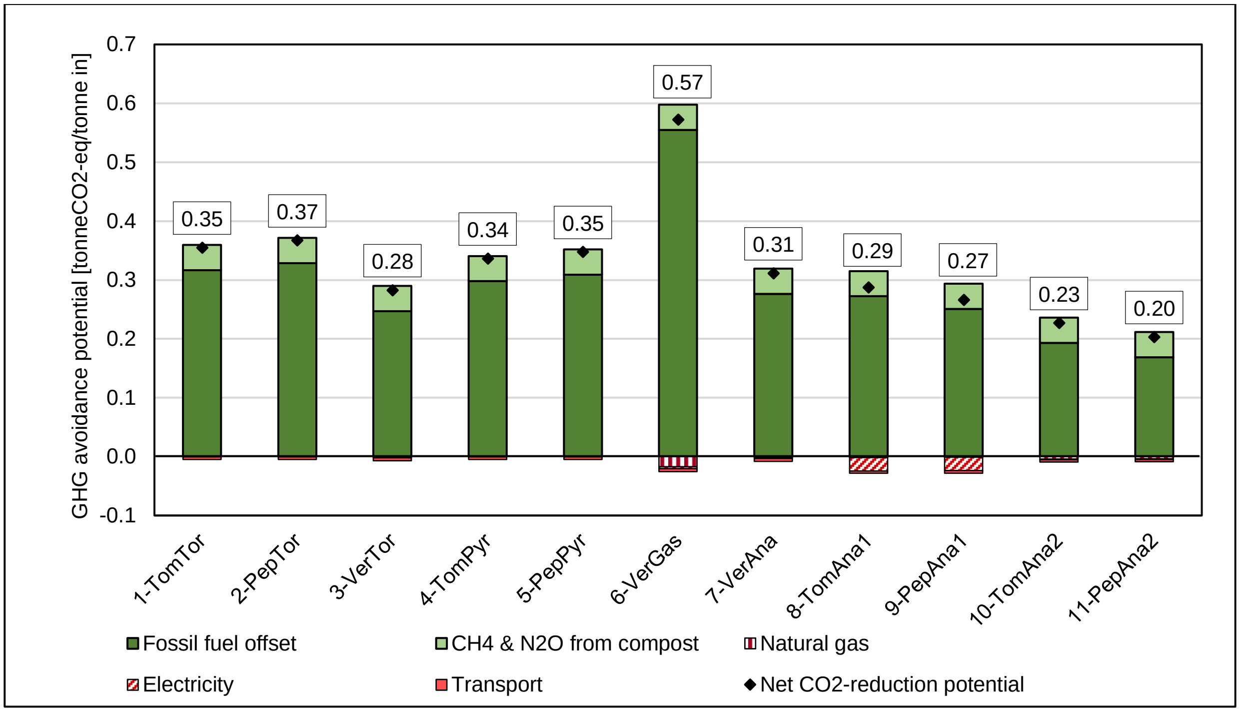


Figure 13. GHG avoidance potential for the conversion routes, based on process emissions (electricity, transport, natural gas) and offsetting emissions (fossil fuel replacement, avoidance of compost emissions).

4.4.3 Economic performance

Table 12 shows an overview of the economic KPI results for the various routes. Looking at the NPV, only five routes result in a positive value (routes 1 to 5). The PBP of those routes is within their lifetime (ranging from 3 to 10 years) and their LCOE ranges from 4.5 €/GJ (3-VerTor) to 14.8 €/GJ (4-TomPyr).

Table 12. Economic performance of the conversion routes analysed measured in net present value (NPV), payback period (PBP) and levelized cost of energy (LCOE) for a biomass input of 70.000 tonne/year.

Conversion route	LCOE [€/GJ]	PBP [yrs]	NPV [M€]
1-TomTor	9.4	4.5	16.1
2-PepTor	9.1	4.3	17.5
3-VerTor	4.5	2.8	22.8
4-TomPyr	14.8	10.0	5.7
5-PepPyr	14.1	9.4	8.1
6-VerGas	11.7	33.6*	-14.5
7-VerAna	12.5	- **	-33.8
8-TomAna1	19.1	- **	-58.5
9-PepAna1	18.9	- **	-53.9
10-TomAna2	17.3	297.0*	-30.6
11-PepAna2	17.1	183.2*	-26.2

** PBP exceeds lifetime; ** there is no PBP*

Looking more specifically at the LCOE, Figure 14 gives an overview of the contributions of different costs and processes to the overall values. The cost type that makes the biggest contribution to the LCOE is either investment costs or variable costs for all routes. Especially for the pyrolysis routes, the specific investment costs comprise a large share of the LCOE. Looking at the process types, the final conversion comprises the largest share of the LCOE. Notable are the relatively high process costs involved with pressing and ensiling caused by their high electricity use.

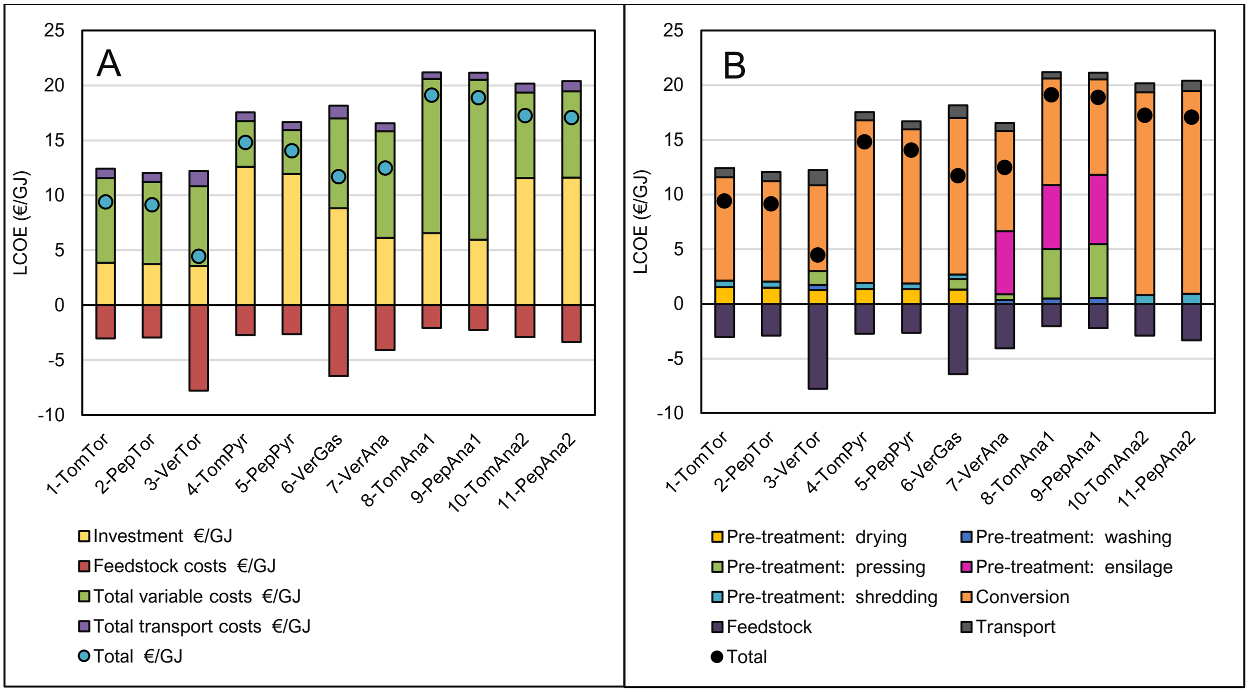


Figure 14. LCOE results for the analysed conversion routes, and the contributions divided according to cost type (A) and process type (B). The dots show the net LCOE, after subtracting the negative costs of the feedstock.

For the NPV (Figure 15A), routes 1 to 5 give a positive output, meaning these projects are economically viable. The highest NPV is of route 3-VerTor and lowest of route 4-TomPyr. For routes 1 to 5, the calculated PBP is within the expected lifetime of the plant (Figure 15B). The lowest is for route 3-VerTor and the highest for route 4-TomPyr.

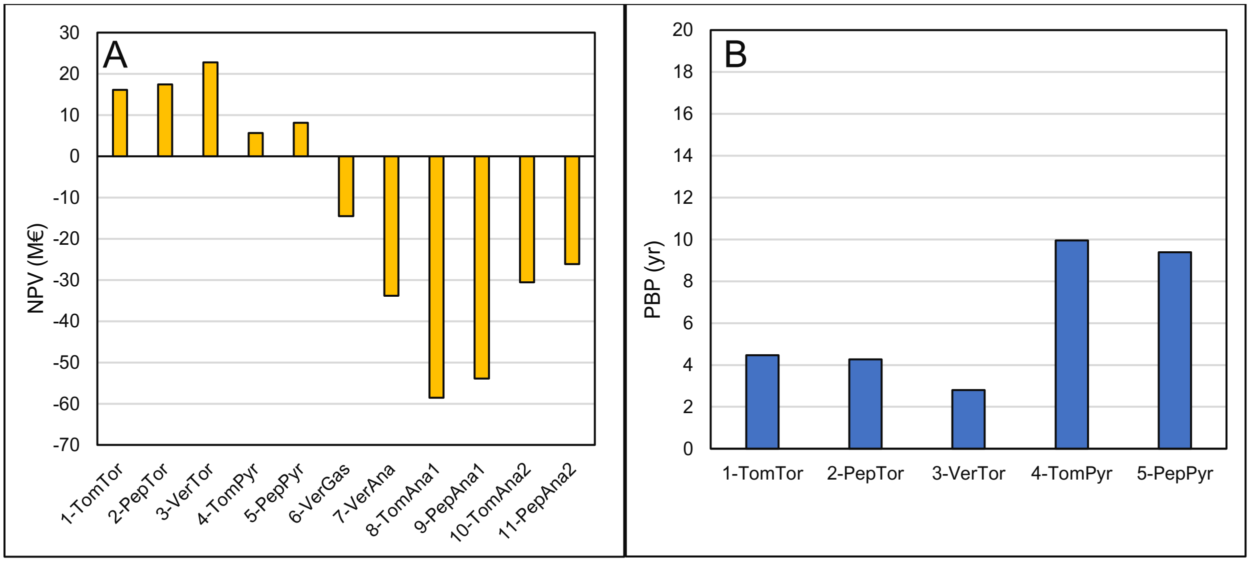


Figure 15. Results of the economic analysis: net present value (A) and payback period (B). In graph B, the y-axis was scaled to the average plant lifetime. Routes with a negative NPV (A) are excluded from the PBP graph (B).

4.5 Comparative analysis of conversion routes

When looking at the technical indicators, routes 7-VerAna, 8-TomAna1, and 9-PepAna1 score best (>59%), both in terms of dry mass efficiency and energy efficiency. Routes 1-TomTor, 2-PepTor, 4-TomPyr, and 5-PepPyr end-up as middle-of-the-road routes with both efficiencies being around 40-50%. This middle category also includes 6-VerGas, which has a high dry mass efficiency, but a low energy efficiency. The lowest efficiencies calculated were for 3-VerTor, 10-TomAna2 and 11-PepAna2, in which either one or both efficiencies score at 40% or lower.

When judging the environmental performance based on the GHG-avoidance potential, 6-VerGas scores best at 0.57 kg CO_2eq/kg input. This score is significantly higher than the scores of other routes, which range from 0.20 (11-PepAna2) to 0.37 (2-PepTor).

Looking at the economic viability of the routes, only routes 1 to 5 have a positive NPV. In terms of LCOE, the torrefaction routes show best values (around 12 €/GJ), followed by pyrolysis and gasification routes (around 17 €/GJ) and finally the anaerobic digestion routes (> 20€/GJ). These routes also have a payback period within the lifetime of the plant.

Merging these different perspectives, the following can be said on the conversion routes.

1) The torrefaction routes (routes 1 to 3), score mediocre to low in terms of technical performance, but relatively high for environmental and economic performance.
2) The pyrolysis routes (route 4-TomPyr and 5-PepPyr) score middle-of-the-road in terms of technical performance and LCOE, but relatively high in terms of PBP, NPV, and GHG avoidance.
3) The gasification route (6-VerGas) scores very low in terms of energy efficiency but has the highest GHG performance. Also considering the economics, it scores intermediate.
4) The anaerobic digestion routes including ensiling (routes 7 to 9) have the largest difference over the indicators: while they are scoring best on technical performance, they have the worst economic performance.
5) The anaerobic digestion routes excluding multiple pre-treatments (routes 10-TomAna2 and 11-PepAna2) score poorly in all categories: lowest GHG performance and efficiencies, high LCOEs and PBPs, and low NPV.

4.6 Sensitivity analysis

This section shows the results of the sensitivity analysis (Figures 16-21).

Looking at the sensitivity to a change in discount rate (Figure 16), it can generally be observed that NPVs for all routes are influenced by a changing discount rate. Overall, the NPV is highly sensitive to changes when the discount rate ranges from 0-20%, after which additional increases affect the NPV less strongly. This is because discounting with higher discount rates decreases the benefits and costs over time, showing a limited effect on NPV. For the conversion routes that reach an NPV of zero, the internal rate of return (IRR) can be estimated at the value for the discount rate where the NPV is zero (intersection with the x-axis). The lowest IRR values are between 5-10% for routes 4-TomPyr and 5-PepPyr (pyrolysis). Subsequently, it can be observed that routes 1-TomTor and 2-PepTor (torrefaction) have an IRR between 20-25%. Lastly, route 3-VerTor (torrefaction) has an IRR of around 35%.

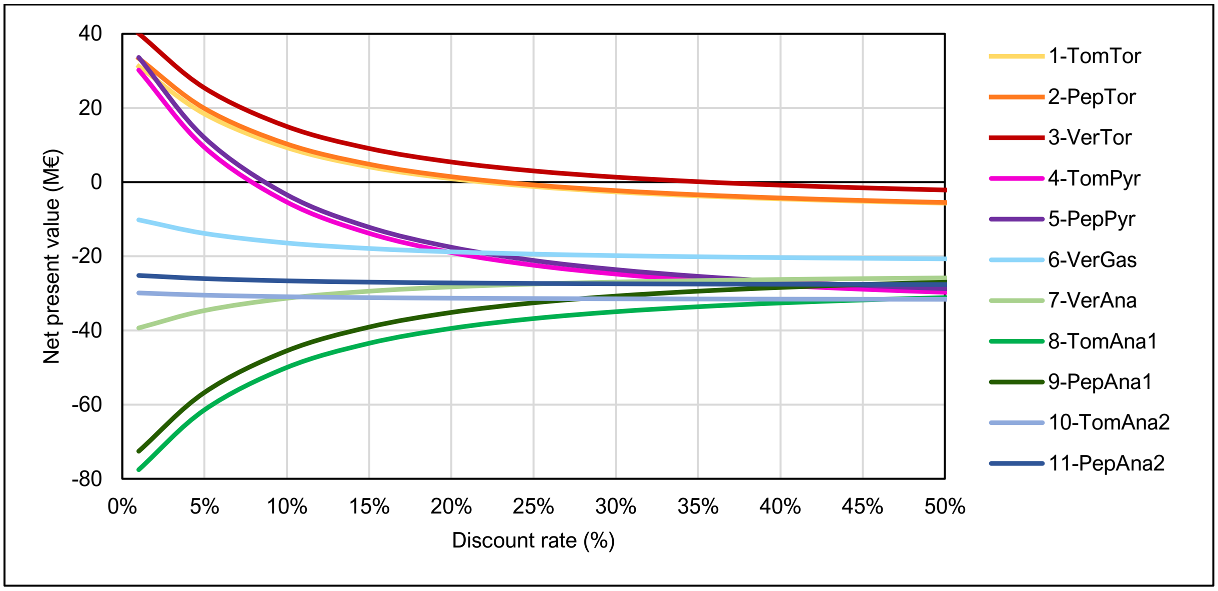


Figure 16. Sensitivity diagram showing the effect of a changing discount rate on the NPV.

The results for the sensitivity of NPV and LCOE to feedstock prices can be seen in Figure 17. In the original settings, the feedstock prices were set at -20 €/tonne for verge grass and -10 €/tonne for tomato and bell pepper waste, effectively being a benefit to the conversion route. Since feedstock prices are volatile (Eneco, personal communication, May 25, 2022), and an increase in demand for waste streams may increase the price of feedstocks, it is likely that these prices will become positive.

Looking at the NPV (Figure 17A), an inverse relationship between NPV and feedstock prices can be observed (i.e. when feedstock price increases, the NPV decreases). The NPV is very sensitive to changes in feedstock prices: a slight increase in feedstock price results in a large decrease in

NPV. When prices rise above 15 €/tonne, no route will have a positive NPV. Routes 6 to 11 will only reach a positive NPV at a feedstock price of below -40 €/tonne. It is unlikely that the price will decrease from current prices and thus that these routes will ever reach a positive NPV.

Looking at the effect of changing feedstock prices on LCOE (Figure 17B), there is a strong positive relationship. For route 3-VerTor the LCOE is most sensitive to the changes in feedstock price. The LCOEs of routes 7-VerAna and 8-TomAna1 are the least dependent on the feedstock price.

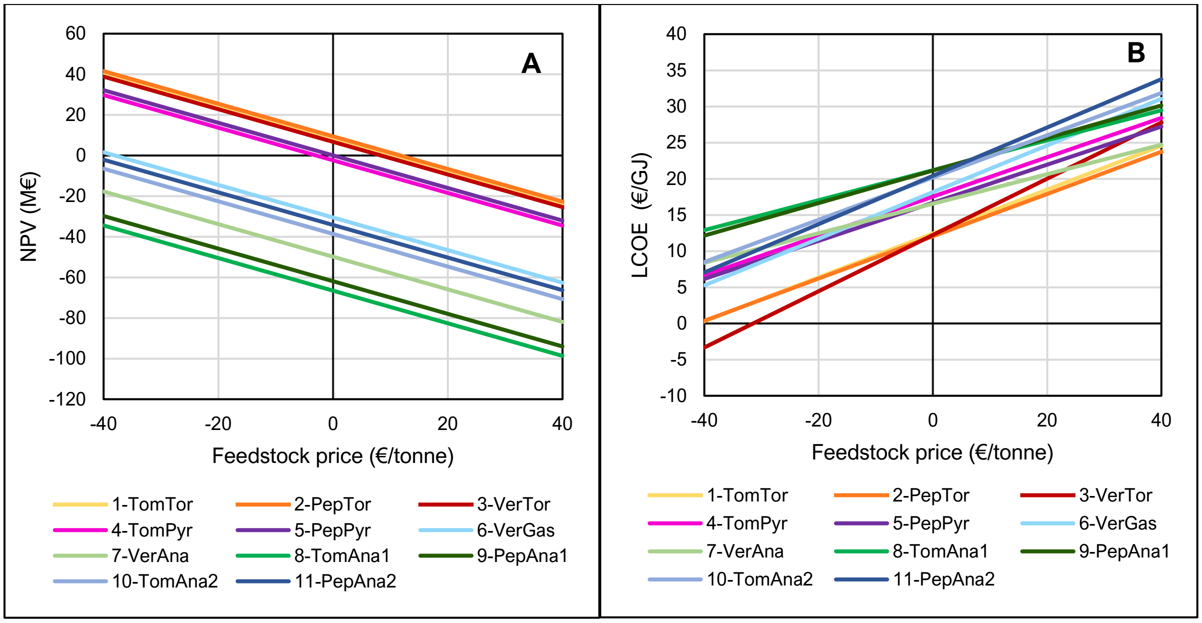


Figure 17. Sensitivity diagram showing the effect of changes in feedstock price on the NPV (A) and LCOE (B) of different conversion routes.

The effect of changing natural gas prices can be seen in Figure 18. The original analysis (where the change is 0%) uses the average natural gas price over 2021 (Appendix E). Considering the volatility of gas prices, a range from -50% to 200% was chosen. Results indicate that increasing the natural gas price improves the business case for the conversion routes that produce bio-gas (Figure 18A). However, only at very high gas prices (compared to 2021) the NPV of routes 6-VerGas, 9-PepAna1, and 10-TomAna2 becomes positive. This is due to the fact that they produce more bio-gas than they consume, and the bio-gas price is linked directly to the natural gas price (i.e. a 200% increase in NG price also results in a 200% increase in bio-gas price). Because of a net outflow of gas, the benefits will increase according to the increasing prices. Since the LCOE is only dependent on the costs and the natural gas use is relatively low, the LCOE is not very sensitive to changing gas prices (Figure 18B).

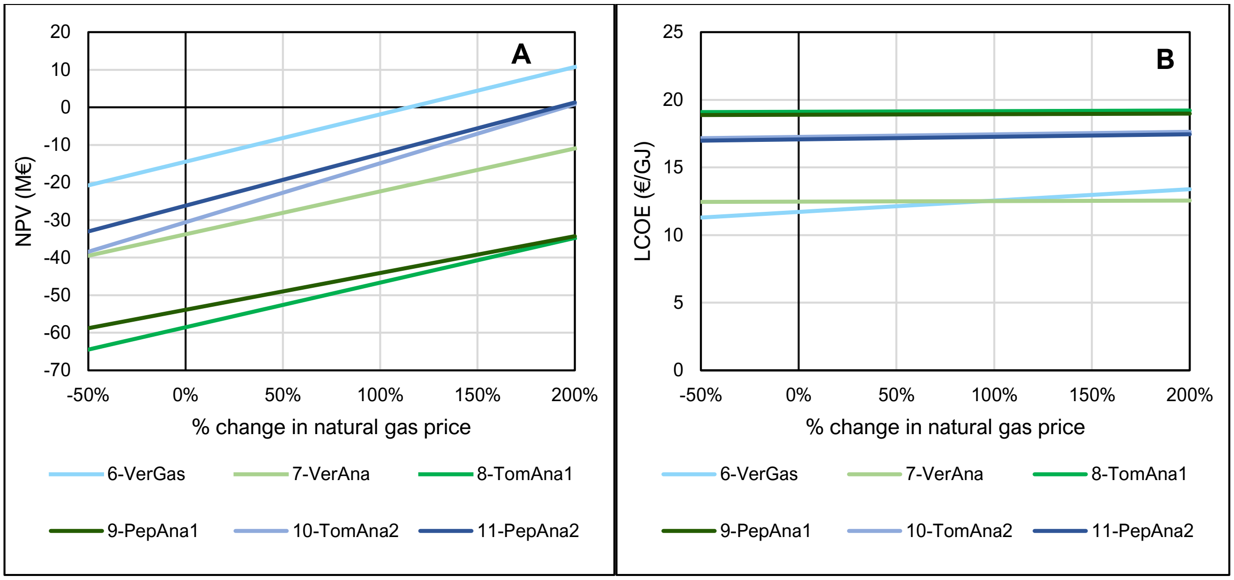


Figure 18. Sensitivity diagram showing the effect of price changes of natural gas on the NPV (A) and the LCOE (B) of different conversion routes (only routes that are linked to natural gas are included).

Figure 19 shows the effect of changing electricity prices on the NPV and LCOE. For all routes there is an inverse relationship with NPV and a direct relationship with LCOE. Mostly, this effect is marginal, except for routes 8-TomAna1 and 9-PepAna1. This is caused by the fact that these routes require relatively high amounts of electricity in the pre-processing.

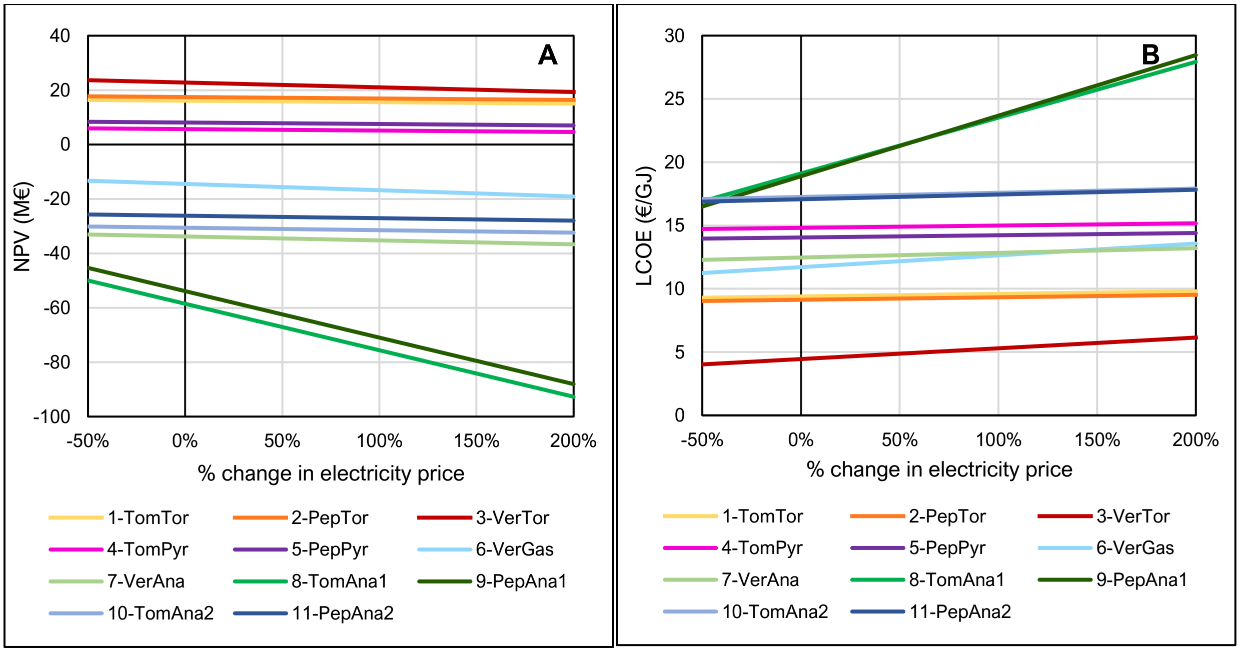


Figure 19. Sensitivity diagram showing the effect of price changes of electricity on the NPV (A) and LCOE (B) of different conversion routes.

As becomes clear from Figure 20, the effect of a change in diesel prices on NPV and LCOE is marginal for all routes. Higher prices result in slightly lower NPVs and slightly higher LCOEs. This can be explained by the fact that diesel prices only influence the transportation costs, which have a relatively small share in the total costs. Therefore, the sensitivity of NPV and LCOE to changes in the diesel price is low.

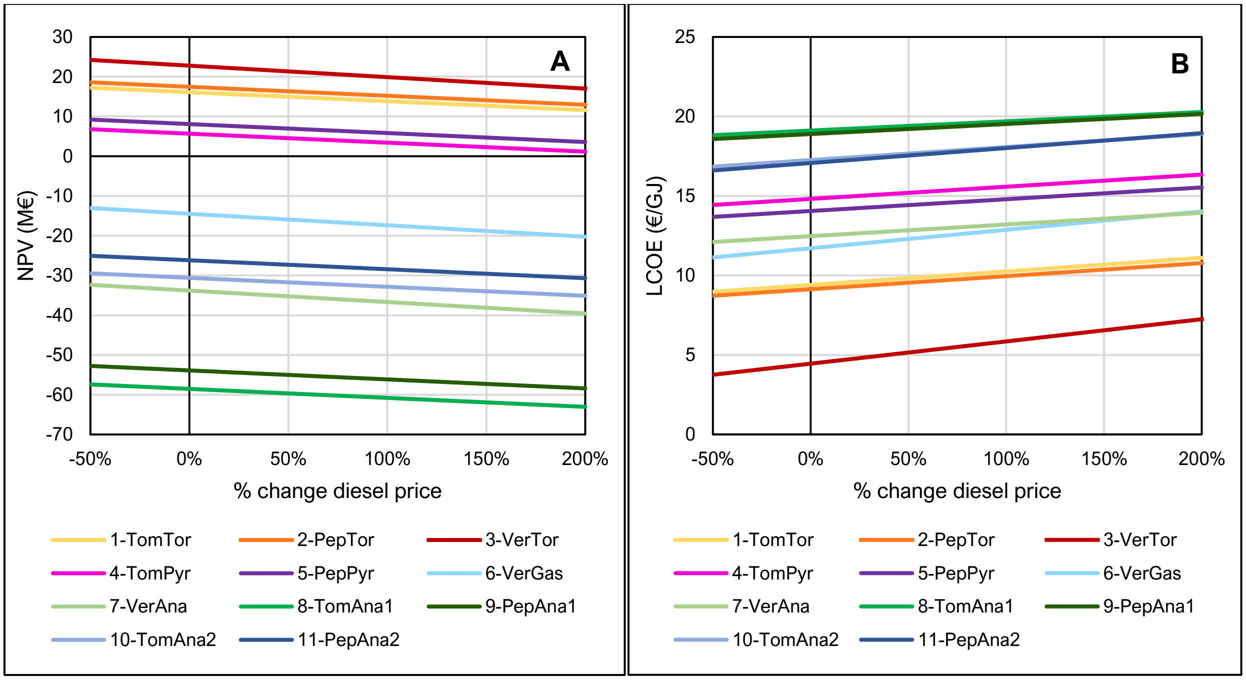


Figure 20. Sensitivity diagram showing the effect of diesel price change on the NPV (A) and LCOE (B) of different conversion routes.

Lastly the effect of changes in the CAPEX values used is analysed on the LCOE and NPV. Since the effect of a scaling factor is missing in the model (see discussion) and the uncertainty is quite high, the values are analysed from -50% to +50%.

There is an inverse relation between CAPEX and NPV, though it is very weak for the torrefaction routes (Figure 21A). Figure 21B shows that an increasing CAPEX results in an increase in the LCOE of all routes. This effect is stronger for route 4-TomPyr, 5-PepPyr, 6-VerGas, 10-TomAna2 and 11-PepAna2 compared to the other routes, indicating a higher sensitivity.

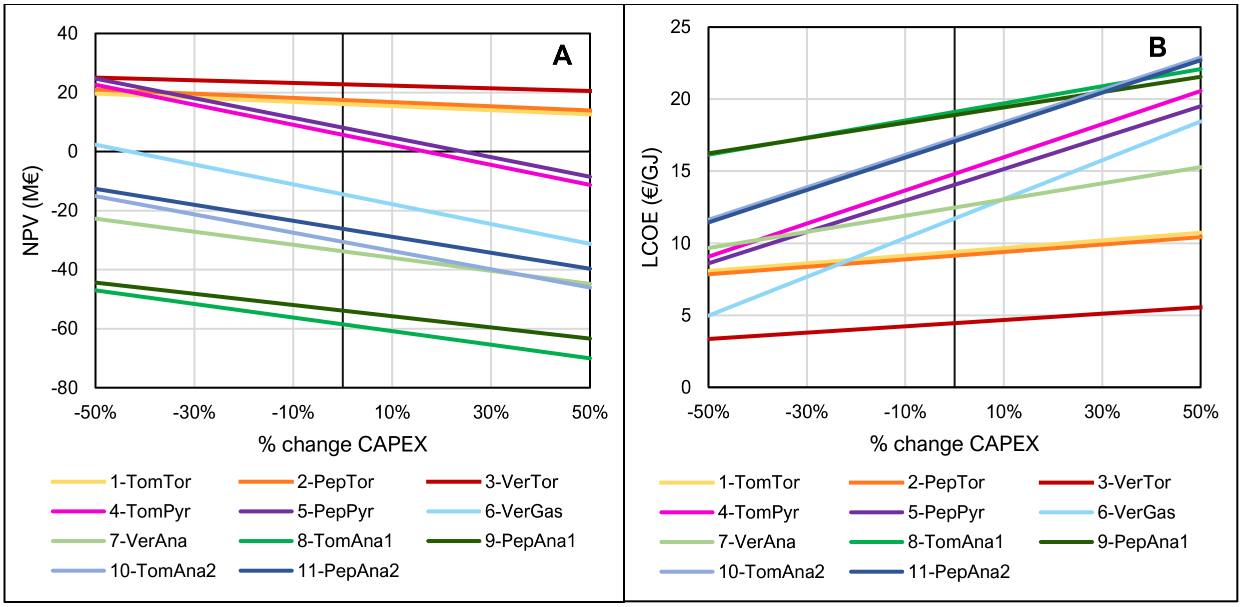


Figure 21. Sensitivity diagram showing the effect of price changes of the CAPEX on the NPV (A) and LCOE (B) of different conversion routes.

5 Discussion

5.1 Interpretation of the results

The first results of this research consider the biomass waste stream and conversion routes inventories. Verge grass, greenhouse bell pepper, and greenhouse tomato waste were found to be the most promising waste streams for energy applications in the Netherlands. This is in line with findings from previous research by BlueTerra (Larrivee & van Dijk, 2022). The conversion routes themselves were found through literature review; a discussion of routes present in literature was given in Section 4.3.

The spatial analysis results are relevant when selecting the location for a low-grade biomass waste treatment plant. They indicate that it might be more economically viable for paprika and tomato waste to be processed at a centralized location in Zuid-Holland, while the upgrading of verge could also be done decentralized (i.e., per province, or at nearby farms in case of conversion through anaerobic digestion). However, the transport costs were found to only contribute marginally to the LCOE in this study. An investor must make a trade-off for reducing transport distance and transport costs on the one hand (favouring decentralization) and reducing investment costs by possible scaling effects on the other hand (favouring centralization).

When interpreting the modelling results, the KPIs are a useful tool to put the findings into context of research literature. Looking at the efficiencies of the torrefaction process, the results (38-48% energy efficiency) are lower than found in literature for verge grass (62%; Abelha & Kiel, 2020). These results, however, do not allow for direct comparison, since the mentioned paper included the upgrading of process waste through anaerobic digestion to increase process efficiency, which might partly explain the difference. For pyrolysis at 600˚C, Mokrzycki & Rutkowski, (n.d). found a dry mass efficiency of 35%. This is similar to the results of route 4-TomPyr and 5-PepPyr, which might be explained by the fact that this study also includes the dry-weight in the bio-oil rather than just the biochar weight in the mass efficiency. For gasification of verge grass (6-VerGas), literature suggests higher energetic efficiencies are possible, with ranges of 58-64% compared to the 39% in this research (Van Der Drift et al., 2001). However, that research excluded the pre-treatment steps from the efficiency, and worked with pre-processed products in the pilot. It is likely that the extensive pre-treatment in this route lowered the efficiency. Anaerobic digestion energy efficiencies in literature are around 35% (Beegle & Borole, 2018), which is significantly lower than the results of routes 7 to 11. However, the results of this research confirm the assumption that the anaerobic digestion routes including ensiling, washing, and pressing perform better than those without these pre-treatments, which could possibly be linked to the separation of easier-to-convert volatiles from the fibres.

Looking at efficiencies in general, it has been found that trade-offs are present in terms of efficiencies of separate technologies and efficiencies of the overall process. For example, drying is an energy-intensive pre-treatment process that one might want to limit in a conversion route. However, the efficiencies of conversion technologies increase when the moisture content of the feedstock is lower. Thus, a trade-off must be made to find a balance between pre-treatment and conversion and optimize the overall process efficiency.

For the environmental performance, two main aspects should be considered for the interpretation of the results: 1) the choice of reference scenario, and 2) the emission calculations.

For the former, this research used composting as reference scenario since it is currently the main use for low-grade biomass and is a low-value application. The place of composting within biomass cascading is, however, disputed. Glastuinbouw Nederland sees compost as a high-value application, enhancing the circularity of the carbon cycle by embedding carbon in the soils (Glastuinbouw Nederland, personal communication, June 1, 2022). This is in line with the Dutch climate agreement, which states that: “biomass is seen in a cascade: primarily to keep and make the soils fertile, followed by use for food and feed, feedstock for materials, chemicals and finally for energy” (Klimaatakkoord, 2019). Thus, composting is seen as the highest value application of biomass and energy as the lowest. However, for the low-grade biomass covered in this research, contamination issues prevent it from being transformed into high-grade compost. Along with the competition of manure in the compost market, the compost from low-grade biomass can thus be seen as a low-value application (BVOR, personal communication, May 13, 2022).

For the latter, the choice of emission calculations influences the results. Looking at the KPI of GHG avoidance potential, the CO_2-equivalent of the avoided CH_4 and N_2O emissions from composting make up between 7-21% of the total potential. It should however be noted that this might be a slight overestimation of the avoided emissions. This is due to the fact that CO_2 emissions from the biomass are neglected in the emission results because of their biogenic origin. When looking at composting, about 40-70% of the organic matter (including carbon) can be degraded (released as emissions) during composting (Sánchez et al., 2015). However, the remaining 30-60% stays in the compost as fixed carbon and might be embedded in the soil for a longer time. Comparing this to the energy conversion routes, the emissions released during composting are avoided, but the soil carbon storage potential is lost as well. In the energy conversion routes, this carbon would be released as CO_2 during combustion of the products or even leaked in the form of CH_4 during bio-gas transport. Therefore, accounting for the CO_2 emissions in both processes could lower the contributing effect of composting emissions to the GHG avoidance potential.

Looking at the economic results, LCOE values allowed for easy comparison to literature. In this research the LCOEs of torrefaction are in the range of 4 - 9 €/GJ, depending on the feedstock. For a similar plant size, Abelha & Kiel (2020) found an LCOE of 6.2 €/GJ. In their report, however, the LCOE decreases to 1.4 €/GJ for a torrefaction plant with an annual capacity of 120 tonne dry biomass input due to a scaling factor, indicating that up-scaling of torrefaction plants can be beneficial for the economic performance. The LCOE of gasification is 11.7 €/GJ, which is slightly lower than 15.8 €/GJ found by You et al. (2017). It should be noted that direct comparison of these values is not possible since the LCOE from literature is based on a gasification plant combined with a CHP plant. When accounting for the efficiency of the CHP plant, the values for gasification output are similar. In literature, LCOEs found for anaerobic digestion are in the range of 8.4 - 11.2 €/GJ (Huang & Fooladi, 2021). Thus, the values found for anaerobic digestion in this research (12.5 - 19.1 €/GJ) are relatively high. This difference might be explained by the pre-treatment steps included in this research.

Finally, for the sensitivity results it was found that the economic indicators were especially sensitive to changes in feedstock prices. With the current volatility of feedstock prices (Eneco, personal communication, May 25, 2022), this is an important finding to consider when looking at the robustness of the business case.

5.2 Limitations

5.2.1 Scope limitations

A first scope limitation of this study is that the potential of biomass waste streams not chosen for analysis was not investigated further, while these streams might be suitable for mixing with the analysed feedstocks. This might be beneficial to reduce transport costs and increase total availability. For example, cucumber and aubergine stems contain similar chemical and physical properties to tomato and bell pepper stems and could therefore be considered for mixing (Oleszek et al., 2016). Flower waste can be used for anaerobic digestion, since the anaerobic digestion process can be fed using a mix of feedstocks (Singh & Bajpai, 2012). Reed could be considered for mixing with verge grass because of its relatively similar properties (Elbersen et al., 2015). Lastly, manure might be considered for manure co-digestion (Zwart et al., 2006). While feedstock mixing might come with its own set of technological challenges, applying mixing might change the outcome of the results presented here and therefore present an opportunity for further research (Pant & Mohanty, 2014; Meegoda et al., 2018).

A second limitation to this study is that it did not consider the seasonality of feedstocks. Greenhouse horticulture waste from tomatoes and bell peppers is produced during a two-week period around the end of the year (DES B.V., personal communication, May 30, 2022). Road verges are generally cut twice a year in July and October/November (Holshof et al., 2014). This means that either biomass installations need to manage extreme peaks of biomass, or that the biomass needs to be stored. Ensiling biomass is an effective method for storing biomass over a longer period by sealing it airtight (Teixeira Franco et al., 2016). In this study only routes 7-VerAna, 8-TomAna1, and 9-PepAna1 involve an ensiling pre-treatment step. However, for commercial-scale implementation of a low-grade biomass installation one should consider adding an ensiling pre-treatment step in all routes. This might influence the conversion process characteristics and should be investigated further. Some research has found a positive effect of ensiling on grass or straw pyrolysis, gasification, and anaerobic digestion (van Poucke et al., 2016; D'Jesús et al., 2006; Nizami & Murphy, 2011; Egwu et al., 2022).

A third limitation is that feedstock contamination was not considered. Verge grass, tomato stems, and bell pepper stems are partly considered as low-grade biomass because of material contaminations. Verge grass can be contaminated with sand, rocks, and trash coming from the road. Tomato and bell pepper stems are often contaminated with plastic strings which help the plant grow within the greenhouse (Larrivee & van Dijk, 2021). The contaminants add extra filtering requirements to the process, which might lead to additional costs.

A fourth limitation to this study was that finding high-resolution spatial data on greenhouse horticulture waste and verge grass proved to be challenging. This resulted in the use of equations to calculate the spatial distribution of verge grass streams and horticulture waste. The lack of high-resolution spatial data limited this study's spatial analysis to a province scale approach. The province scale approach subsequently informed less accurate transportation distance estimates. The central point of the province with the greatest production was chosen as the destination point under the assumption that a potential investor would want to limit its transport costs. However, finding a location might not be as easy since other factors play an important role as well, such as infrastructure availability, permits, and public support.

Building on this, a fifth limitation is that this study did not consider a detailed design of the supply chain of the various routes, other than the location of production and conversion. A trade-off that could still be considered is whether transport should take place between processing steps. Drying and shredding might significantly increase the bulk density of the feedstock compared to its density after harvest. This gives a potential investor the option to transport after pre-treatment, thereby reducing transport costs. However, this might come at the cost of having to build installations at multiple sites. While these trade-offs were not considered here, this study does indicate that transport costs only contribute marginally to the total costs, which would favour the case of building one large installation where all processing is done.

A sixth limitation in this study is that a minimum TRL of 6 was a selection requirement for the conversion technologies. However, this score was based on the technology itself and not necessarily on the combination of the technology with the specific feedstock. Despite this specific TRL possibly being lower than 6, the conversion routes (combination of feedstock with technology) were all proven in literature.

A final limitation can be found in the exclusion of subsidies in the economic analysis. The importance of subsidies was put forward in interviews with W. Lexmond (personal communication, June 6, 2022) and Glastuinbouw Nederland (personal communication, June 1, 2022). Often, biomass cannot compete with fossil alternatives for energy purposes. This is especially a problem for the Dutch horticulture industry since there is little to no financial room for investments (Glastuinbouw Nederland, personal communication, June 1, 2022). Higher CO_2 taxes and higher gas prices could incentivise investments in biomass plants.

5.2.2 Data and model limitations

There are some limitations related to the data collection. Since this data was used to set up the Excel model, these limitations should be considered when interpreting model data.

First, expert interviews were used as a means of data collection. Due to reasons of confidentiality, the interviewees were often not able to give exact values or ranges for relevant parameters, though they aided in understanding the processes and context of the research.

Second, since literature was used for collection of modelling data, some assumptions had to be made. One of these assumptions was the type of conversion technology. Most conversion processes (pyrolysis, gasification) can be performed by various types of installations, each with their own set of input parameters, such as temperature, technical limitations, and input requirements. For this research, either a specific technology or parameter was chosen (and mentioned in the methods), or average values were computed from literature findings. The same holds for the pre-treatment processes, where values had to be chosen for time, temperature, and resulting product specifications, linking to the efficiency trade-off mentioned in section 5.1. For example, it was assumed is that drying was done until a moisture content of 15% was achieved, since this was the maximum allowed value for certain conversion technologies.

Third, it should be noted that often data from different sources were used to model one process. Since each research comes with its own set of assumptions the compatibility of the data might be low. To overcome this often averages of different studies were taken. However, this might decrease the accuracy of the model outputs.

Finally, there are some limitations to the model. A model is always a simplification of reality, but due to time constraints there were certain parts that could not be included. For example, each conversion route was limited to one conversion technology, combined with one or multiple pre-treatments. In practice, it could make sense to combine different conversion technologies to optimally use all process outputs. For example, when pressing is applied as pre-treatment, both the press cake and press juice are suitable for high-grade conversion. Extending the conversion routes can alter the overall results. Also, even though the salt and ash contents of the feedstocks were included in the biomass waste stream inventory, these were not incorporated in the technology specifications in the model. Further, it was not possible to add a scaling factor or technological learning to the economic analysis due to time constraints. This leads to less realistic results, which were only partially overcome by using a broad range in e.g. CAPEX values in the sensitivity analysis.

6 Recommendations

Based on the findings of this study, the recommendations made to investors are:

1. The torrefaction and pyrolysis routes (routes 1 to 5) should be investigated further. These routes have a relatively good environmental performance and are economically viable in current circumstances according to the findings of this study. Other routes should only be investigated if relevant subsidies are implemented which alter the economic performance significantly.
2. Feedstock prices should be set at a fixed value in supply contracts. Due to the large sensitivity of both the NPV and LCOE to changes in feedstock prices, and the likely increase in demand for biomass waste streams, it is important to create certainty in the business case by setting fixed feedstock prices to ensure a viable business case.
3. A single large installation would be recommendable for processing bell pepper or tomato waste due to concentrated production in Zuid-Holland and relatively low contribution of transport costs to LCOE. Multiple installations could be considered for processing verge grass because of its dispersed spatial distribution and its greater availability.
4. Further research should be conducted on the effect of energy potential of other (mixed) feedstocks, seasonality of waste production, higher resolution spatial analysis, varying supply chain set ups, scaling factors, and multiple conversion technologies in a single conversion route on the results of this study.

7 Conclusion

This study analysed the potential of low-grade biomass waste streams for energy applications in the Netherlands. First, literature review and expert interviews were used to compile an inventory of waste streams and potential conversion routes, which informed the selection of those most suitable for energy applications. Second, an Excel model was built to perform a techno-economic and environmental analysis of the selected conversion routes. Specifically, energy and mass balances and related efficiencies; NPV, PBP and LCOE; and GHG avoidance potential were calculated for each route. Third, a comparison and analysis of the results was conducted, informing final recommendations to investors.

It was found that the waste streams most suitable for energy applications in terms of availability and quality are verge grass, greenhouse bell pepper waste and greenhouse tomato waste. The spatial distribution of verge grass is dispersed due to the dispersed distribution of roads but is highest in Noord-Brabant. The spatial distribution of bell pepper and tomato waste is more concentrated due to the concentrated distribution of greenhouses and is highest in Zuid-Holland.

11 conversion routes compatible with the identified waste streams were selected for further analysis. These consisted of a feedstock, pre-treatment process(es), and a conversion process. Four conversion technologies were analysed: torrefaction, pyrolysis, gasification, and anaerobic digestion. Results indicated that the conversion routes with the highest dry mass and energy efficiencies were routes 7-VerAna, 8-TomAna1, and 9-PepAna1. Routes 10-TomAna2 and 11-PepAna2 had the lowest dry mass efficiencies and route 3-VerTor and 6-VerGas the lowest energy efficiency. Economically, the routes with torrefaction and pyrolysis (Routes 1 to 5) were the only ones that were economically viable with a positive NPV. Environmentally, the conversion route with the highest GHG avoidance potential was verge grass combined with gasification (Route 6-VerGas). Thus, in selecting a conversion route for a low-grade biomass installation, there will be trade-offs between technical, economic, and environmental performance. Moreover, additional trade-offs arise in relation to the size of the installation and the design of the supply chain.

Having this in mind, the first recommendation made is to further investigate routes 1 to 5 due to their economic viability, good environmental performance, and moderate technical performance. Additionally, it is recommended that feedstock prices are set at fixed values in supply contracts as NPV and LCOE are highly sensitive to changes in feedstock prices. Moreover, due to concentrated production in Zuid-Holland and transport costs constituting a relatively small portion of LCOE, a single large installation is recommendable for processing bell pepper or tomato waste. Due to the dispersed nature of verge grass production, multiple dispersed installations could be considered.

It is important to note that the results of the study are specific to the input parameters and assumptions of the model created. Moreover, important considerations out of the scope of the study include the energy potential of other (mixed) feedstocks, seasonality of waste production, higher resolution spatial analysis and implications for transportation, varying supply chain set ups, effect of scaling factors, and the combination of multiple conversion technologies in a single conversion route. All these present opportunities for further research.

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Appendix A: Interview contacts

In Table A.1, an overview of the interviewed experts in the field of horticulture, biomass, and bioenergy can be found, along with the type of company, rationale for the interview, and date on which the interview was conducted. An overview of the interview minutes are provided in a supplementary document.

Table A.1. Brief overview of companies/people that are interviewed.

Company	Type of Company	Rationale for interview	Date
BVOR	Dutch association of biowaste streams	Inventory	13.05.2022
PerpetualNext	Pilot project – recovers carbon from organic waste	Efficiencies and costs conversion route.	23.05.2022
Eneco	Producer and supplier of natural gas, electricity, and heat	Current biomass projects, future strategy, possibilities of using different feedstocks.	25.05.2022
Glastuinbouw Nederland	Entrepreneurial network for Dutch greenhouse horticulture sector	Inventory, challenges for entrepreneurs, trends in the sector.	01.06.2022
DES bv	Project by three horticulture entrepreneurs – bioenergy from waste wood	Challenges and opportunities for greenhouse horticulture growers.	30.05.2022
Wim Lexmond – Wagro pilot	Green waste recycling – pilot project on tomato waste and verge grass conversion	Efficiencies and costs of the conversion routes, challenges for the pilot.	06.06.2022

Appendix B: Waste stream calculation

Table B.1: Horticulture waste stream calculation based on equation 1

Crop	Specific waste (tonne/ha)	Area 2021 (ha)[4]	Waste stream (tonne/year)
Tomato	46.4[5]	1846	85587
Bell pepper	43.3	1628	70547
Cucumber	45.2	636	28778
Aubergine	44.7	119	5324
Strawberry	1.4[6]	574	796
Pot plants	10.0	508	5073
Flowers	10.0	1986	19843
Fruit	1.4	118	164

Table B.2: Total dry weight availability per biomass stream of the top-8 streams.

	Biomass type	Availability [wet tonnes/yr]	Specific dry weight [kg dry/kg fresh]	Availability [dry tonnes/yr]
1	Cattle manure	3,010,000	0.243	732,634
2	Verge grass	1,722,000	0.400	688,800
3	Pig manure	760,000	0.297	225,720
4	Open horticulture waste	588,000	0.180	105,781
5	Champost	490,000	0.479	234,710
6	Tomato	80,125	0.500	40,063
7	Paprika	75,545	0.500	37,773
8	Poultry manure	70,020	0.255	17,834

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[4] CBS

[5] Afval uit de landbouw

[6] Bioboost

Appendix C: Spatial Analysis

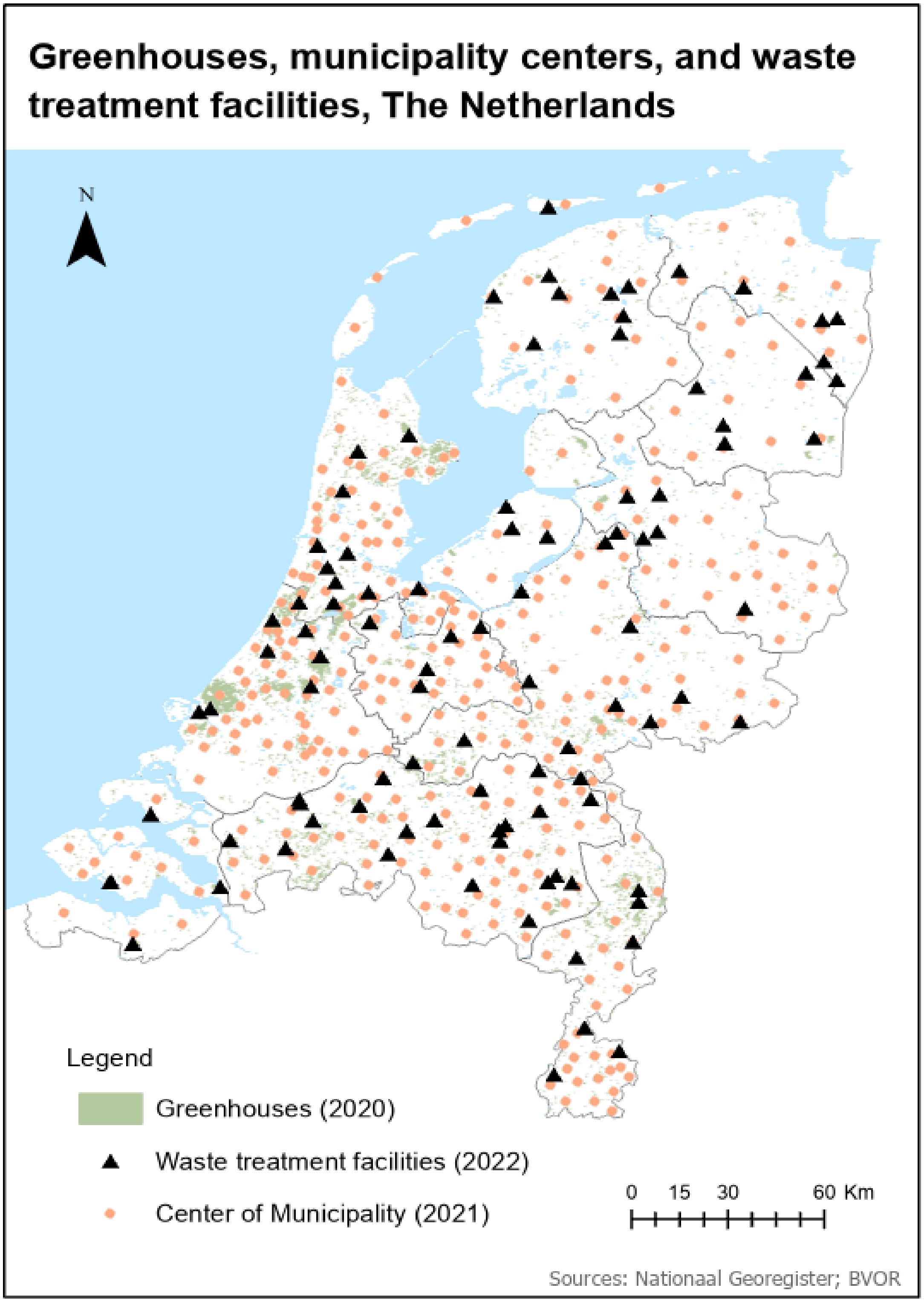

Figure C.1 Greenhouses, waste treatment facilities, and municipality centres in The Netherlands

Appendix D: GHG emissions input data

Table D.1: GHG emission input data for the model.

Input parameter	Amount	Unit	Source
Natural gas emission factor	0.056	$kgCO_2eq/MJ$	U.S. Energy Information Administration, 2021
Coal emission factor	0.096	$kgCO_2eq/MJ$	U.S. Energy Information Administration, 2021
Diesel emissions factor	0.058	$kgCO_2eq/MJ$	P.J. Zijlema, 2019
Syngas from coal emission factor	0.179	$kgCO_2eq/MJ$	Afzal et al., 2018
Crude oil emission factor	0.073	$kgCO_2eq/MJ$	P.J. Zijlema, 2019
Transport emissions	0.059	$kgCO_2eq$/tonne-km	Blok & Nieuwlaar, 2016
CH_4 GWP	28	GWP	Shindell et al., 2013
N_2O GWP	265	GWP	Shindell et al., 2013

Appendix E: Economic input data

Note: costs have been converted to €$_{2022}$ using Inflationtool

Table E.1: Economic input data for the model.

Input parameter	Sub	Amount	Unit	Source
Feedstock availability	Tomato stems	70 000	tonne/yr	Estimation based on section 4.1
	Bell pepper stems	70 000	tonne/yr	Estimation based on section 4.1
	Verge grass	70 000	tonne/yr	Estimation based on section 4.1
Feedstock costs	Tomato stems	-10	€/tonne	Estimation
	Bell pepper stems	-10	€/tonne	Estimation
	Verge grass	-20	€/tonne	Brinkman, 2014
Fossil fuel prices	Natural gas (2021 average price)	0.030	€/kWh	Centraal Bureau voor de Statistiek, 2022a
	Diesel	1.957	€/L	Centraal Bureau voor de Statistiek, 2022b
	Syngas	0.183	€/m3	Pei et al., 2016
Biofuel prices	Presscake	0.028	€/kg	Qureshi et al., 2020
	Bio-gas	0.021	€/kWh	EBA, 2022
	Bio-oil (bio-crude)	0.017	€/MJ	European Commission, 2015
	Bio-char	0.020	€/kg	Argus, 2022
Other energy prices	Electricity (2021 average price)	0.50	€/kWh	Centraal Bureau voor de Statistiek, 2022a
	Ditchwater	0	€/L	Estimation
Transport energy use	Truck (>20 tonne)	0.8	MJ/tonne-km	Blok & Nieuwlaar, 2016
Transport harvest – pre-processing	Tomato stems	65	km	Section 4.2
	Bell pepper stems	65	km	Section 4.2
	Verge grass	83	km	Section 4.2
Transport pre-processing – conversion	Tomato stems	0	km	-
	Bell pepper stems	0	km	-
	Verge grass	0	km	-
Installation inputs	Lifetime	20	Year	-
	Capacity factor	90%	%	-
	Discount rate	6%	%	-
Torrefaction	CAPEX-1	218	€/tonne dry	Abelha & Kiel, 2020

	O&M-1	49	€/tonne dry/yr	Abelha & Kiel, 2020
Gasification	CAPEX-1	2 083	€/kW	Brown et al., 2009
	CAPEX-2	2 728	€/kW	Holmgren, 2015
	CAPEX-3	3 619	€/kW	Renewable Energy Agency, 2012
	CAPEX averaged	*2 810*	*€/kW*	-
	O&M-1	183	€/kW/yr	Susanto et al., 2018
Anaerobic digestion	CAPEX-1	5 059	€/kW	Nelissen, n.d.
	CAPEX-2	3 084	€/kW	
	CAPEX-3	3 084	€/kW	Balaman & Selim, 2014
	CAPEX averaged	*3 665*	*€/kW*	
	O&M-1	143	€/kW/yr	Nelissen, 2020
	O&M-2	304	€/kW/yr	Balaman & Selim, 2014
	O&M-3	157	€/kW/yr	Engler et al., 2002
	O&M averaged	*201*	*€/kW/yr*	-
Pyrolysis	CAPEX-1	1 713	€/kW	Waldheim et al., 2017
	CAPEX-2	5 663	€/kW	van de Kaa et al., 2017
	CAPEX averaged	*3 688*	*€/kW*	
	O&M-1	94	€/kW/yr	Waldheim et al., 2017
Shredding	CAPEX-1	12	€/tonne dry/yr	Wendt et al., 2018
	O&M-1	0.6	€/tonne dry/yr	5% of investment costs per year
Drying	CAPEX-1	66	€/tonne dry	Abelha & Kiel, 2020a
	O&M-1	3.3	€/tonne dry/yr	5% of investment costs per year
Washing	CAPEX-1	22	€/tonne dry	Abelha & Kiel, 2020
	CAPEX-2	17	€/tonne dry	Meesters et al., 2018
	CAPEX averaged	*19*	*€/tonne dry*	-
	O&M-1	0.9	€/tonne dry/yr	5% of investment costs per year
Pressing	CAPEX-1	10	€/tonne dry	Abelha & Kiel, 2020)
	O&M-1	0.5	€/tonne dry/yr	5% of investment costs per year
Ensiling	CAPEX-1	11	€/tonne dry	Manitoba, 2018
	O&M-1	27	€/tonne dry/yr	Wendt et al., 2018