Integration of LCC and LCA results to higher system levels: The German meat and EU tomato cases

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Table of Contents

List of Tables

List of Figures

List of abbreviations

EU	Europe Union
GHG	Greenhouse Gas
MFA	Material Flow Analysis
DM	Dry Matter
PE	Process Energy
EAF	Edible Animal Fat
CW	Carcass Weight
LW	Live weight
TSE	Transmissible Spongiform Encephalopathy
SRM	Specified Risk Material
FAO	Food and Agriculture Organization
FLW	Food loss and waste
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
PE	Process energy
BSE	Bovine spongiform encephalopathy
EAF	Edible animal fat
TSE	Transmissible spongiform encephalopathy
SRM	Specified risk material
SDG	Sustainable Development Goals

1 Executive Summary

Food production and consumption are two essential anthropogenic activities with significant impacts on resource use and environmental sustainability. Globally, it is estimated that greenhouse gas (GHG) emissions (e.g., nitrous oxide) from agriculture represent 10% to 30% of the global total (Willett et al., 2019; Wood et al., 2019). Meanwhile, food loss and waste (FLW) occurring at each stage along the food supply chain has also become a worldwide concern in recent years and has been widely recognised as a barrier to global sustainability. Therefore, a better understanding of the whole food system's efficiency is important to develop effective actions for mitigating associated environmental impacts.

The EU H2020 funded project REFRESH (Resource Efficient Food and dRink for the Entire Supply cHain) aims to contribute to food waste reduction throughout the food supply chain and evaluation of its environmental impacts and life cycle costs. This report aims to highlight the potential contribution of food waste reduction to improving the sustainability of agri-food sector, by integrating the Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) results and upscaling them to a higher system level. Using a material flow analysis (MFA) approach and taking Germany meat and EU tomatoes as examples, this report provides an overview of the mass and energy flows, as well as GHG emissions, of these specific agri-food supply chains in 2016. Based on the understanding of these two agri-food supply chains' environmental efficiency in 2016, this report further discusses the emission reduction potential of different mitigation strategies in an integrated and mass-balance framework. To do so, this report develops individual scenarios covering a wide range of mitigation strategies (with low, medium, and high levels of reduction), such as process and technology efficiency, waste reduction and valorisation, trade pattern change, and dietary shift. A combined scenario that synthesises all individual scenarios is developed to examine the incremental effects of individual mitigation strategies. The scenario analysis results show that diet structure change at the consumption stage and reducing food waste occurring at the retailing stage both have significant emissions reduction potential. Besides, the results also show that waste treatment could also bring a net environmental benefit. Some key conclusions of meat and tomato cases are listed as follows:

The German meat supply chain (including beef, pork, and poultry) covers production, slaughtering, processing, retailing, consumption, by-products rendering, and a range of meat waste treatment (e.g., food production, feed production, biodiesel production, biogas production, industry use, composting, and incineration). Our results show that most meat wastes occur at the consumption stage and reaffirm the low energy conversion efficiency of the meat supply chain (among which beef is the least efficient) and the high GHG emissions at the meat production stage. While diet structure change (either reducing the meat consumption or substituting beef by pork and poultry) shows the highest emissions reduction potential, eliminating meat wastes from the retailing and consumption stages, as well as reducing by-products generation in slaughtering and processing, can have profound effects on emissions reduction. The rendering of by-products and waste treatment adds up to a net environmental benefit, accounting for about 5% of the total GHG emissions. The combined scenario of all mitigation strategies shows that the total GHG emissions could be reduced by 43% comparing to the current level. This could inform future policy making on climate change mitigation in animal production and meat processing sector.

The EU tomato supply chain includes a range of stages: production, postharvest handling and storage, processing, distribution, retailing, consumption, and waste treatment. The mass flow results show that most tomato wastes occur at the processing and consumption stages. Our scenario analysis demonstrates that reducing retailing waste or consumption waste could be a universal measure for GHG emissions reduction in all EU countries. However, significant amounts of GHG emission could be reduced at the upstream stages, especially the production stage. Strategies for reducing GHG emissions at the tomato production stage should be country-specific, because the structure of production technologies (i.e., greenhouse versus open-field) varies a lot by country. To some extent, improving processing energy efficiency could reduce GHG emissions along the entire supply chain, which is particularly the case in Italy. It should be noted that reducing tomato consumption does not necessarily reduce GHG emissions in some countries, due to the fact that these countries' production technology is less emission-intensive than the countries they are trading with.

Economic impacts resulting from different GHG emission reduction measures are not linked to the mass flow model yet, since this would have required an in depth inventory covering a narrow time period to give consistent results, which was not achievable. Nevertheless, the preliminary analysis on economic impacts in this report demonstrates the potential win-win cases or trade-off between environmental and economic impacts. In the case of German meat, increased efficiency in the use of feed could be also economically beneficial considering the relevance of this cost item. Also the valorisation of byproducts and the prevention of waste could have positive direct and indirect economic impacts. Instead, it is difficult to evaluate the effect of a dietary shift, especially taking into account the potential welfare effects for farmers and consumers. Similarly, in the case of tomato, production or processing efficiency improvements could yield positive economic outcome depending on the relevance of energy costs (e.g. greenhouse heating) or the presence of incentives (e.g. biogas from byproducts). Other scenarios such as dietary shift or trade pattern modification need to be assessed carefully to avoid unintended consequence. By using financial or policy instruments, such as subsidy, taxes, and command and control approach, could economically incentivise the adoption of emission reduction measures and by that facilitate a sustainable and viable transition in the agri-food sector. However, any incentive needs to be assessed carefully in the given context to avoid unintended consequences.

The combination of environmental and economic considerations to higher system levels provides an overview of the efficiency of a food system and a comparative representation of different measures' efficacy on the entire system, and thus helps understand the priority of these measures and to what extent the food system could be improved in terms of its environmental impacts.

2 Introduction

Food production and consumption are two essential anthropogenic activities with significant impacts on resource use and environmental sustainability. Globally, it is estimated that direct GHG emissions from agriculture represent 10% to 30% of the global total (Willett et al., 2019; Wood et al., 2019). Meanwhile, FLW has also become a worldwide concern in recent years and is widely recognised as a barrier to global sustainability. It is estimated that roughly one third of food ever produced is lost or wasted globally, which amounts to about 1.3 billion tons per year[1]. This significant amount of FLW would mean 4.4 Gt (or 8% of the world's total) CO_2 equivalent (FAO, 2013).

Options for a sustainable transformation of the agri-food chain is of importance to the EU. This report presents two case studies on the agri-food supply chain and its related environmental impacts (i.e., GHG emissions).

The first one is about the German meat supply chain. Germany is the most populated country in Europe, with a population of 81.7 million in 2015[2]. Germany was ranked 23rd in meat consumption per capita (87.5 kg) in the world in 2013, which is more than double of the world's average (41.9 kg/cap)[3]. This number has stagnated in the past decade (2005-2016), but the consumption structure has changed: per capita consumption of beef and poultry has increased by 14.6% and 18.1%, respectively, while that of pork has decreased by 8.6%. To meet the huge demand of meat and meat products, 55% of agricultural land in Germany is used for cereal cultivation. About 57.4% of cereal production is used for feeding cows, pigs, and chickens (Mayr et al., 2014). Germany has become the biggest producer of meat (18.3% of total production) in the EU in 2016[4]. Such a growing trend of meat consumption leads to increased environmental burdens associated with the animal production sector (Steinfeld et al., 2006), because meat production requires more natural resources (e.g., land, water, and energy) and emits more GHGs than grain-based food (Djekic and Tomasevic, 2016; Priefer et al., 2016). However, a high level of FLW (about 18 Mt) is generated along Germany's entire food supply chain, accounting for almost one-third of the current food consumption (Noleppa and Cartsburg, 2015). Households make up the largest share (61%) of FLW (Kranert et al., 2012). While the major types of food waste generated from households are vegetables, fruits, and cereals, meat does present a 11.8% of the total food waste (Eberle and Fels, 2016a).

The second case is about the EU tomato supply chain. Tomato is the most consumed vegetable in the EU. Its production has increased 10.7% during 2000-2016. The EU has become the third largest tomato producer in 2016 (18 Mt), accounting for 10.3% of the total production in the world. However, about 31.2%

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1 http://www.fao.org/3/a-i2697e.pdf
2 https://www.nationsonline.org/oneworld/germany.htm
3 http://www.fao.org/faostat/en/#data/
4 http://ec.europa.eu/eurostat/web/prodcom/data/database/

of EU's fresh tomatoes are produced in greenhouse and 60% of these greenhouse-based tomatoes are grown for processing, which makes the EU's tomato supply chain more emission-intensive. Italy, Spain, and Portugal are among the top 10 tomato processing countries globally, making up about 30% of the amounts of tomatoes processed in these top ten countries[5]. Though the consumption of fresh tomatoes is expected to go down, the demand for processed tomatoes is expected to increase marginally[6]. This is related to a Mediterranean lifestyle and the general demand for processed food[7]. Besides, it is also expected that the EU would be a net exporter of processed tomatoes by 2030[8]. However, tomato processing is an emission-intensive and generate significant amounts of by-products or wastes (e.g., peels and seeds).

In this report, we aim to map the mass flows of a national whole meat supply chain and EU28's tomato supply chain at country levels. We pair the mass flows mapping with LCA results, explore GHG emissions mitigation potentials of a wide range of measures from production side to consumption side. Such mass flows mapping could add values to the literature, because most existing studies (Xue et al., 2017) on FLW quantification are limited to several individual stages (mainly households). Only a few studies (Cofresco Frischhalteprodukte Europa, 2011; Jörissen et al., 2015) have covered an entire agri-food supply chain or provided product-specific insights. In addition to the mass flow mapping the economic perspective of different intervention strategies, linked to the developed scenarios, are considered qualitatively from a life cycle perspective. The integrated analytical method developed in this report enables a systematic assessment on a wide range of emission mitigation measures of agri-food sector.

3 Methodology

3.1 System definition

3.1.1 German meat supply chain

Meat categories and meat supply chain

Three major categories of meat products were included: beef, pork, and poultry (including chicken, turkey, duck, and goose). We used a Material Flow Analysis (MFA) approach to quantify the dry matter (DM) balance of meat and meat products, which includes animal production, slaughtering, processing, retailing, consumption, trade of animal and meat products, and by-products rendering and

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[5] http://www.tomatonews.com/en/background_47.html
[6] https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/farming/documents/agricultural-outlook-2017-30_en.pdf
[7] https://ec.europa.eu/jrc/en/publication/eu-commodity-market-development-medium-term-agricultural-outlook-0
[8] https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/farming/documents/agricultural-outlook-2017-30_en.pdf

waste management (Figure 1). Specifically, various by-products and waste treatment routes were considered, such as composting, incineration, biogas production, biodiesel production, industry use (e.g., soap and pharmaceuticals production), animal feeding, and food use (e.g., edible animal fat like lard used as a frying agent).

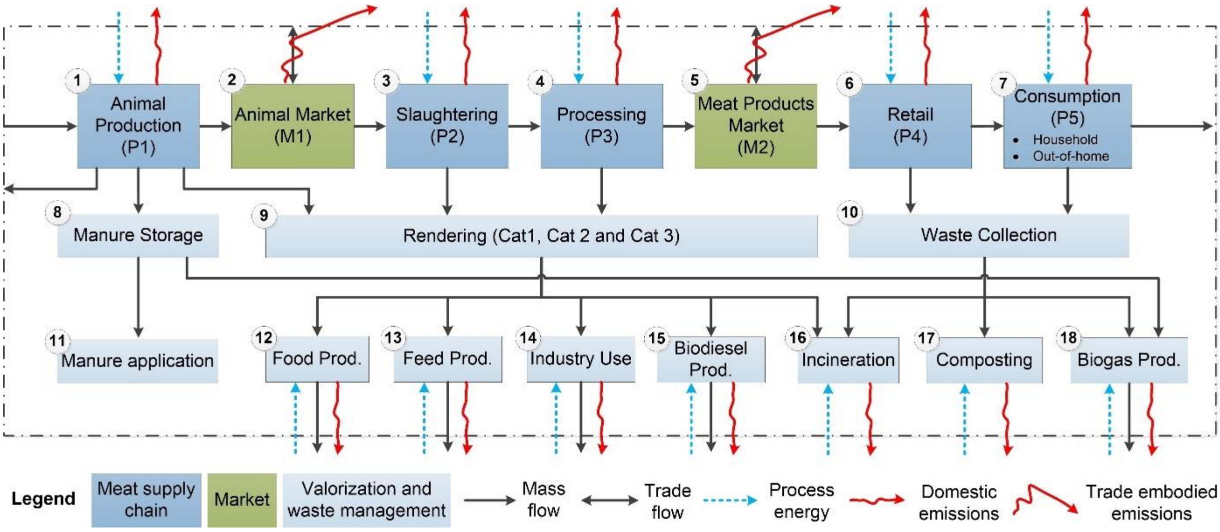

Figure 1. System definition of the German meat supply chain and its associated energy use and emissions.

Energy and emission accounting framework

The energy layer was then additionally calculated based on the mass layer, containing both the gross energy of biomass itself and the process energy (PE) used to process the goods (e.g., fossil fuel and electricity). Further, the emissions layer encompasses the consequent GHG emissions along the meat supply chain, which includes all emissions from animal production (those related to feed production, enteric fermentation, manure management, N_2O emission, fertilizer production, and cultivation of organic soils) and related to process energy use in other stages. The trade-embodied emissions for live animals and meat products were calculated by considering the production and processing emission intensity of the trading countries. Due to lack of data and large variation for animals as well as meat products, energy use for transportation and related emissions in all stages were not considered; nor were packaging-related emissions in the meat processing accounted.

There are two types of emission accounting approaches, depending on how the international trade of live animals and meat products was considered. A territory-based accounting includes emissions occurring within the German national boundary only, while a consumption-based accounting encompasses emissions from domestic final consumption of meat, and thus those caused by the imports of meat products from Germany. We have tested both accounting approaches in our analysis. The consumption-based emissions were presented in our results aiming to reveal the efficiency of the meat supply chain and explore mitigation options linked to consumption. The territory-based accounting results were detailed in Section 8.1.3.

Definition of meat by-products and waste

By-products in the meat supply chain include edible materials such as tongue, edible fats and casings, as well as hides/skins and other non-food materials. In recent years, especially because of bovine spongiform encephalopathy (BSE), the value of by-products has reduced substantially and much of the material previously used is now disposed of as waste, such as incineration (WS Atkins-EA, 2000).

The animal by-products industry handles all of the raw materials that are not directly destined for human consumption. The Regulation (EC) 1069/2009 and Commission Regulation (EU) 142/2011 of the European Parliament govern the use and disposal routes permitted. Animal by-products are divided into three categories according to the level of their risk. Category 1 by-products (Cat 1) refer to materials of high risk, while Category 2 by-products (Cat 2) and Category 3 by-products (Cat 3) are with medium and the lease risk, respectively (Council, 2009)'(Liu et al., 2015). It is assumed that edible animal fat (EAF) is a part of Cat 3. The categorization determines the processing and possible utilization options for the material[9].

- Category 1 by-products (Cat 1) refer to materials of high risk, such as bodies or parts of animals of transmissible spongiform encephalopathy (TSE), wild animal suspected of being infected with possible transferable diseases to humans, specified risk material (SRM) linked to TSE when to be removed, animal by-products contaminated with banned substances like hormones and veterinary medicinal products, or materials that are handled with Cat 1.
- Category 2 by-products (Cat 2) are materials of medium risk. It includes dead animals killed for other reasons (e.g., disease control) than slaughtered for human consumption, embryos and semen not intended for breeding purposes, and fallen stock without SRM. Animal by-products containing residues of authorized substances or contaminants as well as gastric and intestinal contents are considered as Cat 2.
- Category 3 by-products (Cat 3) are with the least risk. It can be parts of animals intended for human consumption without any signs of communicable diseases, for example, poultry heads, hides and skins, horns and feet, bristles, and feathers and blood. There is also some edible material produced from animals that are fit for human consumption. Most of it contains fat and protein accounts for a little, so we call it edible animal fat (EAF) in brief. It is assumed that Cat 3 and EAF as a part of Cat 3 are both mainly used as feed ingredient (such as pet food, fish feed, and animal feed).

According to these risk levels-based categories of meat by-products, we assumed that animal by-products occurred at the production, slaughtering, and processing stages. All dead cattle bodies (in rearing) are classified as Cat 1, and dead pig, chicken, turkey, duck, and goose are considered as Cat 2. The slaughtering stage

[9] European Commission EU Rules Home Page. https://ec.europa.eu/food/safety/animal-by-products/eu-rules_en/; Federal Ministry of Food and Agriculture (BMEL) Animal by-products Home Page. https://www.bmel.de/DE/Tier/Tiergesundheit/TierischeNebenprodukte/nebenprodukte_node.html/

covers all the three categories and the meat processing stage generates only Cat 3 of animal by-products (Figure 2).

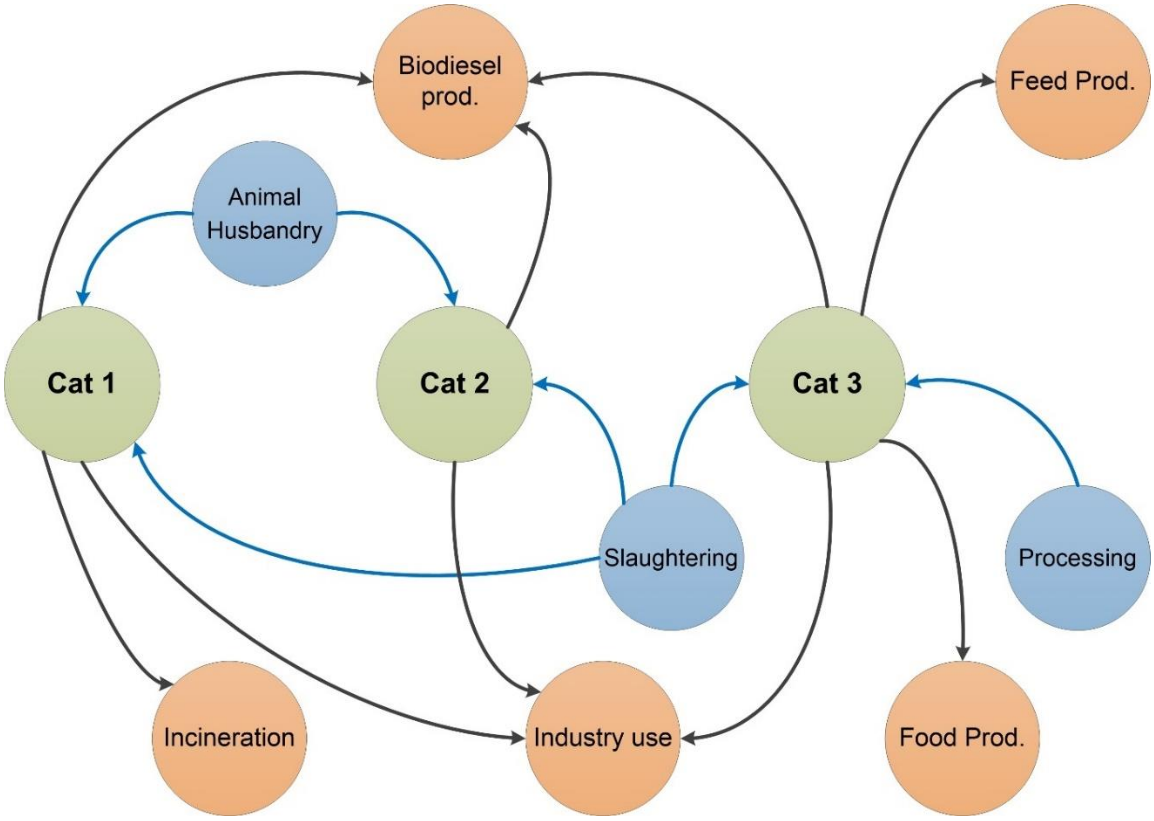

Figure 2. Description of the rendering of different animal by-products.

In addition, meat waste refers to meat discarded or spoiled during the retailing and consumption stages due to expiration, negligence, and other stakeholder or consumer behaviours. It is assumed that such kind of meat waste is collected by the municipal waste management associations and thus further treated by either incineration, composting, or anaerobic digestion.

3.1.2 EU tomato supply chain

Tomato categories and tomato supply chain

The supply chain of tomato has several stages: production, postharvest handling & storage, processing, distribution (fresh tomato or tomato products), retailing, and consumption (Figure 3). In Europe, tomato production systems differ from region to region. In Southern Europe, industrial and fresh tomato is mainly grown in open-field systems. In other regions, greenhouse production systems are widely used for fresh tomato production in soil or soilless culture, such as hydroponics (Ntinas et al., 2017).

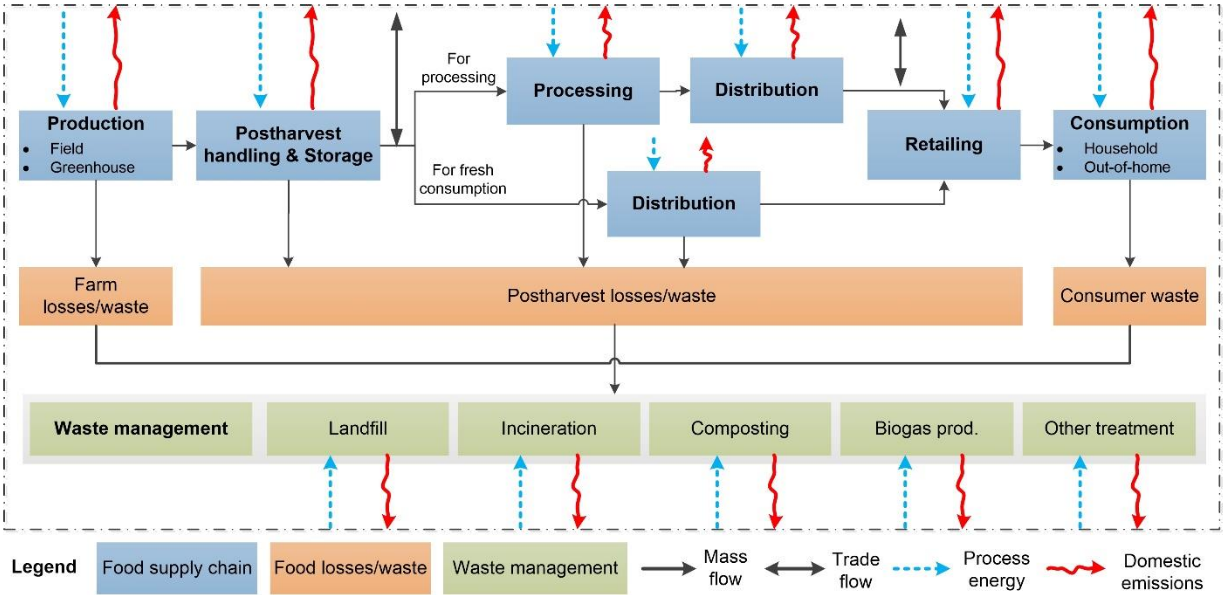

Figure 3. System definition of the tomato supply chain and its associated energy use and emissions.

Tomato production is based on grafting in order to avoid soil-borne diseases, in either an open-field cultivation system or a greenhouse one. Before replanting, tomato seedlings are grown in highly artificialized nurseries that are equipped with air-conditioning and moisture control systems. In an open-field cultivation system, tomato crops are grown in natural soil; in a greenhouse system with heating, natural gas combustion is the most used heating system (Dias et al., 2017).

At maturity, tomatoes are harvested with an initial sorting on the field. In this stage, mature tomatoes are selected and unsuitable ones are discarded. Crop residues are usually burned or used for composting in the field (Garofalo et al., 2017).

After harvesting, tomatoes are delivered to processing factories, unloaded on a conveyor belt, and discharged in a washing tank in order to remove all foreign materials. To enable tomatoes' use in various lines of production, a secondary wash on rotating rollers helps to remove the fine particles. During transit on the rollers, a manual or optical selection is used to discharge the crushed, immature, and rotted fruits, and keep the suitable ones for the following steps (Manfredi and Vignali, 2014).

We categorized tomato products into four main types: tomato juice, tomato whole or in pieces, tomato sauces, or tomato other than whole or in pieces. According to Food and Agriculture Organization's definition (FAO)[10], products derived from tomato include tomato juice, tomato paste, and peeled tomato (see Table 1). FAO

[10] http://www.fao.org/waicent/faoinfo/economic/faodef/fdef07e.htm#7.01

defines “tomato juice” as juice obtained by treating tomatoes with cold or hot water or with steam. The juice then undergoes various processes, such as clarification, homogenization, sterilization, etc. Tomato paste refers to tomatoes prepared or preserved by vinegar, in the form of paste, puree or concentrate. It includes juice of dry weight content of 7% or more. Peeled tomato refers to prepared or preserved by vinegar; either whole or in pieces. UN Comtrade database and EU Prodcom’s definitions of tomato products differ from each other.

Table 1. Categorisation of tomato products

<table>
<tr><th>FAO</th><th>EU Prodcom</th><th>UN Comtrade</th></tr>
<tr><td>Tomato juice</td><td>Tomato juice</td><td>Tomato juice</td></tr>
<tr><td>Peeled tomato</td><td>Preserved tomatoes, whole or in pieces</td><td>Tomato whole or in pieces</td></tr>
<tr><td rowspan="3">Tomato paste</td><td>Tomato ketchup and other tomato sauces</td><td>Tomato sauces</td></tr>
<tr><td>Concentrated tomato puree and paste</td><td rowspan="2">Tomato other than whole or in pieces</td></tr>
<tr><td>Un-concentrated tomato puree and paste</td></tr>
</table>

The production of processed tomato products varies from each other. In general, however, the first step is to steam blanch the fresh tomatoes and pass through a peeling machine. For tomato whole or in pieces, they are cut in small cubes or mixed with lightly concentrated tomato juice before sealed and pasteurized; for other tomato products, the fresh tomatoes are crushed, heated, and then sieved to eliminate the seeds and peels. The sieved tomatoes then pass through concentration machines where water content is removed through evaporation. The concentration process time differs depending on the level of concentration. The concentrated products are then pasteurized and packed, tinned, canned, or bottled into containers. Finally, fresh tomatoes or tomato products are delivered to retailers.

GHG emissions accounting framework

GHG emissions accounting is based on the process energy (PE) used to process the goods (e.g., fossil fuel and electricity). The consequent GHG emissions take account of energy use along the entire tomato supply chain, including tomato production (cultivation and harvesting), postharvest handling and storage, processing, distribution, retailing, and consumption. The emissions embodied in traded fresh tomatoes and tomato products were calculated by considering the production and processing emission intensities of the trading countries. Due to lack of data and large variation in transport modes for fresh tomato and tomato products in different countries, energy use for transportation and related emissions in all stages were not considered; nor were packaging related emissions in the tomato processing and retailing accounted.

There are two types of emission accounting approaches, depending on how the international trade of fresh tomatoes and tomato products was considered. A territory-based accounting includes emissions occurring within a nation’s boundary only, while a consumption-based accounting takes account of emissions from domestic final consumption of fresh tomatoes and tomato products, as well as emissions caused by the production of its imports elsewhere. We have tested both accounting approaches in our analysis. The consumption-based emissions accounting aims to reveal the efficiency of the tomato supply chain and explore mitigation options linked to consumption.

Definition of tomato by-products and waste

By-products along the tomato value chain include culled tomatoes and residues from processing. Biomass residues (including plant residues, plant wastes, or residual biomass) left on the field after harvesting are excluded in this report.

Culled tomatoes include defective, damaged, or immature tomatoes that are discarded after sorting (Fritsch et al., 2017). The culled tomatoes are normally generated during packaging and processing stages. In processing, tomatoes that are unable to pass the washing and inspection will be discarded. Fresh culled tomatoes comprise 14–20% crude protein, 4–5% ether extract, 22% cellulose and lignin (acid detergent fibre), 40–60% non-structural carbohydrates (of which 90–95% are soluble sugars) and 5–10% pectin (dry matter base). These residues often represent an added cost for the manufacturer due to the disposal procedures. Due to the putrescible nature of culled tomato wastes, a duration of storage longer than 6–7 days should be avoided. During storage, uncontrolled anaerobic fermentation releases methane that has a significant greenhouse effect.

Tomato residues at the production and processing stages are more homogenous than wastes at the retailing and consumption stages, which allow for composting or anaerobic digestion. Wastes generated at the downstream stages of tomato value chain are mixed with other waste fractions, hindering the possibility of recovering energy from them (either technologically or for legislative reasons). Residues from processing are mainly constituted of tomato skins and seeds, which are a rich source of lycopene. The main commercial use of lycopene is as a colouring agent in food, nutraceuticals, and pharmaceutical industries. Another use of tomato skin is cutin extraction, since its cuticle forms a protecting film covering the epidermis of tomato fruits. In this report, we excluded these applications.

3.2 Data collection and model quantification

3.2.1 Mass and energy flow of German meat supply chain

Mass flow

The dry matter (DM) balance and related energy and emissions of the whole system were calculated based on the MFA principles. Primary data were collected from German statistical databases (e.g., Statista), industry reports, and scientific articles. Several federal organizations associated with agriculture processes (e.g., Federal Ministry of Food and Agriculture, BMEL), biodegradable waste, and food waste were targeted. The reference year for data collection is 2016.

The starting point of the mass flow analysis was animal production in live weight equivalent, which was calculated based on the carcass weight data, which was obtained from the Federal Agency for Agriculture and Food (BLE) (Data sources shown in the Table A1). To get the live weight (LW) (including CW, innards, and by-products) of animals in terms of DM, the relation of CW to LW and innards to LW, and water content of different parts of animals were used in the calculation (Table A2, A3, A4). During the production stage, dead animals were also considered by using the animal death ratio (Table A5). The manure production of animals was calculated based on the manure produced per life (Table A6 and Table A7).

The trade data of animals are reported in CW equivalent, so the calculation of import and export of animals is the same as the production stage. Then the amount of CW, innards, and by-products entering the slaughtering stage can be obtained by mass balance. The share of the three by-product categories (Cat 1, Cat 2, and Cat 3) and EAF of different animals from slaughtering were listed in Table A8. For the meat processing stage, the CW from slaughtering, the relation of meat for human consumption (Table A9) to LW and CW to LW were used to calculate how much meat left this stage. The retailing sector is complex since various kinds of businesses exist. An average rate of wasted meat for this sector was identified based on the studies conducted in Germany or Europe (Table A10). For the consumption stage, an average dining-out ratio was used to estimate the meat consumption in household and out-of-home (Table A11). Then the total amount of consumer meat waste was obtained based on the waste ratio of these two sectors (Table A12).

The three categories of collected animal by-products are processed into protein and fat for various further uses. The share of different by-product categories, the ratio of protein and fat to by-products, and the utilization rate of protein and fat within different treatment (Table A8, A13, A14) were used to calculate the amount of protein or fat of by-products to various uses as shown below:

$$Q_{i,j,n} = \sum_{k=1}^{4} B_{i,j} \times R1_{i,j,k} \times R2_{k,m} \times R3_{k,m,n}$$

Where *i* indexes the meat type, $Q_{i,j,n}$ is the total amount of protein or fat of meat *i* from stage *j* processed in industry sector *n*, $B_{i,j}$ is the amount of by-products produced at stage *j* from meat *i*, $R1_{i,j,k}$ represents the share of category *k* (Cat 1, Cat 2, Cat 3, and EAF) at stage *j* of meat *i*, $R2_{k,m}$ represents the ratio of protein or fat from category *k*, m represents protein or fat, and $R3_{k,m,n}$ represents the utilization rate of protein or fat for industry sector *n* from category *k*.

The manure produced by animals is staying in the agricultural production system and either applied to agricultural land or used as a feedstock in biogas plants and then applied to land. It is reported that about 13% of manure is going to biogas production (Dünger and Landwirtschaft, 2013), and the remaining (87%) as well as digestate, was assumed to be applied to agricultural land. Though the Waste

Management Act (2012)[11] regulates the bio-waste collection and should be introduced nationwide in Germany, this goal has not yet been achieved in all districts and cities. Biogas plants in Germany use mostly agricultural waste and manure[12]. Since there are no reported data, in this case, we assumed that 70% of the collected waste from retailing and consumption stages is incinerated, 20% for composting, and the remaining 10% goes to biogas production.

Biogas from manure was calculated based on the biogas yield from manure and biogas density (Table A15). Biogas from food waste was calculated by using the energy equivalent of meat waste for biogas production, the energy equivalent of biogas, biogas density, as well as the efficiency of biogas production (Table A15, A17). Biodiesel production out of rendering animal by-products fat was calculated based on the yield from by-products fat to biodiesel (Table A16). More details related to the data sources and all the calculation processes are shown in the Table A46.

Energy flow

The energy calculations were mostly based on the mass. The energy within the mass was calculated based on their corresponding energy coefficients (caloric value) (See detailed data sources and analytical solutions in Table A47 and A18-A24). It was considered that animals can convert about 15% of the feed input energy to meat products on average (Høgh-Jensen and Kristensen, 1995). Accordingly, PE (fuels and electricity) for the production stage was obtained based on the share of feed energy in total energy input. At the slaughtering stage, the energy of CW, innards, and by-products were calculated separately. We used the same energy coefficient for the meat processing, meat products market, retailing, and consumption stages because they all relate to the meat itself. The PE for meat slaughtering and processing consists of fuel oil, natural gas, and electricity, but only electricity was considered for retailing, household, and out-of-home.

The energy of the rendered by-products was calculated based on the amount of protein and fat from by-products for different uses, and the energy content of protein and fat. The energy equivalent of meat products was used to translate the mass of meat waste into energy for various treatments. The energy density of biogas and biodiesel were used to translate the mass into energy.

3.2.2 Mass flow of EU tomato supply chain

The reference year for the production and trade data collection was 2016. The production of fresh tomatoes and tomato products was obtained from the EUROSTAT and the trade of them were from the UN-Comtrade database. The tomato loss and waste rate of each stage was calculated based on relevant references. The estimation of the waste management options used for tomato

[11] European Commission EU Rules Home Page. https://ec.europa.eu/food/safety/animal-by-products/eu-rules_en/

[12] European Biogas Association annual report 2016; http://european-biogas.eu/wp-content/uploads/2017/02/EBA-Annual-Report-2016.pdf

waste was based on EUROSTAT (Database: env_wastrt) for vegetal waste and for the case of co-mingled fractions from households and similar waste.

To map the mass flow of fresh tomatoes and tomato products, the tomato products (including tomato whole or in pieces, tomato other than whole or in pieces, tomato juice, and tomato sauces and ketchup) were converted into fresh tomato equivalents. Two markets (fresh tomatoes and tomato products) and corresponding import and export flows were quantified based on trade statistics, and the tomato products were also converted into fresh tomato equivalents.

The starting point of the mass flow was the fresh tomato production, followed by the postharvest handling and storage stage (see Table 2). By considering the loss rate at this stage and the import and export of fresh tomatoes, we got the amount of fresh tomatoes available for processing and for consumption. Since fresh tomatoes used for tomato products (i.e., tomato processing) are available, fresh tomatoes used for direct consumption is the rest of apparent consumption of fresh tomatoes.

For fresh tomatoes, they directly entered the distribution stage. Then how much fresh tomatoes left this stage to the retailing and consumption stages was calculated based on the loss and waste rate at these stages and mass balance principle. The remaining food products are eaten by consumers.

Table 2. Food loss and waste rates along the tomato supply chain.

	Postharvest handling & storage	Processing	Distribution	Retailing	Consumption
Fresh tomato	5%	37.2%	5%	6.5%	15.5%
Tomato whole or in pieces	-	-	1%	3.8%	14.3%
Tomato other than whole or in pieces	-	-	1%	3%	11.1%
Tomato juice	-	-	1%	3.3%	10%
Tomato sauces	-	-	1%	3.3%	10%

3.2.3 GHG emissions accounting

German meat supply chain

The GHG emissions from each stage were calculated based on emission factors of meat reported in the literature. The GHG emission factors of the production of beef, pork, and poultry were quoted from a European study (Lesschen et al., 2011). Details are tabulated in Table A25. The emissions occurring at slaughtering and processing stages were calculated based on the PE (excluding rendering of by-products), the amount of meat, and the emission factor for the different energy (fuel oil, electricity, and natural gas) used (Table A26). The average emission factors of meat in retailing (0.08 kg CO_2 eq/kg), household (0.08 kg CO_2 eq/kg), and out-of-home sectors (0.51 kg CO_2 eq/kg) were quoted from studies in Germany (Eberle and Fels, 2016a) and Switzerland (Beretta et al., 2017). For the emissions embodied in the import of live animals, the share of imported animals as well as GHG emission factors of different sourcing countries were considered (Table A27). For meat products, we considered the top 3 GHG emission imported countries and their share in total imported quantity specially. The remaining partners were mostly EU countries, which were treated as a whole. An average value of emission factor was used to calculate their embodied GHG emissions during meat production and processing (Table A28).

The environmental impacts and benefits of rendering by-products and meat waste treatment were also considered. By-products from rendering are tallow and meat and bone meal, which are currently used in a wide range of industries, such as food industry (e.g., EAF can be used as a frying agent, which could replace vegetable oil), animal feed (e.g., processed animal protein with better nutritional properties can substitute some vegetable proteins), and biodiesel production (lower carbon footprint than fossil fuel) (Barber et al., 2007). We have additionally made a rough estimation of the net environmental benefits for the goods substituted. Due to data gap, the effect of non-food industry use was not considered. For food (mainly EAF can be produced from by-products Cat 3), feed, biodiesel production, and composting, its substitution with palm oil, soymeal, fossil fuel, and fertilizer was modelled[13], respectively. We replaced palm oil based on the caloric content, while soymeal based on the protein content since for feeding energy more local feed can be used than soymeal, such as cereals, grass, potatoes, associated with lower emissions. The efficiency of food and feed production was assumed to be 33%. The energy use in rendering for food and feed production was 525 kwh/t (11% of electricity and 89% of fuel) (European Commission, 2006a). The GHG emissions of biodiesel from tallow as well as rendering were considered. For incineration, heat and electricity substitution were modelled to the energy produced from the incineration of all the meat waste referring to a Swiss study (heat as 1.251 MJ/kg waste and electricity as 0.679 MJ/kg waste) (Beretta et al., 2017). To better indicate the environmental benefits of biogas production, the emissions from manure and waste were considered separately, and biogas yield and avoided GHG emissions from electricity and heat production were modelled

[13] European Fat Processors and Renderers Association (EFPRA) Home Page. http://efpra.eu/

(Schleiss, 2008). For composting, the emissions during processing meat waste and the substitution of fertilizer (based on the reported replacement rate) were considered (CARB, 2017) (Table A29).

EU tomato supply chain

The GHG emissions from each stage were calculated based on energy intensities of tomato production and tomato processing reported in the literature (see Table A32-A34) (Almeida et al., 2014; Boulard et al., 2011; Pérez Neira et al., 2018). Emission factors of electricity mix were taken from International Energy Agency's statistics[14]. Emissions factors of fertilisers were taken from literature[15]. For the emissions embodied in the import of fresh tomato, the share of imported fresh tomato as well as GHG emission factors of different trading countries were considered. For tomato products, an average value of emission factor was used to calculate their embodied GHG emissions during tomato processing. Emissions from transportation are excluded due to unavailability of food mileage data, especially bilateral transportation distance for specific products.

The environment impacts and benefits from waste management along the tomato supply chain were also considered. Shares of different waste management options are detailed in Table A36-A45. GHG emissions from tomato wastes differ by their dry matter content and volatile solids (see Table 3). However, emission factors of specific waste streams, such as tomato waste, is lacking. Therefore, emission factors for waste management options are based on biodegradable waste as a proxy. Impact data were mainly taken from GaBi 6.0 database[16]. Emission factors of anaerobic digestion and land spread were taken from the generic models in a report from REFRESH[17]. Carbon within food is of biogenic origin and accounted as carbon neutral and therefore only methane, nitrogen dioxide and fossil carbon were taken into account.

- For the landfilling process, data were taken from the GaBi database (landfill of biodegradable waste), including recovery of landfill gas for electricity production.
- For co-generation (i.e., incineration with energy recovery), data were taken from the GaBi database (i.e., waste incineration of biodegradable waste fraction in municipal solid waste) with substitution of electricity from the EU electricity grid mix, as well as EU District Heating mix.
- For incineration where energy output is not used, those substitutions were not assessed.

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[14] https://www.iea.org/statistics/co2emissions/
[15] https://www.fertilizerseurope.com/fileadmin/user_upload/publications/agriculture_publications/carbon_footprint_web_V4.pdf
[16] http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation
[17] https://eu-refresh.org/sites/default/files/D5.4%20Simplified%20LCA%20and%20LCCof%20foodwaste%20valorisation_with%20ISBN.pdf

- For the composting process, composting of biodegradable waste in a closed system from the GaBi database was considered with environmental benefits from substitution of fertilisers (e.g., nitrogen, phosphorous and potassium) and peat.
- Anaerobic digestion was assumed to substitute fertilizer, electricity from the grid mix and heat from natural gas. The generic model used in the REFRESH report was used to calculate the emission factor for an input of bio-waste (input parameters: biogas yield of 130 Nm^3/t FM, 30% DM, CH_4 content 60%).

Table 3. Emission factors of different waste treatment routes.

Unit: kg CO_2-eq/kg	Landfill	Incineration without energy recovery	Incineration with energy recovery	Composting	Anaerobic digestion	Land spread
All stages	0.62	4.97E-02	-1.41E-04	4.28E-03	-6.01E-02	2.9E-02

Note: positive values are GHG emissions, negative values are GHG savings.

3.3 Scenarios development

3.3.1 Scenarios for German meat case

Different scenarios were developed to quantitatively investigate the emission reduction potentials of different mitigation strategies. These strategies were grouped into five categories as elaborated below:

- ***Production efficiency.*** The reduction of GHG emission intensity of production could be achieved, for example, by increasing the efficiency of animal feed production. Previous estimate shows that emissions could be reduced by 17% with improved manure management and energy saving equipment (Gerber et al. 2013), thus scenarios were set for a decreased production emission intensity of 5%, 10%, and 20%.
- ***Process optimization*****.** Improving the process efficiency in meat slaughtering and processing would mean less meat cut off and by-products generation. The technology efficiency improvement in for example cooling could reduce process energy. According to BMEL[18], the process energy use in meat processing sector has already decreased by 16.5% between 2006 and 2015. A reduction potential of 5%, 10%, and 20% of energy use was assumed.
- ***Food waste reduction*****.** The reduction of avoidable part of food waste is already targeted by national food waste prevention campaigns and EU regulations (e.g., the adoption of SDG Target 12.3). If meat can be prevented from being wasted at the consumer stage, less meat needs to be produced.

[18] European Commission Eurostat Home Page. http://ec.europa.eu/eurostat/web/prodcom/data/database/

The reduction of meat waste was also considered to take place in the retailing and consumption stages. It was assumed that a maximum of 50% of edible meat waste in households, food services, and retailing can be reduced, because it is reported that approximately 50% of food waste at households is avoidable (Schneider et al., 2012).

- ***Trade pattern change*.** Trade patterns matter for emissions of the German meat supply chain, especially with the consumption-based accounting approach, because of the varying emission intensity in different countries. The import and export change scenarios were developed individually (The import remains unchanged when reducing or halting export of live animals or meat products, and vice versa.): For import change scenarios we considered the import of live animals and meat products from the top 3 GHG emissions partners and their corresponding GHG emission intensities; for export scenarios we considered the export of these products to non-EU 28 countries (decreased export would lead to less meat produced domestically), but the substitutes of the reduced imports (would lead to more meat produced in Germany) from these countries were not considered. The share of them to EU 28 and non-EU 28 countries were considered (Table A30). Scenarios were set with a reduction of 25%, 50%, and 100%.
- ***Diet structure change*.** Three types of dietary change were considered: (i) The first one was a diet with less meat consumption. As the study aims to address a consumption-based approach (the mass of meat consumption stays the same in all scenarios), the reduced meat consumption needs to be replaced by other protein sources, and so we selected soybeans and nuts as the substitute (while keeping the energy intake constant) and considered their whole life cycle GHG emissions. The consumption structure, energy equivalent of soybean and nuts, and emission intensity data were detailed in the Table A31. (ii) The second one was substituting beef by pork and poultry, while the total energy intake remained constant and the ratio of pork and poultry consumption was kept unchanged. A potential decrease of 10%, 25%, and 50% for total meat consumption and a reduction of 5%, 10%, and 25% for beef consumption were assumed, since the German Nutrition Society (DGE) has reported that Germans eat twice as much meat as is recommended from a nutritional standpoint (Harald von Witzke et al., 2011). (iii) A third scenario considered that less offal was thrown away and instead could be consumed as food. This would result in a reduction of meat consumption, and we assumed a reduction potential of 10%, 25%, and 50% when keeping energy intake constant.

The baseline scenario was the current emissions based on the German meat supply chain in 2016. We first developed individual scenarios as detailed in Table 4 using a one-factor-at-a-time approach. The consumption was assumed to be constant for all the scenarios except the three addressing diet structure change (S6 and S7). We then calculated potentials of assumed low, medium, and high levels of reduction for each strategy. In the end we built a combined scenario to discuss the combined effects of some of these mitigation strategies that have more influence on emissions, based on the assumed high levels of changes in Table 4 in a rank order for assumed level of difficulty of implementation (roughly from technology options down to economic measures to human behaviours, Table 5). The consequences of these scenarios on larger socioeconomic systems, e.g., changes of emissions in other countries due to trade pattern change are not considered.

Table 4. Description of the individual scenarios (PE = Process Energy)

Strategies	Symbols	Detailed assumptions	Reduction (%)		
			Low	Medium	High
Production efficiency	S1	Production emission intensity	5	10	20
Process optimization	S2a	Slaughtering PE	5	10	20
	S2b	Processing PE			
	S2c	Slaughtering and processing PE			
	S3a	Slaughtering by-products	5	10	20
	S3b	Processing by-products			
	S3c	Slaughtering and processing by-products			
Food waste reduction	S4a	Retailing waste	10	25	50
	S4b	Consumption waste			
	S4c	Retailing and consumption waste			
Trade pattern change	S5a	Animals import from the top 3 GHG emission partner countries	25	50	100
	S5b	Animals export to non-EU countries			
	S5c	S5a + S5b			
	S5d	Meat products import from the top 3 GHG emission partners			
	S5e	Meat products export to non-EU countries			
	S5f	S5d + S5e			
	S5g	S5c + S5f			
	S6	Meat consumption	10	25	50

Diet structure change	S7	Beef consumption	5	10	25
	S8	Offal consumed as food less thrown away	10	25	50

Table 5: Description of the combined scenario (PE = Process Energy)

Scenarios		Item	Reduction (%)
SA	S2c	Slaughtering and processing PE	20
SB	S2c +S4c	Retailing and consumption waste	50
SC	S2c+ S4c+S5f	Meat products import from the top 3 GHG emission partners and export to non-EU countries	100
SD	S2c+ S4c+S5f+S8	Offal thrown away	50
SE	S2c+S4c+S5f+S7+S8	Beef consumption	25
SF	S1+S2c+S4c+S5f+S7+S8	Production emission intensity	20

Note: S1: Production emission intensity, S2c: Slaughtering and processing PE, S4c: Retailing and consumption waste, S5f: Meat products import from the top 3 GHG emission partners, and meat products export to non-EU countries, S7: Beef consumption, S8: Offal consumed as food less thrown away.

3.3.2 Scenarios for EU tomato case

In parallel with the German meat case, a variety of scenarios was developed as well to quantitatively investigate the emission reduction potentials of different mitigation strategies in the tomato supply chain. These strategies were grouped into five categories as elaborated below:

- ***Production efficiency.*** The reduction of GHG emission intensity of production could be achieved, for example, by increasing the efficiency of tomato production. Scenarios were set for a decreased production emission intensity of 5%, 10%, and 20%.
- ***Process optimization*.** Improving the process efficiency in tomato processing would mean less by-products generation. For example, the application of pulsed electric fields as a tool could improve the energy efficiency and yield efficiency of tomato processing (Arnal et al., 2018). A reduction potential of 5%, 10%, and 20% was assumed.
- ***Food waste reduction*.** The reduction of avoidable part of food waste is already targeted by national food waste prevention campaigns and EU regulations (e.g., the adoption of SDG Target 12.3). If tomatoes can be prevented from being wasted at the consumer or retailing stage, less tomato needs to be produced. We took the same assumption from the German meat case, in which a maximum of 50% of food waste can be reduced, because it is reported that approximately 50% of food waste at the retailing and households

stages is avoidable (Schneider et al., 2012).

- ***Trade pattern change.*** Trade patterns matter for emissions of the tomato supply chain because of the varying emission intensity in different countries. In the import change scenarios, the export and consumption in EU-28 were kept unchanged. We assumed there was a reduction or halting of the import of fresh tomatoes or tomato products from countries other than EU-28, which thereby the amount of domestically produced tomatoes would increase. In terms of the export scenarios, we assumed there was a reduction of exporting fresh tomatoes and tomato products to countries other than EU-28, which thereby reduces the amount of domestically produced fresh tomatoes and tomato products. Scenarios were set with a reduction of 10%, 25%, and 50%.
- ***Diet structure change.*** It is assumed that people change to a diet with less tomatoes by substituting it with other vegetables. Emissions arising from substitution are also considered in this report. It was assumed that a potential decrease was with 5%, 10%, and 25% for fresh tomato consumption and the same decrease for tomato products consumption.

The baseline scenario was the current emissions based on the tomato supply chain in 2016. We first developed individual scenarios as detailed in Table 6 using a one-factor-at-a-time approach. The consumption was assumed to be constant for all the scenarios except the two addressing diet structure change (S6 and S7). We then calculated potentials of assumed low, medium, and high levels of reduction for each strategy. In the end, we built a combined scenario to discuss the combined effects of these mitigation strategies, based on the level of difficulty of implementation (roughly from technology options down to economic measures to human behaviours, Table 7). The consequences of these scenarios on larger socioeconomic systems, e.g., changes of emissions in other countries due to trade pattern change, are not considered. Consequences on tomato consumption due to diet structure change, such as substitution by other 5 most consumed vegetables, are considered. Emission factors of other vegetables are tabulated in Table A35.

Table 6. Description of the individual scenarios for the tomato case.

Strategies	Symbols	Detailed assumptions	Reduction (%)		
Production efficiency	S1a	Field production emission intensity	5	10	20
	S1b	Greenhouse production emission intensity	5	10	20
	S1c	Greenhouse production substituted by field production	5	10	20
Process optimization	S2a	Processing energy	5	10	20
	S2b	Processing loss	5	10	20
	S3a	Postharvest handling & storage loss	5	10	20

	S3b	Distribution loss	5	10	20
Food waste reduction	S4a	Retailing waste	10	25	50
	S4b	Consumption waste	10	25	50
	S4c	Retailing and consumption waste	10	25	50
Trade pattern change	S5a	Tomato export to non- EU28 countries	10	25	50
	S5b	Tomato import from non-EU28 countries	10	25	50
	S5c	Tomato products export to non-EU28 countries	10	25	50
	S5d	Tomato products import from non-EU28 countries	10	25	50
Diet structure change	S6	Fresh tomatoes consumption	5	10	20
	S7	Tomato products consumption	5	10	20

Table 7. Description of the combined scenarios for the tomato case.

Strategies	Reduction (%)
S1a	20
S1a+S1b	20
S1a+S1b+S1c	20
S1a+S1b+S1c +S2a	20
S1a+S1b+S1c+S2a +S2b	20
S1a+S1b+S1c+S2a+S2b +S3a	20
S1a+S1b+S1c+S2a+S2b +S3a+S3b	20
S1a+S1b+S1c+S2a+S2b +S3a+S3b+S4a	50
S1a+S1b+S1c+S2a+S2b +S3a+S3b+S4a+S4b	50
S1a+S1b+S1c+S2a+S2b +S3a+S3b+S4a+S4b+S5a	50

S1a+S1b+S1c+S2a+S2b +S3a+S3b+S4a+S4b+S5a+S5b	50
S1a+S1b+S1c+S2a+S2b +S3a+S3b+S4a+S4b+S5a+S5b+S5c	50
S1a+S1b+S1c+S2a+S2b +S3a+S3b+S4a+S4b+S5a+S5b+S5c+S5d	50
S1a+S1b+S1c+S2a+S2b +S3a+S3b+S4a+S4b+S5a+S5b+S5c+S5d+S6	20
S1a+S1b+S1c+S2a+S2b +S3a+S3b+S4a+S4b+S5a+S5b+S5c+S5d+S6+S7	20

4 German meat case

4.1 Mass and energy balance of the meat supply chain

4.1.1 Characteristics of the mass balance

The mass flow (all numbers on a DM basis) of the German meat supply chain shows that 2516 kt of meat (CW, including bones) was produced domestically before slaughtering and 1634 kt ended up for human consumption from the retailing sector in 2016 (Figure 4). Pork made up the biggest share in the production as well as consumption, both of which accounted for about 59% and 58%, respectively, followed by poultry (24% and 29%) and beef (17% and 13%). As to the animal trade, poultry and cattle were exported in large amounts, whereas the import of pig was higher than export. For the trade of meat products, however, a higher import than export can be seen for beef and poultry, and it is the opposite for pork. Altogether, the self-sufficiency for beef, pork, and poultry was about 159%, 170%, and 119% (all on a DM basis), respectively.

Figure 4 also shows that the cumulative by-products and meat waste along the cattle, pork, and poultry supply chain accounts for 74%, 59%, and 56% of the total mass flow in domestic animal production, respectively. The pork by-products appeared the largest at the animal production, slaughtering and processing stages, accounting for 59%, 50% and 67%, respectively, of the total meat by-products at each sector. All the by-products made up 44% of the meat entering the slaughtering stage. The waste (including the inedible parts/unavoidable food waste) from retailing and consumption stages combined made up roughly 27% of the meat products for human consumption.

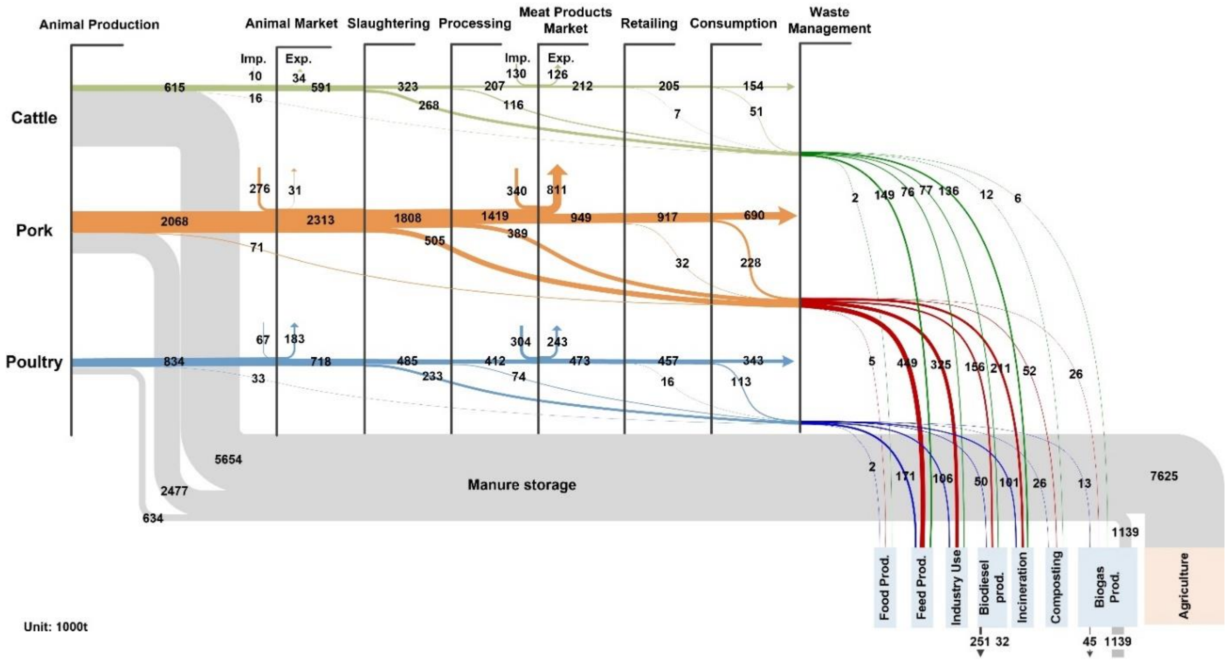


Figure 4. Mass balance for the meat supply chain in Germany in 2016 (on a dry matter basis).

4.1.2 Meat waste management

Figure 5 illustrates the share of different by-products and waste along the supply chain of each meat category to different treatment sectors. At the animal production stage, dead cattle were mostly incinerated (66%) while dead pigs and poultry mainly went for industry use (63%). At the slaughtering and processing stages, most Cat 3 by-products were used for feed production, and most Cat 2 by-products went for industrial use and biodiesel production. Due to lack of data, most of the meat waste from retailing and consumption was assumed to be mostly incinerated, followed by composting and anaerobic digestion. In total, the majority of by-products and waste for beef was processed in feed production (33%) and incineration (30%), while for pork and poultry were in feed production (37% and 36%, respectively) and industry use (27% and 23%, respectively).

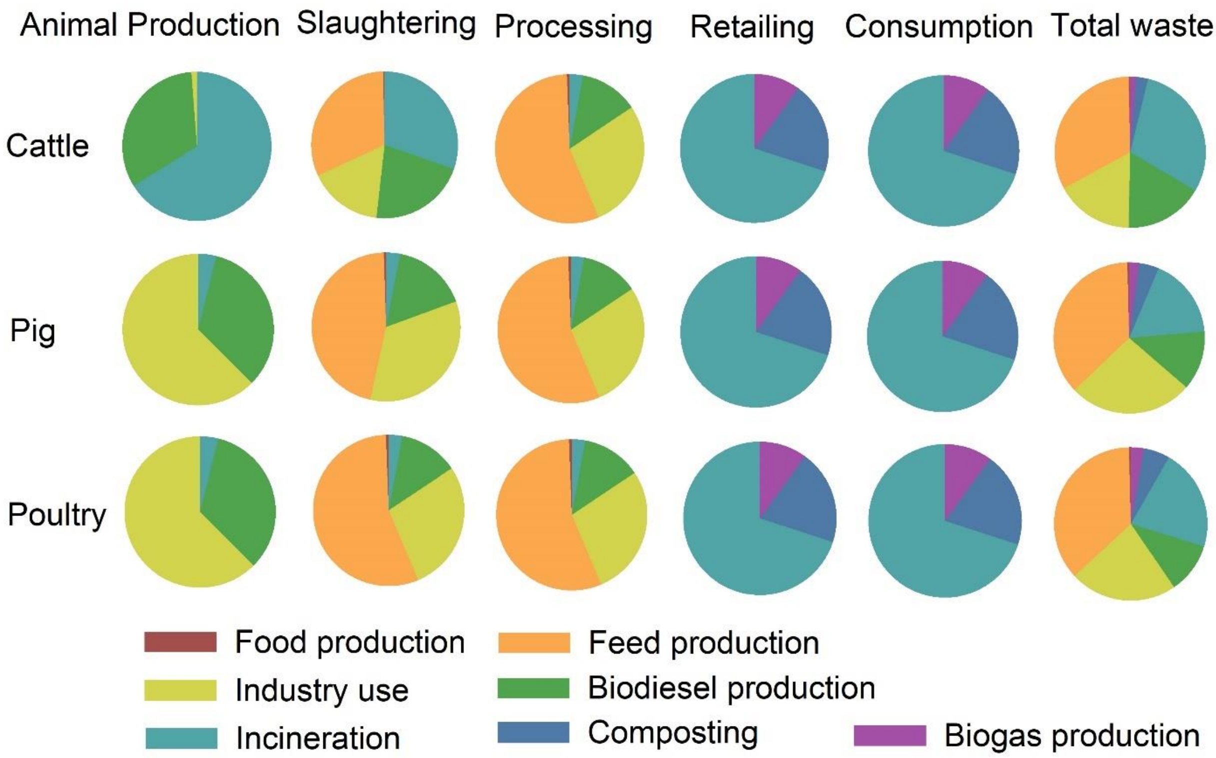


Figure 5. By-products and meat waste treatment in Germany.

In terms of protein or fat of each by-product category, the beef supply chain did not generate Cat 2 by-products, and the pork and poultry supply chains did not produce Cat 1 by-products (Schmidt, 2011). Figure 6 shows that the protein from Cat 1 went to incineration plants, protein from Cat 2 ended up for industry use, and most protein from Cat 3 was used as feed ingredients. Fat from Cat 1 and Cat 2 was mainly for biodiesel production, and most fat from Cat 3 went to industry use.

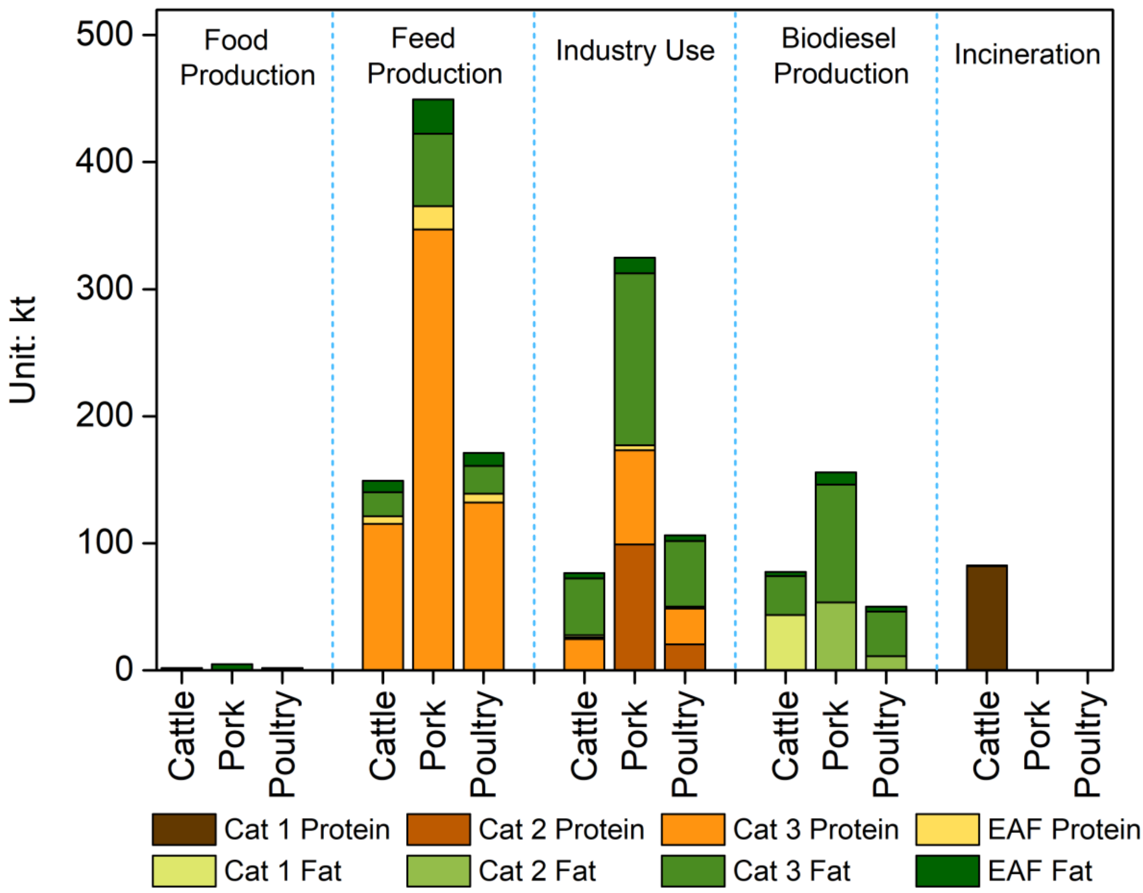


Figure 6. Distribution of protein and fat from animal by-products.

4.1.3 Characteristics of the energy balance

The largest energy flows of the whole system related to the production, especially for feed energy flows with 5.6×10^5 TJ in total (Figure 7). The energy equivalent of manure accounted for 21% of all feed inputs. As for the individual animal category, the energy equivalent of meat after slaughtering was 10%, 15%, and 9% of the feed input for beef, pork, and poultry, respectively. When it comes to consumption, the energy equivalent of beef, pork, and poultry entering retailing for human consumption represented only 11.5%, 18.3%, and 12.7%, respectively, of the feed used for animal production, indicating an overall low energy conversion efficiency of the meat supply chain (out of which pork was comparatively the most efficient and beef was the least).

In terms of by-products, the energy equivalent of slaughtering and processing by-products together comprised of 84% of the energy of animals entering slaughtering. In addition, the energy equivalent of meat waste from retailing and consumption processes totalled to 2.9×103 TJ (majority in consumption), accounting for 27% of the energy equivalent of meat input to the retailing stage. In total, the energy equivalent of all the by-products and meat waste represented 14% of the total feed inputs.

In terms of PE (e.g., for heating and lighting), the highest value was in the animal production sector (2.2×105 TJ) with a share of 94%, followed by meat processing (5.9×103 TJ, 2.5%) and slaughtering (4.2×103 TJ, 1.8%). The cumulative PE was 2.3×105 TJ, which was about 41% of the feed used or roughly 3 times of the energy equivalent of total by-products and meat waste.

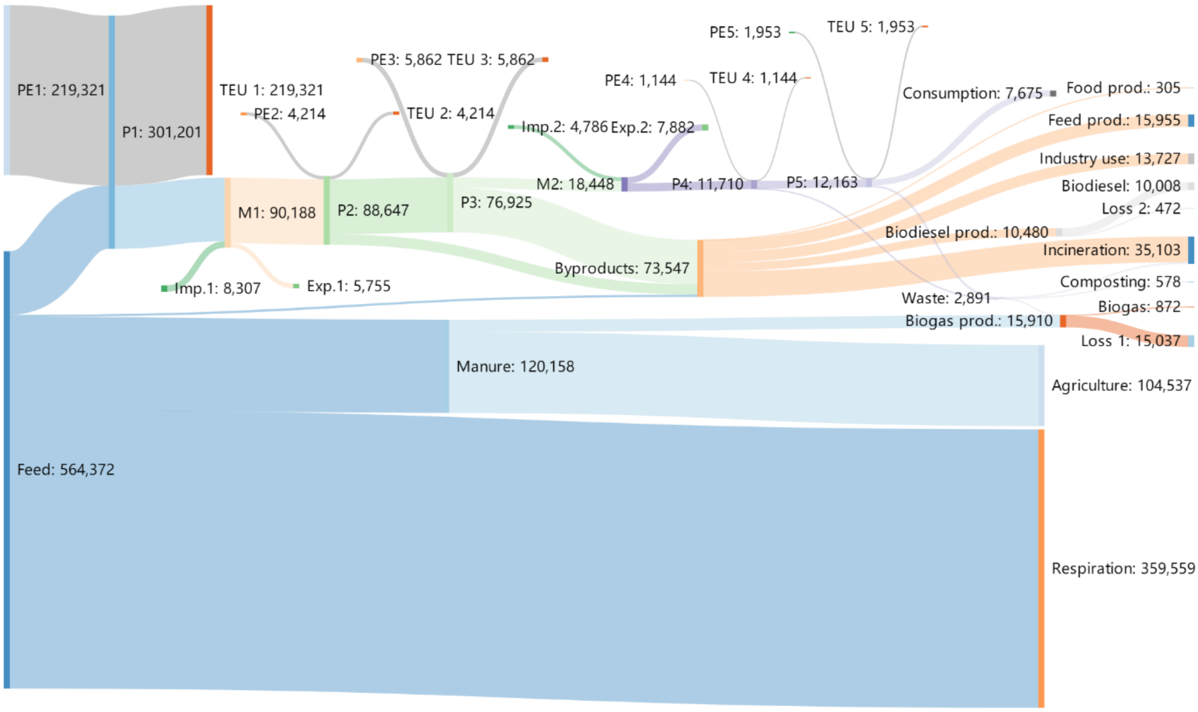


Figure 7. Energy balance for the German meat supply chain (beef, pork, and poultry combined) in 2016.

4.1.4 Data quality and uncertainty

This analysis relied on data from multiple sources and various assumptions, which unavoidably leads to uncertainties. A qualitative uncertainty evaluation of the data used and corresponding mass flow, energy flow, and GHG emissions were summarised in the Figure A1-A3 based on three levels (low, medium, and high) of uncertainty. Data taken directly from governmental statistics (e.g., the amount of CW produced and the trade values of live animals and meat products) was deemed to have low uncertainty. The statistical data can provide an overall picture of the whole country, though they are not always accurate due to data coverage and collection methods. The slightly varying coefficients data found in several references (e.g., meat waste rate in retailing and the energy equivalent of manure) were categorised as medium uncertainty. If only a single reference was identified and the representativeness is unclear (e.g., the ratio of meat consumption in household and out-of-home and the treatment of meat waste), the data uncertainty was considered high.

Despite the limitations and data gaps mentioned above, the entire model was assessed to be sufficiently robust to reveal the whole chain efficiency of the German meat supply chain. The mass balance allowed for crosschecking between mass, energy, and nutrient (e.g., protein and fat). We compared the data of meat for human consumption between results in this study and the numbers reported by BMLE. For example, the calculated value (722 kt) for beef and pork (2829 kt) were within an acceptable range of 10% compared to the BMLE estimate (793 kt, 2974 kt).

4.2 GHG emissions of the German meat supply chain

Figure 8 shows that the majority of GHG emissions were found in the production sector either for the total meat production (64%) or for individual meat category (65%, 68%, and 45%, respectively, for beef, pork, and poultry) based on the consumption-based accounting. The second largest contributor was the emissions embodied in the import of live animals and meat products, making up 34%, 27%, and 46%, respectively, of the total emissions for the beef, pork, and poultry supply chains. This can be explained by the relatively large amount of net trade of live animals and meat products and the varying emission intensity between Germany and trading partners. Then it was followed by emissions from slaughtering (1.1%), processing (1.06%), consumption (1.05%), and retailing (0.5%) stages.

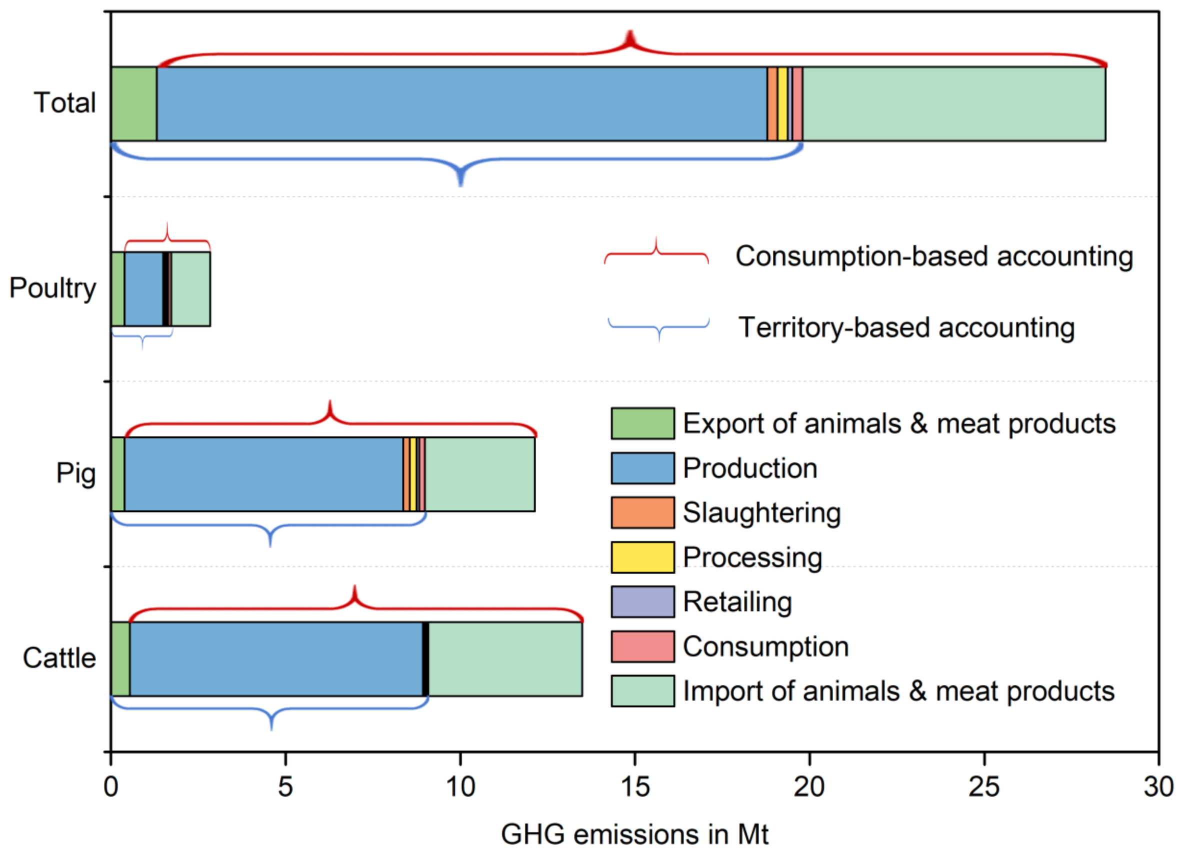


Figure 8. Distribution of GHG emissions in the meat supply chain.

Note: The GHG emissions in 2016 is the reference scenario.

In terms of the GHG emissions of each meat category during production, the largest was from the production of beef (48%), followed by pork (46%), and poultry accounted for the least (6%). However, when it comes to the amount of meat produced of each type, about 60% of the LW (DM basis) produced came from pig, followed by poultry (24%), and cattle had the smallest share (Figure 9). This indicates again the lower efficiency of beef production comparing to pork and poultry.

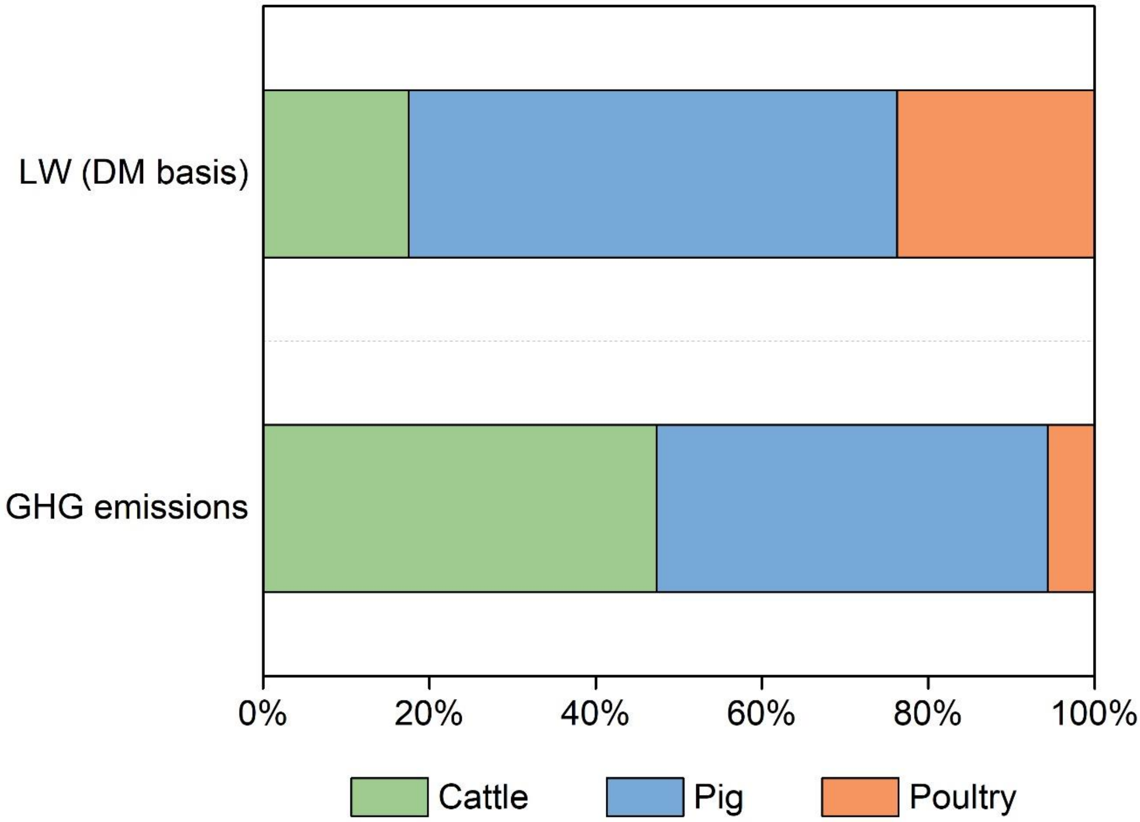


Figure 9. LW (total live weight, DM basis) production and GHG emissions in animal production.

Note: They are the reference scenario (results in year 2016).

4.3 Scenarios for GHG emissions reduction

4.3.1 Individual scenarios

Figure 10 shows the percentage change of the total GHG emissions of the whole meat supply chain under different scenarios (as detailed in Table 1) with respect to the reference scenario in 2016. Most scenarios show a gradually increasing reduction potential under different levels of changes (from low to medium to high). The changes of the amount of GHG emissions under different levels is shown in

Figure 11. The changes of total meat CW produced in different scenarios are detailed in the Figure A4-A5.

The greatest difference to the base scenario was the reduction of meat consumption by 50% (S6), which resulted in a 32% reduction of the GHG emissions (consumption-based). A diet to a higher amount of offal with less needs to be thrown away (S8) showed the second largest reduction potential of 14% reduction of the original GHG emissions, followed by reducing GHG emissions intensity in production (S1) with a reduction of 13%. In the case of reducing retailing and consumption waste (S4c) by 50%, a reduction of 2747 kt GHG emissions can be achieved. Halting the import of meat products from the top 3 GHG emission partners and the export to non-EU 28 countries (S5f) would also reduce the total emissions by 6%. When beef consumption was reduced by 25% (S7), though the emissions from pork and poultry supply chains would increase by 2-3% due to increased consumption of pork and poultry, the total GHG emissions would still decrease by 7% relative to the base scenario. Similarly, halting the import of live animals (S5a) from high intensity emission countries (with the increase of live animal production domestically) would reduce the total emissions by 1% slightly. The energy use reduction by 20% at the slaughtering as well as processing stages (S2c) would also result in a reduction of GHG emissions (117 kt; or 0.4% of the total). However, halting the import of meat products (S5d) from high intensity emission countries (with the increase of meat production domestically) would increase the total emissions by 2% slightly.

Reduction scenarios		Low					Medium					High				
		%	Cattle	Pork	Poultry	Total	%	Cattle	Pork	Poultry	Total	%	Cattle	Pork	Poultry	Total
S1	Emission intensity	-5	-3	-3	-2	-3	-10	-6	-7	-5	-6	-20	-13	-14	-9	-13
S2a	Slaughtering PE		0	0	0	0		0	0	0	0		0	0	0	0
S2b	Processing PE	-5	0	0	0	0	-10	0	0	0	0	-20	0	0	0	0
S2c	S2a + S2b		0	0	0	0		0	0	0	0		0	-1	-1	0
S3a	Slaughtering byproducts		-3	-1	-1	-2		-5	-2	-2	-4		-9	-4	-5	-7
S3b	Processing byproducts	-5	-2	-1	-1	-1	-10	-4	-2	-1	-3	-20	-7	-4	-2	-5
S3c	S3a + S3b		-4	-2	-2	-3		-8	-4	-3	-6		-15	-8	-6	-11
S4a	Retail waste		0	0	0	0		-1	0	-1	-1		-1	-1	-1	-1
S4b	Consumption waste	-10	-2	-2	-2	-2	-25	-5	-4	-6	-5	-50	-10	-8	-10	-9
S4c	S4a + S4b		-2	-2	-3	-2		-6	-5	-6	-5		-11	-9	-11	-10
S5a	Animal import		0	0	0	0		0	-1	0	0		0	-2	-1	-1
S5b	Animal export		0	0	0	0		0	0	0	0		0	0	0	0
S5c	S5a + S5b		0	0	0	0		0	-1	0	0		0	-2	-1	-1
S5d	Meat products import	-25	0	0	0	0	-50	1	1	0	1	-100	2	2	0	2
S5e	Meat products export		-1	-3	-1	-2		-2	-6	-2	-4		-4	-12	-4	-7
S5f	S5d + S5e		-1	-2	-1	-1		-1	-5	-2	-3		-2	-10	-4	-6
S5g	S5c + S5f		-1	-3	-1	-2		-1	-6	-2	-3		-2	-11	-5	-6
S6	Meat consumption	-10	-7	-6	-7	-6	-25	-17	-14	-18	-16	-50	-34	-29	-35	-32
S7	Beef consumption	-5	-3	0	0	-1	-10	-7	1	1	-3	-25	-17	2	2	-7
S8	Offal thrown away	-10	-4	-2	-1	-3	-25	-10	-5	-2	-7	-50	-20	-9	-4	-14

Figure 10. Different scenarios of GHG emissions in a consumption-based accounting.

Note: Negative values mean the reduction percentage compared to the reference scenario, and positive values mean the increase percentage relative to the baseline.

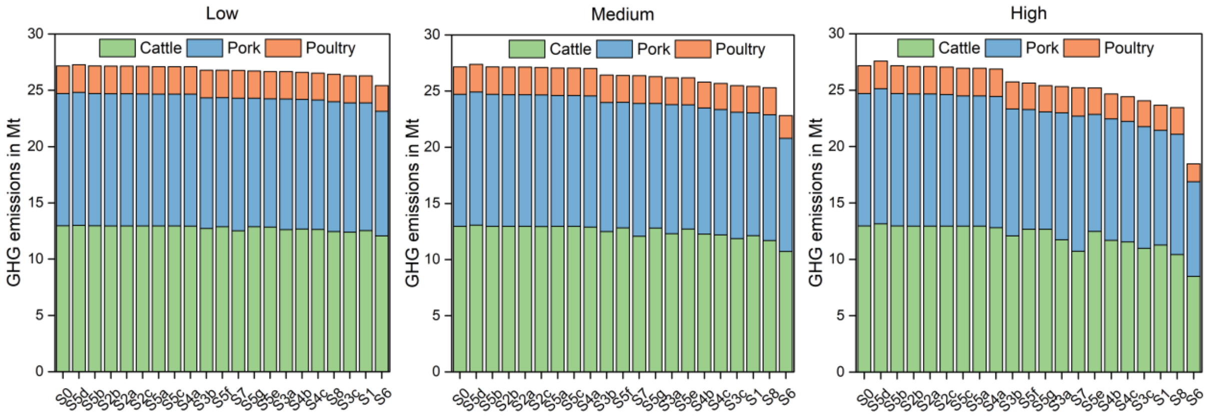


Figure 11. The change of the amount of GHG emissions under three levels (low, medium, and high).

4.3.2 Combined scenario

Figure 12 shows the combined effects of the important emissions mitigation strategies under the combined scenario described in the SI Table S3. The biggest change (proportionally as 26%) of emissions occurred when offal thrown away in slaughtering stage was reduced by 50% and consumed as food (less animals need to be produced to get the same amount of animal energy consumed) (SD). The second largest reduction of emissions could be seen in the case of reducing meat waste in retailing and consumption stages by 50% (SB), with a share of 23% in the total reduction of emissions, followed by reducing the emission intensity at the production stage by 20% with a share of 22%. Halting the import of meat products from the top 3 GHG emission countries and the export to non-EU countries would also contribute to the reduction of emissions (18%). In total, a combination of process optimization, radical meat waste reduction, trade pattern changes of meat products, radical diet structure change with less beef and substituting meat by edible offal, and reducing the emission intensity of meat would largely reduce the climate impacts by 43% relative to the base scenario.

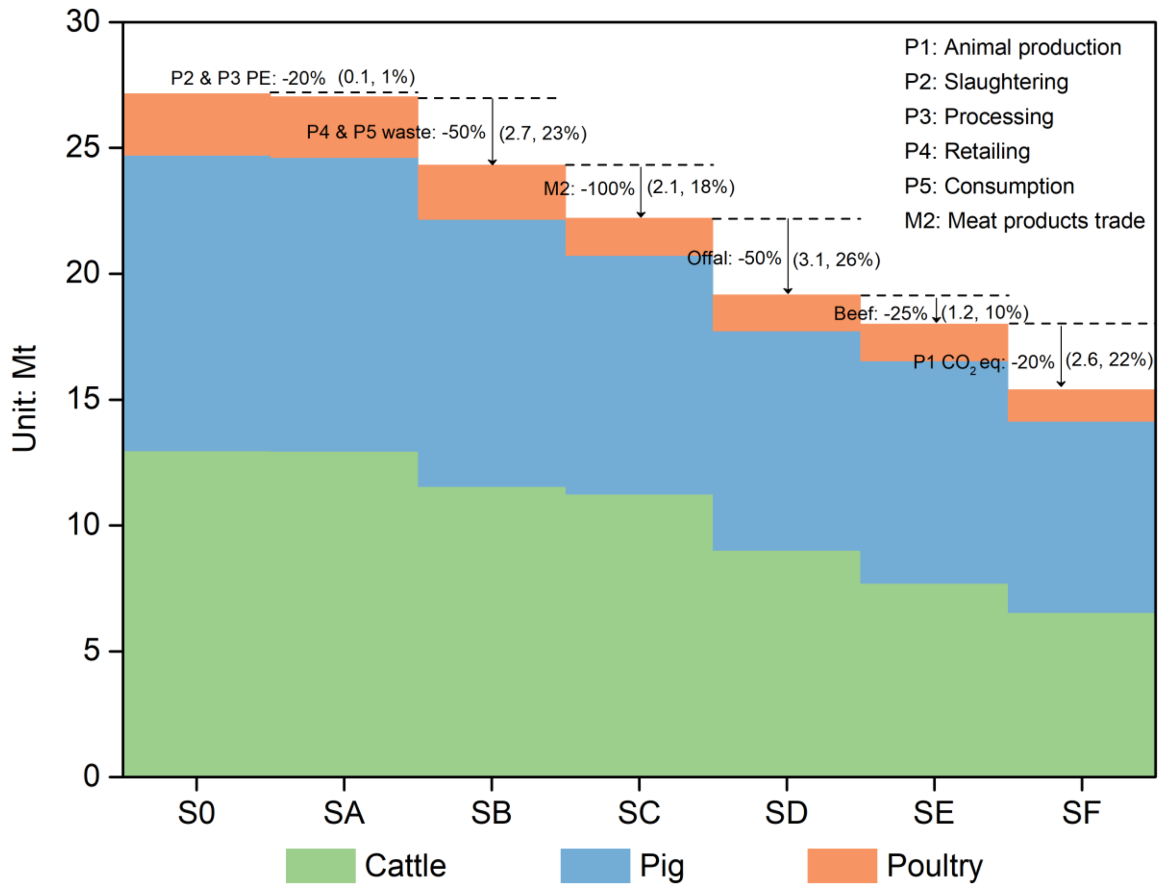


Figure 12. Combined scenario result of GHG emissions reduction. S0 is the baseline scenario.

Note: The numbers along the vertical arrows represent the absolute amount of GHG emissions reductions and the shares in the total reduction, respectively. SA=S2c, SB=S2c+S4c, SC=S2c+S4c+S5f, SD=S2c+S4c+S5f+S8, SE=S2c+S4c+S5f+S7+S8, SF=S1+S2c+S4c+S5f+S7+S8.

4.3.3 Net environment benefits of the rendering and waste treatment

Figure 13 shows the net environment benefits of the rendering of meat by-products and waste treatment by considering credits from the substitution of resources and energy (e.g., soymeal, electricity, and heat). The total GHG emission saving was 1425 kt. The largest came from the feed production with a reduction of 806 kt CO2-eq, accounting for 57% of the total saving, followed by biodiesel production (561 kt, 39%). Although these emissions savings were low (5.2%) compared to the whole supply chain climate impacts, they almost have the same net environmental benefits as reducing meat waste from retailing and consumption stages by 25%.

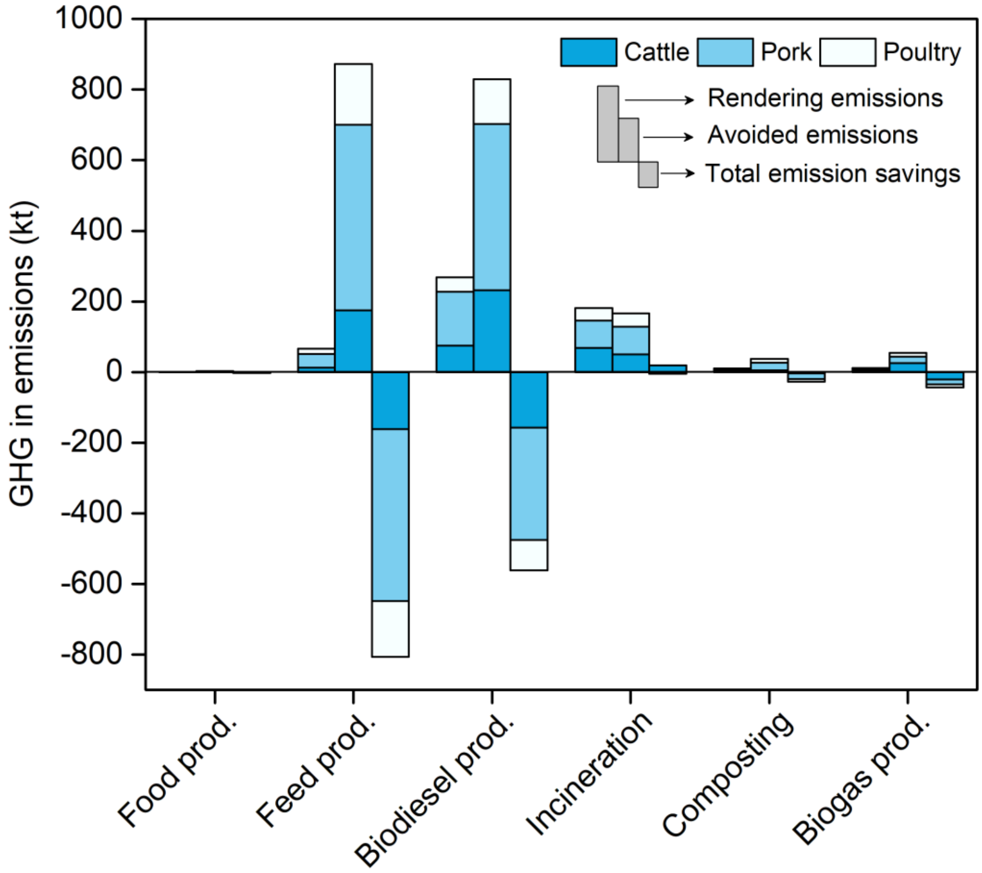


Figure 13. Net environment benefits from rendering of meat by-products and meat waste treatment.

4.4 Economic impacts

This section presents the results of a qualitative analysis aimed at evaluating the potential economic impacts of outlined strategies for the meat case. Since modelled scenarios and related percentages were not associated to a specific intervention (i.e. a precise innovation reducing emission intensity or preventing food waste), a full life cycle costing was not carried out. Therefore, secondary data and literature on possible examples of strategies and scenarios were collected and analysed, aiming at providing generic indications of the potential outcomes, in terms of costs for various stakeholders affected by proposed changes.

4.4.1 Production efficiency

According to the EU Agricultural Outlook 2017-2030 (European Commission 2030), world meat consumption will increase by 14% by 2030, leading to higher EU meat exports and counterbalancing the slight contraction of EU consumption. In particular, EU production should reach 47.5 Mt, with an increase of poultry, pork, and sheep/goat meat, and a decrease of beef. In terms of production, the economic outlook for livestock farmers will be likely characterised on one hand by lower revenues due to increased competition, and by relatively low feed prices on the other. Within this perspective, the scenario related to a decreased production emission intensity, to be reached, for example, by increasing the efficiency of animal feed production, improved manure management, or energy saving equipment, could have quite variable outcomes in terms of economic impacts.

As reported in section 4.1, 2.5 Mt of meat was produced in Germany before slaughtering, with pork accounting for about 59% of production, followed by poultry (24%) and beef (17%). Current production costs for different types of meat in Germany are characterised by similar structure and reflects the corresponding European average. Feed constitutes a relevant share of total cost, ranging from 31% in the case of beef finishing (not including feed eaten by animals before finishing) to 60% in the case of poultry (Table 8).

Table 8. Production costs of different meat at farm in Germany (in €/kg CW)

Cost	Pork	Poultry	Beef
Feed	*0,84 €*	*0,72 €*	*1,30 €*
Others (incl. animals)	*0,31 €*	*0,31 €*	*1,40 €*
Variable costs	**1,15 €**	**1,03 €**	**2,70 €**
Labour	*0,15 €*	*0,05 €*	*0,45 €*
Depreciation & other	*0,24 €*	*0,10 €*	*1,02 €*
Fixed costs	**0,39 €**	**0,16 €**	**1,47 €**
Total costs	**1,54 €**	**1,19 €**	**4,17 €**
Notes			Beef finishing
Reference year	2016	2017	2015
Source	[19]	(Horne, 2018)	(Hocquette et al., 2018)

Global prices of main ingredients, such as wheat, maize and soybeans, largely drive feed prices in EU countries. In Germany, the average compound price for

[19] 2016 Pig cost of production in selected countries. Agriculture and Horticulture Development Board. https://pork.ahdb.org.uk/media/274535/2016-pig-cost-of-production-in-selected-countries.pdf

farm feed was 31,5 €/100kg and 22,8 €/100kg in the case of poultry and pork respectively. Animals (e.g. piglets, day-old chicks, and calves) constitutes another significant source of variable cost, while fixed costs are particularly relevant only in the case of beef.

As highlighted in section 4.2, the production sector has a large share of total GHG emissions and addressing livestock rearing should be prioritized, and especially the enteric fermentation of the digestive system in the case of cattle. The improvement of feed digestibility could increase the feed intake efficiency and this in turn could have beneficial economic effects. In fact, on one hand, it could lower the amount and total feeding cost while, on the other hand, it could result in a better yield in terms of meat weight per kg of feed purchased. This is also suggested by recent research. For example, the environmental and economic impacts of 4 production systems of a typical farm in the southern region of Brazil were analysed (Florindo et al., 2017). They found that by changing the feed combination (pasture, supplementation, and commercial ration) and anticipating the age at slaughter, it was possible to achieve a 45% reduction of GHG emissions per kg of live weight and a 38% increase of the profitability per hectare. Feed composition and quality were identified as key drivers of increased profit margins in the case of dairy farms (Buza et al., 2014). It was suggested that further improvements could be accomplished by increasing the stocking rate and the average daily gain, so to avoid the conversion of further land to pastures. The importance of these parameters was also confirmed for the profitability of beef cow-calf to finishing systems, by comparing the average Irish farm with farms participating in an improvement programme and two experimental farms using finishing male progeny as steers or bulls respectively (Taylor et al., 2018).

Another intervention that could target this hotspot of livestock farming is the valorisation of food waste as feed. Recent literature (Dou et al., 2018; Salemdeeb et al., 2017; van Zanten et al., 2015; zu Ermgassen et al., 2016) and case studies from various countries (Kim and Kim, 2010; Takata et al., 2012) suggested that, with the adoption of appropriate treatment technologies and safety measures, it could be possible to derive valuable products to be included in the diet of various species, mostly non-ruminants. In EU, 5 million tonnes of former foodstuffs (FFs), mostly bakery and confectionary-type goods, are processed into animal feed. Maximising this valorisation would diminish by 1.2% land used for pig feed crops, while processing further surplus food derived from manufacturing, retail, and consumption could result in a 21.5% decrease (zu Ermgassen et al., 2016). Environmental benefits in terms of GHG emissions would regard both feed and food waste management (Kim and Kim, 2010; Takata et al., 2012). A recent report[20] within the REFRESH project assessed the environmental impacts and cost of the valorisation of food surplus as pig feed through the introduction of the processing techniques currently applied in Japan, in two EU countries, namely UK and France. Results showed that, compared to current situation, about 1 million tonnes and 2 million tonnes of carbon dioxide equivalents could be saved in the case of UK and France respectively, mostly thanks to the replacement of

[20] https://eu-refresh.org/results

conventional feed. In UK this would also have a beneficial economic effect with an overall saving of 278 million €, while in France overall costs would increase by 413 million €, mostly due to the larger transport distance between food waste generation and pig farming. Considering current feed costs for German pig farming and the even distribution of pig farms in the national territory, it is possible to say that such intervention would be quite beneficial.

Targeting manure management through, for example, anaerobic digestion would help reducing the environmental burden of livestock farming both by avoiding methane emissions and by potentially reducing the energy used on farm (e.g. heat). While manure management is not a major hotspot of costs, anaerobic digestion of manure and cogeneration of electricity and heat from biogas can be viable and profitable options. In Germany, manure-based small-scale biogas plants (< 75 kWel) are incentivised with a premium tariff and specific conditions. Unlike other substrates, subsides for manure-based plants were not reduced in the last policy revisions. As a result, new installation have kept rising in the last years and there are currently ab. 600 operating plants of this type in the whole country (Daniel-Gromke et al., 2018). Feed-in tariffs for the electricity and incentives for the efficient use of co-produced heat (including on-farm use, e.g. for stable heating) could result in a win-win outcome.

Finally, it is important to notice how not all efficiency improvements in the livestock production have overall positive effects. For example, a study (Maples et al., 2018) examined how incentivizing increased beef cattle efficiency in the U.S. historically led to a higher output of meat per animal (e.g. larger CW) but also to some unintended consequences. Specifically, retailers started to reduce the thickness of some cuts (e.g. steaks) in order to keep down packaging cost. Nevertheless, since consumers prefer thicker cuts, they likely had to face a welfare change estimated by the author in $8.6 billion annual loss.

Therefore, the final economic outcome in terms of costs and profits for the overall value chain will likely depend on the specific measures that will be implemented and the attention paid to unintended trade-offs. In general, reducing the amount and price of feeding as well as diversifying the income of farmers could present important benefits.

4.4.2 Process optimization

Results in Section 4.2 showed how meat slaughtering and processing play a relatively residual role in the overall GHG emission. This is likely due to the comparatively high efficiency of the sector in terms of resource consumption and waste generation and recovery. As a result, the reduction potential of related scenarios is also limited.

This situation is also reflected by the limited availability of literature on the cost of meat processing industry and the economic impacts of efficiency measures and innovations. An analysis in the U.S. showed that the productivity of meat industry steadily increased since 1970, although at declining rates (Xia and Buccola, 2002). Capital-intensive and material-saving technical innovations allowed decreasing costs and raising yields. Coherently, facing a highly competitive market, meat industry constantly looks for innovations related to processing, packaging and quality evaluation, in view of improving their efficiency (Cummins, 2016). The authors list a series of technologies - from irradiation and high-pressure processing, to light-based technologies and robotics, from smart packaging and probiotics, to rapid methods for microbial analysis - that presents some efficiency gains. However, they also stress that several factors affecting market uptake must be taken into consideration. The financial aspect, especially the initial capital, is definitively important, but is not the only consideration, since some novel solutions are economic in terms of operating cost and/or can yield a better product than conventional methods. For example, a study assessed the cost-effectiveness of 4 decontamination technologies in reducing risks from Salmonella in Danish abattoirs and they found that, despite the higher capital costs, a new technology such as steam-ultrasound was the best-performing with respect to traditional technologies using more energy and water (Lawson et al., 2009).

By-products from the slaughtering and processing of meat are another possible focus of intervention. According to the United States Dept. of Agriculture Economic Research Service[21], between 7 and 10% of the gross income of meat industry derives from by-products. Innovative and efficient utilization of these side flows could avoid economic loss and improve profit margins of meat processors. Some examples from the literature include both the recovery and valorisation of waste for energy own-use and the possible value of side streams for other supply chains. A study analysed the conversion of paunch and dissolved air flotation (DAF) sludge into solid fuel to be reused on-plant through a cost-benefit analysis (Hamawand et al., 2017b). Their results showed that production costs of paunch pellets would be lower than some fossil fuels (e.g. coal) but with similar energy density. Their utilization as fuel would ensure a potential payback period of up to 3.2 years. A study assessed the techno-economic feasibility of bio-polyester production from slaughtering waste streams and they found that production costs could vary from 1.41 €/kg to 1.64 €/kg, with a payback time of up to 4.5 years depending on the market for plastic, electricity, biodiesel, and heat (Shahzad et al., 2017). A study assessed the potential profitability of plasma and haemoglobin from animal blood in Poland (Kowalski et al., 2011).

Finally, further cost savings and/or income sources could then be generated through intervention on wastewater management, which represent another source of resource consumption of meat processing facilities (Bustillo-Lecompte and Mehrvar, 2017; Hamawand et al., 2017a; Mancl et al., 2018).

4.4.3 Food waste reduction

Meat waste at the retail and consumption level is generally lower than for other commodity groups (e.g. fresh fruits and vegetables). However, due to the higher economic value and embedded resource consumption, the related cost for the economy, the environment, and the society is usually a lot higher. According to FAO, the direct economic value loss due to meat waste in Europe can be estimated in almost 40 billion USD (including subsidies), which is roughly the 20% of the

[21] https://www.ers.usda.gov/publications/pub-details/?pubid=37428

total value of food waste (FAO, 2013). When including environmental costs related to GHG emissions, water scarcity, and biodiversity loss, the figure rises to almost 50 billion USD. Similar figures were found for the US with a total annual cost of ab. 32 billion USD (Hardersen and Ziolkowska, 2018).

For these reasons, prioritizing meat waste reduction at the retail and consumption level would not only yield a significant GHG reduction, as shown in section 4.3, but also important savings in terms of economic and societal costs. This is confirmed by a recent research (Dreyer et al., 2019) proposing a combined environmental and monetary ranking method for the evaluation of food waste reduction priorities at the retail level.

4.4.4 Trade pattern change

Scenarios related to trade pattern changes would likely have major economic impacts in terms of both national livestock sector and potential welfare changes for the consumers. Most of live animal and meat product imports of Germany is coming from few countries (e.g. Denmark, Netherlands, Poland, others), so reducing the import from top emitters would have limited environmental benefits (as shown in section 4.3) and economic effects. On the opposite, since Germany is a net exporter in both categories, the reduction of exports would result in GHG saving but also in potentially negative welfare effects, in particular for livestock farming.

4.4.5 Diet structure change

There is now significant evidence and literature proving that reduction of meat consumption and shifting towards plant-based proteins will be crucial for the future sustainability and security of food systems (Bowles et al., 2019). This is sustained also by the results presented in section 4.3. However, less is known about the potential economic effects of such a huge shift. A study tried to answer this question with reference to the US context, underlining three main aspects (Lusk and Norwood, 2009). First, cost of production and retailing of animal-based protein remains higher than most plant-based ones. Thus, also considering the increased land and processing needed to cultivate and transform plant-based proteins, the probable diet cost would be lower. However, they also noticed that the farmers' share of the final price is higher in the case of meat supply chains, so this aspect should be taken into proper account. The second aspect that the authors analysed is the effect on crop prices. They show that any major shift towards a prevalent vegetarian diet would lower corn prices, paradoxically making meat cheaper, and/or corn production. It is possible to argue that farmers would than shift towards other crops in order to compensate any welfare loss. The third aspect the authors focused on was the consumers' acceptance of such a shift and the related effects. In particular, they estimated the welfare change from a one percent reduction of meat consumption, with constant prices for other foods, in $0.16/week/person, considering the role of meat in the US diet.

Besides the direct economic impacts, also indirect effects, such as health outcomes, could be taken into account in a societal perspective. A study tried to address this aspect by assessing the health and economic effects of Mediterranean and soy-containing diets considering possible health outcomes and related direct and indirect costs in a 20-year time span (Schepers and Annemans, 2018). Their results show that shifting towards a plant-based diet could yield net economic gains and improved health for the society, especially in the case of soy-based diet and depending on the current level of meat consumption.

4.5 Policy implications

Our mapping of the mass and energy flows of the German meat supply chain provides a detailed understanding of the whole system efficiency of meat products and the generation and destination (e.g., valorisation and recycling) of different meat by-products and waste. The study also presents the comparison of the effects of different GHG emissions mitigation strategies based on combined scenario analysis covering production efficiency, process optimization, food waste reduction, trade pattern change, and diet structure change. Such a model framework can be used as a proxy for other countries and agri-food products as well. Although we considered only the climate change impact in this study, other environmental (e.g., water), economic, and social (e.g., animal welfare) implications could also be analyzed and discussed based on the physical mapping.

The results reaffirmed the low energy conversion efficiency of the meat supply chain (Brameld and Parr, 2016; Godfray et al., 2010), and the high GHG emissions at meat production (Peters et al., 2010) (among which the beef production is the least efficient) (Carlsson-Kanyama et al., 2003; Gerber et al., 2015). This implies a priority of mitigation strategies is to address the cattle rearing (accounting for almost half of total emissions of meat production) and especially enteric fermentation of the digestive system. Improving feed digestibility could be a part of the solution, which not only could contribute to the growth of feed intake efficiency, but also could lower the amount of manure excreted. This strategy could yield an increased economic efficiency for animal farming, considering that both feed and manure management are relevant cost items. On the other hand, technology efficiency improvement and process optimization are also important strategies for GHG emissions reduction and could be potentially beneficial from the economic perspective.

Reducing meat consumption, in parallel to making meat production more sustainable, would have profound effect on the GHG emissions. Per capita meat consumption in Germany has decreased from 100.4 kg in 1990 to 87.8 kg in 2016 by 12.5% over a period of 26 years[22], due to an increase number of vegetarians and a shift to a healthy diet. However, the current level is still twice as high as the world's average and the recommended meat consumption by the German Nutrition Society (DGE) (Harald von Witzke et al., 2011). A further reduction is necessary but also challenging. An alternative is to substitute beef with pork and poultry; in fact, poultry has become more popular in Germany in recent years. Furthermore, some edible parts of the animal by-products (e.g., offal, tongue, and casings) are rarely consumed at present due to low demand as food. However, changing

[22] European Commission Eurostat Home Page.
http://ec.europa.eu/eurostat/web/prodcom/data/database/

marketing strategies, converting them to more appealing food, and raising awareness about the value of such products would provide a great potential to substitute meat consumption and further lower the total GHG emissions of the meat chain. The economic effect of such shift is more difficult to estimate, especially when considering the whole supply chain and the welfare effects for farmers and consumers. However, in a societal perspective, indirect savings from reduced health impacts could be considered.

Eliminating the meat waste at the retailing and consumption stages could also achieve a high reduction of emissions. For example, a 25% reduction of retailing and consumption meat waste would almost have the same emissions reduction potential as reducing the total meat consumption by 10%. The majority of meat waste was found at the consumer stage (392 kt in 2016, on a DM basis), especially in the households (259 kt in 2016, on a DM basis). Households can be the focus and many prevention measures are possible (e.g. freezing food leftovers, cooking new meals from meat leftovers, cooking soups with bones and cut-offs, and creating shopping lists to avoid buying food which is not needed). Furthermore, meat waste from out-of-home consumption (e.g., restaurants or hotels) and the retailing sector should not be overlooked, which would be suitable for food donation and redistribution to social organizations. For example, the 'Gadda law' of Italy designed to fight against food waste has come into force in 2016, which makes it easier for businesses to donate unwanted food to people in poverty, and helps raise awareness of consumer to waste less food[23]. Considering the high embedded value of meat and the indirect effects of its wastage, prevention measures would be also economically beneficial.

Our results also show that halting the import of meat products from the top 3 GHG emission countries and the export of meat products to non-EU countries would contribute to reducing the GHG emissions in a consumption-based accounting (while emissions increased in a territory-based accounting; Figure A6). Nevertheless, this would also mean that either the production in other countries needs to increase or the consumption in other countries decreases to hold the overall consumption, but what needs to be considered is that whether it would be replaced by a system with more emissions. Furthermore, since Germany plays a key role in the European market of animal and meat products, it is questionable whether a decreasing export would affect the German economy.

The meat by-products rendered can be further used in different sectors. Our results show that most by-products go to feed production (48%), where protein and fat from Cat 3 are used as feed ingredients due to its nutritional and preservative properties. This is followed by industry use (30%), where fat is used as ingredients to produce cosmetics, lubricants, and cleaning products. It is stated that 1 t of animal protein equates to 1.7 t of soybeans which stands for 0.66 ha of rainforest in Brazil (Heinrich-Böll-Stiftung, 2014). Using the protein for feed production would not only prevent wasting the high value protein, but also reduce the carbon and

[23] The Local Home Page. https://www.thelocal.it/20160803/what-you-need-to-know-about-italys-new-food-waste-laws/

land footprint of meat. In addition, the EAF from Cat 3 that is fit for human consumption can reduce the demand of vegetable oil and thus land use for oil crop cultivation. What's more, about 17% of all the meat by-products that are unfit for human consumption go to biodiesel production, which is less emission intensive than fossil fuels. Therefore, improving the efficiency of meat by-products rendering and waste treatment is a straightforward yet important strategy to mitigate the climate change impacts of the entire meat supply chain. In addition, such scenarios as well as other form of biorefinery can improve the profitability of the system, yielding revenues from byproducts.

5 EU tomato case

5.1 Mass flow of the EU tomato supply chain

5.1.1 Characteristics of the mass flow

Figure 14 shows the mass flow of fresh tomatoes and tomato products of EU28. 18 Mt of fresh tomatoes was produced and 11 Mt of fresh tomato equivalents ended up consumed by humans. Consequently, 7 Mt of fresh tomato equivalents was wasted along the whole food supply chain, accounting for about 42% of the total fresh tomatoes produced in the EU28. The largest portion of tomato waste was generated at the processing stage with a share of over than 50%, followed by the consumption stage with a share of 23%. Tomato wastes occurred at the retailing and distribution stages showed a similar level, accounting for 9% and 6%, respectively.

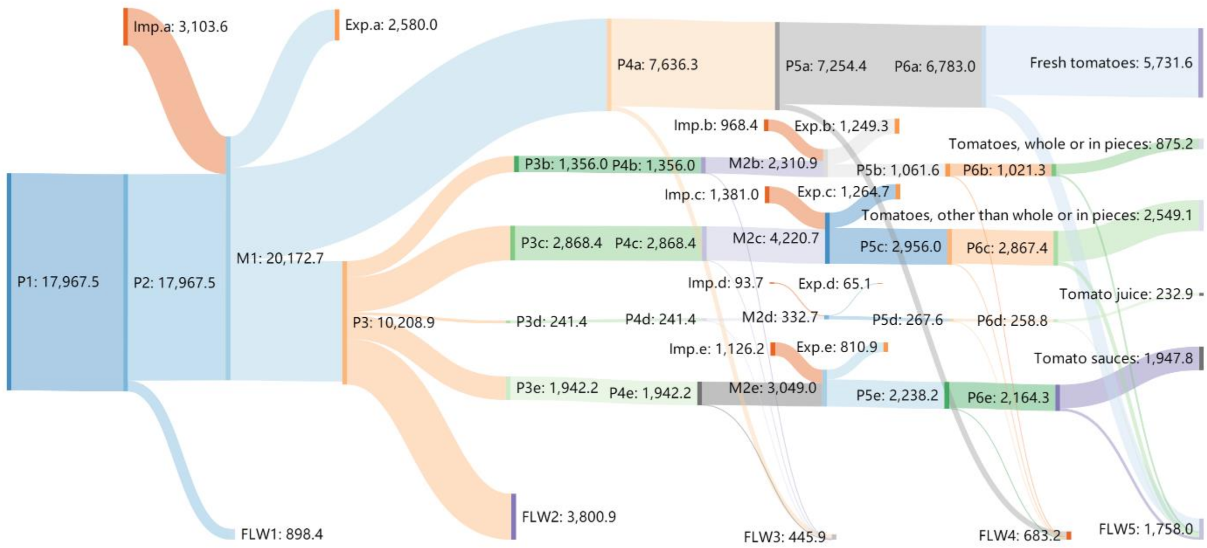


Figure 14. Mass flow of fresh tomatoes and tomato products of EU28 countries.

Note: P1: Tomato production, P2: Postharvest handling and storage, P3: Processing, P4: Distribution, P5: Retailing, P6: Consumption, M1: Fresh tomato market, M2: Tomato products market. a: Fresh tomato, b: Tomatoes, whole or in pieces, c: Tomato, other than whole or in piece, d: Tomato juice, e: Tomato sauces. FLW1: Tomato loss in postharvest handling and storage stage, FLW2: Tomato loss in processing stage, FLW3: Tomato loss in distribution stage, FLW4: Tomato loss in retailing stage, FLW5: Tomato waste in consumption stage. Unit: 1,000 t. The following territory-based and consumption-based accounts are based on the mass flows presented here.

We specifically mapped the mass flow of fresh tomatoes and tomato products for the top 10 countries in the EU28 considering their quantity of tomato production and per capita GDP. These are Italy, Spain, Portugal, Greece, Netherlands, Poland, France, United Kingdom, Germany, and Belgium. These countries show different patterns of fresh tomato production, tomato processing, trade, and waste generation. Detailed mass flows of these countries are listed in Figure A7-A16.

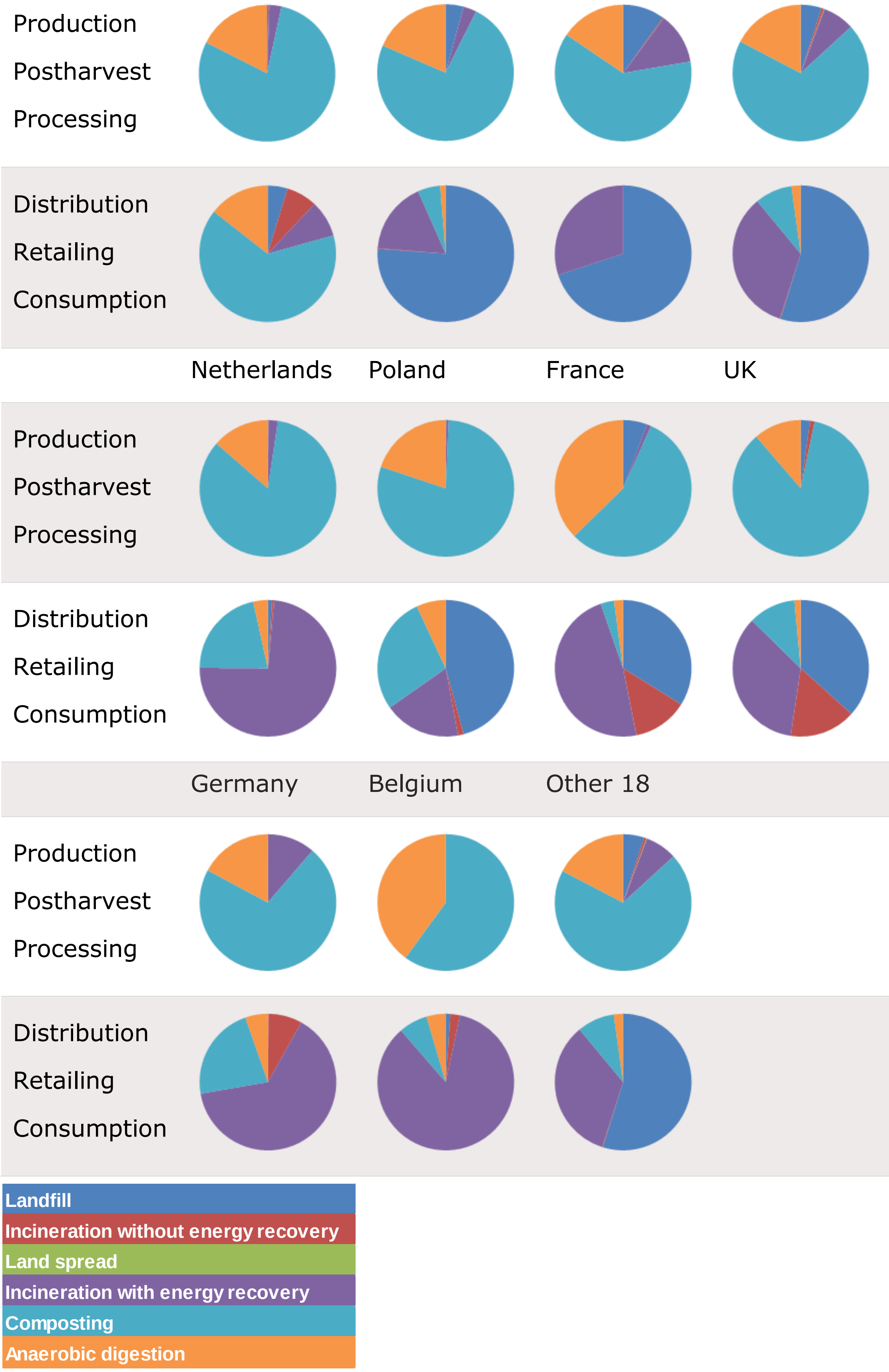
5.1.2 Tomato and tomato products waste management

Table 9 illustrates the share of tomato by-products and waste generated along the supply chain to different treatment sectors. The status of waste management operations in EU-28 countries varies significantly. Options used to treat tomato by-products and waste depend on not only waste treatment infrastructure and capacities available, but also the point of the supply chain where they are generated. Tomato waste generated from the production, postharvest and processing stages is rather homogenous, allowing for a target-oriented recycling (composting or anaerobic digestion) compared to tomato waste from retailing or consumption which is often packed or mixed with other solid waste. The recycling of tomato waste generated in the distribution, retailing, and consumption stages largely depends on the capture rate of separate collected biodegradable waste. The capture rate is the share of the generated quantity of a given material that is separately collected. The capture rate was estimated based on qualitative information from two sources: JRC[24] and ECN[25]. Separate collected biodegradable waste was assumed to be recycled in composting or anaerobic digestion plants. The rest was assumed to undergo different waste management routes, such as landfilling and incineration. Eurostat data for vegetal waste, as well as mixed household and similar waste, was used to determine the composition of waste management routes in different EU28 countries.

Table 9. Waste treatment along the tomato supply chain.

	Italy	Spain	Portugal	Greece

[24] http://publications.jrc.ec.europa.eu/repository/bitstream/JRC87124/eow%20biodegradable%20waste%20final%20report.pdf
[25] https://www.compostnetwork.info/


Production
Postharvest
Processing
Distribution
Retailing
Consumption
Netherlands
Poland
France
UK
Production
Postharvest
Processing
Distribution
Retailing
Consumption
Germany
Belgium
Other 18
Production
Postharvest
Processing
Distribution
Retailing
Consumption
Landfill
Incineration without energy recovery
Land spread
Incineration with energy recovery
Composting
Anaerobic digestion

In terms of tomato waste sources, the amounts of tomato loss and waste vary significantly by country (Figure 15). Italy and Spain are the top two tomato processors within EU28 and thus tomato waste generated from their processing stage has a great potential for waste valorisation. Biodegradable waste from the processing stage is already recycled (via composting or anaerobic digestion) to a high degree, according to Eurostat data. In Italy, recycling is also a dominant practice for biodegradable waste coming from the retailing and consumption stages. However, a great potential for waste valorisation from these stages can be observed in other countries, such as Spain, Portugal, and Greece, where landfilling is still the most used option for waste coming from retailing and consumption. The majority of tomato waste during the processing stage is assumed to end up for composting rather than for anaerobic digestion (based on existing plant capacities), meaning that significant amounts of potential for anaerobic digestion are untapped. Composting results in less GHG savings, compared to anaerobic digestion that produces electricity, heat and organic fertilizer. However, it should be noted that the former is of significance in other environmental categories, because compost is a valuable source for humus accumulation in soils.

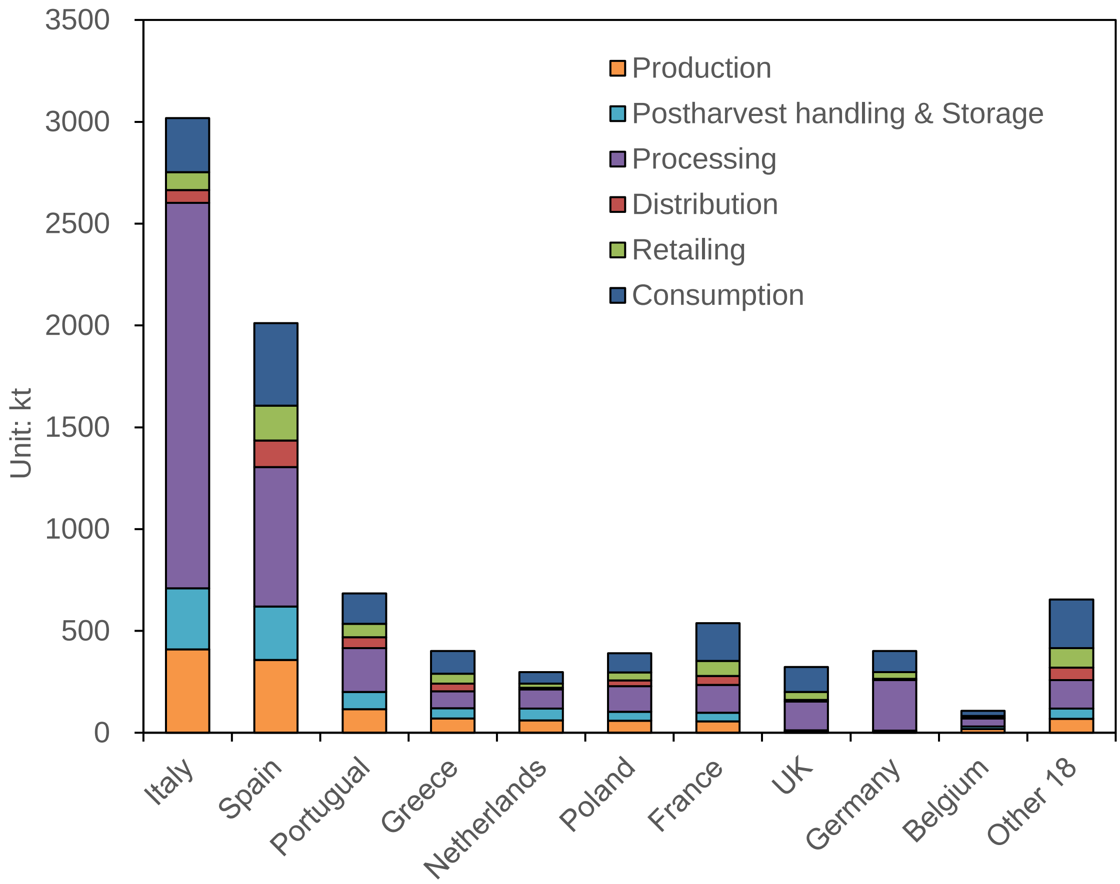


Figure 15. Waste generation during different sources in different countries.

Note: Waste generation is specified in fresh tomato equivalent.

5.2 GHG emissions of the EU tomato supply chain

Ten countries, which cover both the major producers and consumers, were selected to present the GHG emissions arising from all stages along the tomato supply chain in 2016. Figure 16 shows that, for the main tomato producer countries (e.g., Italy, Spain, the Netherlands, Poland, and France), the majority of GHG emissions were arising from the production sector based on the territory-based accounting method. Spain is the largest GHGs emitter in 2016, with its tomato production in greenhouse ranking the first in EU28. Italy was the second largest GHGs emitter in 2016, since it was the biggest producer in both fresh tomatoes and tomato products. The Netherlands was third largest GHGs emitter in 2016 because of its high reliance on greenhouse cultivation system. Three countries (i.e., Germany, UK, and France) were net importers of fresh tomatoes and tomato products and thus contributing significant amounts of GHGs in 2016.

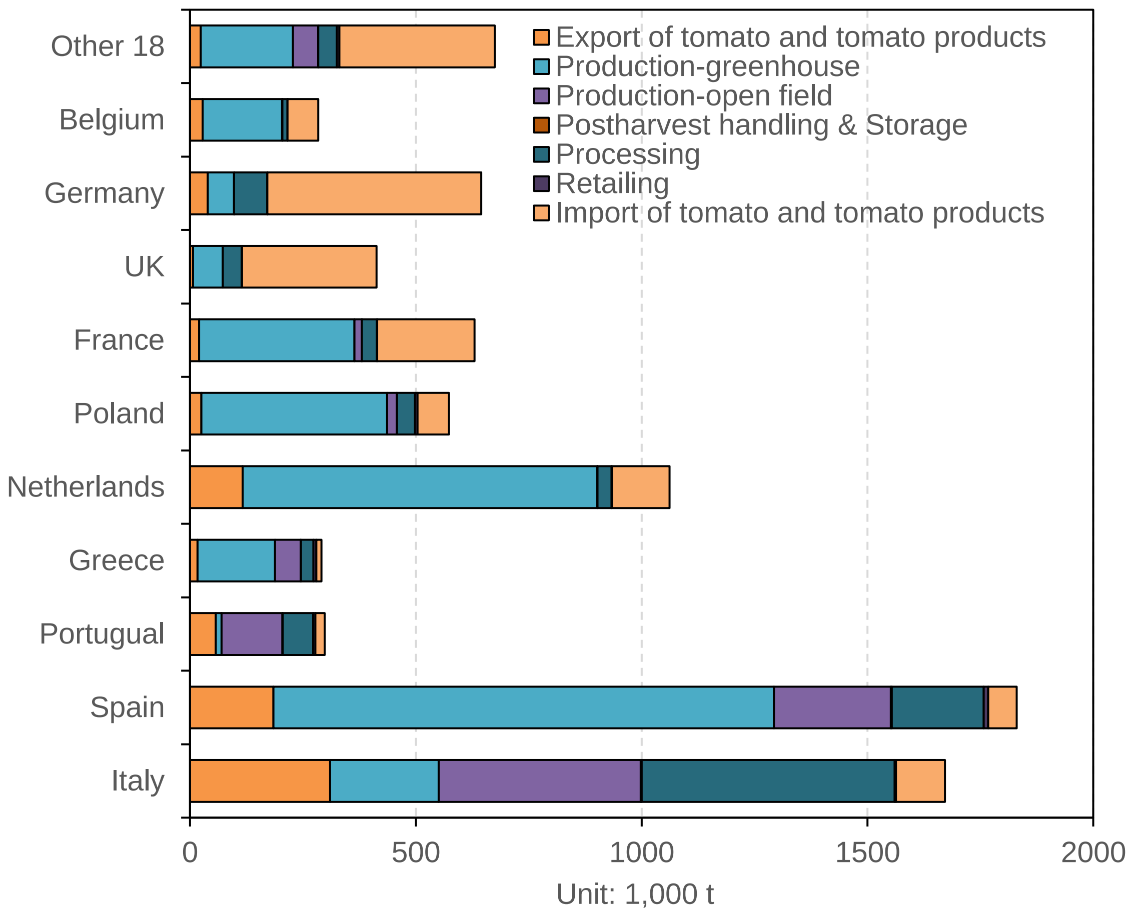


Figure 16. GHG emissions of the tomato supply chain in different countries.

5.3 Scenarios for GHG emissions reduction

5.3.1 Individual scenarios

Figure 17 shows that, with respect to the reference scenario in 2016, changes in the total GHG emissions vary from scenario to scenario and by emission accounting perspective. Most scenarios show a gradually increasing reduction potential under different levels of changes (from low to medium to high) except of the scenarios on import of tomato or tomato products. The changes of the amount of GHG emissions under different levels is shown in the Figure 17 and Figure 18.

The greatest difference to the base scenario was the reduction of tomato products consumption by 20% (S7), which resulted in a 17.2% reduction in the consumption-based GHG emissions or 20.1% in the territory-based GHG emissions. Reducing GHG emissions intensity in greenhouse tomato production (S1b) by 20% has the second largest reduction potential, amounting to a 10.7% reduction in the consumption-based GHG emissions or a 12.5% reduction in the territory-based GHG emissions. In the case of reducing retailing and consumption waste (S4c) by 50%, a 10.4% reduction in GHG emissions could be achieved. Shifting from greenhouse production to open-field production could reduce a significant amount of GHG emissions from both accounting perspectives (10.8% and 9.2%) (S1c). Reducing fresh tomato consumption (S6) by 20% would result in a 8.1% reduction in the territory-based GHG emissions. Halting the export of tomato or tomato products to non-EU 28 countries (S5a or S5c) could reduce a significant amount of GHG emissions as well, while reducing the import of tomato or tomato products would increase both the consumption-based GHG emissions and the territory-based GHG emissions. This is because the reduced import of tomato and tomato products will be compensated by domestic production.

Reduction scenarios		Low			Medium			High		
		%	T	C	%	T	C	%	T	C
S1a	Emission intensity (field)		-0.9	-0.7		-1.7	-1.5		-3.4	-2.9
S1b	Emission intensity (greenhouse)		-3.1	-2.7		-6.2	-5.3		-12.5	-10.7
S1c	Greenhouse substituted by field		-2.7	-2.3		-5.4	-4.6		-10.8	-9.2
S2a	Processing PE	-5	-1.0	-0.9	-10	-2.0	-1.7	-20	-3.9	-3.4
S2b	Processing loss		-0.9	-0.8		-1.8	-1.5		-3.5	-3.0
S3a	Posthar. Stora. loss		-0.2	-0.2		-0.4	-0.4		-0.8	-0.7
S3b	Distribution loss		-0.1	-0.1		-0.3	-0.2		-0.6	-0.5
S4a	Retailing waste		-0.6	-0.5		-1.5	-1.3		-3.0	-2.6
S4b	Consumption waste		-2.0	-1.7		-4.9	-4.2		-9.4	-8.0
S4c	S4a+S4b		-2.6	-2.2		-6.3	-5.4		-12.2	-10.4
S5a	Tomatoes export	-10	-0.4	-0.3	-25	-1.0	-0.6	-50	-2.0	-1.3
S5b	Tomatoes import		0.6	0.3		1.4	0.8		2.8	1.5
S5c	Tomato products export		-1.1	-0.6		-2.7	-1.6		-5.4	-3.1
S5d	Tomato products import		0.7	0.5		1.8	1.2		3.5	2.4
S6	Tomatoes consumption	-5	-2.0	-0.6	-10	-4.1	-1.4	-20	-8.1	-3.2
S7	Tomato products consumption		-5.0	-4.3		-10.0	-8.6		-20.1	-17.2

Figure 17. Different scenarios of GHG emissions along the tomato supply chain in the consumption-based accounting and the territory-based accounting.

Note: T refers to territory-based; C refers to consumption-based. Negative values mean the reduction percentage compared to the reference scenario, and positive values mean the increase percentage relative to the baseline.

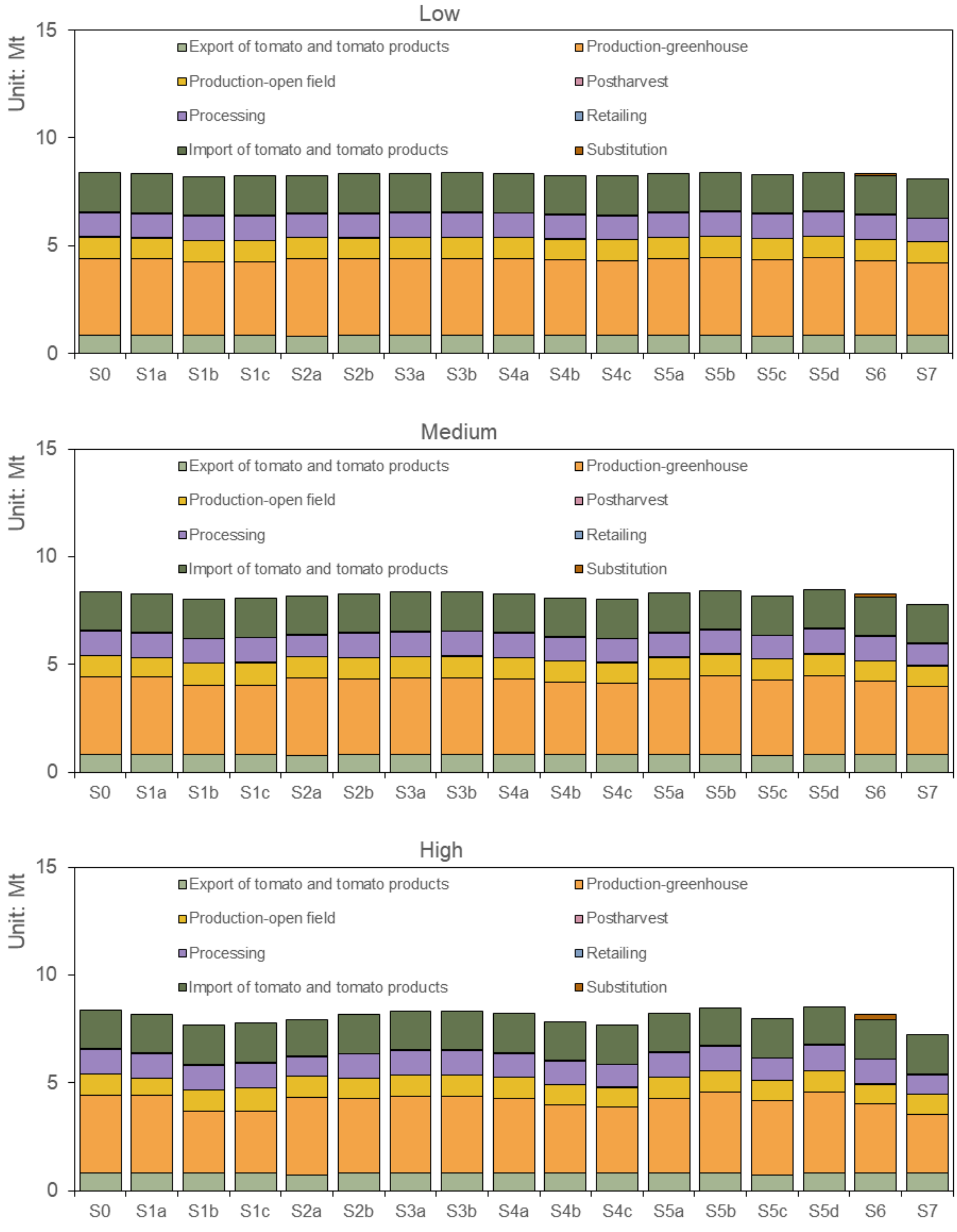


Figure 18. The change of the amount of GHG emissions along the tomato supply chain under three levels (low, medium, and high).

5.3.2 Combined scenario

Figure 19 shows the combined effects of emissions mitigation strategies described in Table 7. The biggest change of GHG emissions (0.91 Mt) occurred when emission intensity in greenhouse and field production was reduced by 20% with a share of 30% in the total reduction of emissions. The second largest reduction of emissions is reducing fresh tomatoes and tomato products consumption by 20% with a share of 24%. On top of that, shifting from greenhouse to open-field could also contribute significant amount of emissions reduction (16%), which was followed by reducing tomato waste at retailing and consumption stages by 50%. In total, a combination of emission intensity reduction, production system change, process optimization, tomato waste reduction, trade pattern changes of tomatoes and tomato products, and diet structure change would reduce emissions greatly by 45% compared to the baseline scenario.

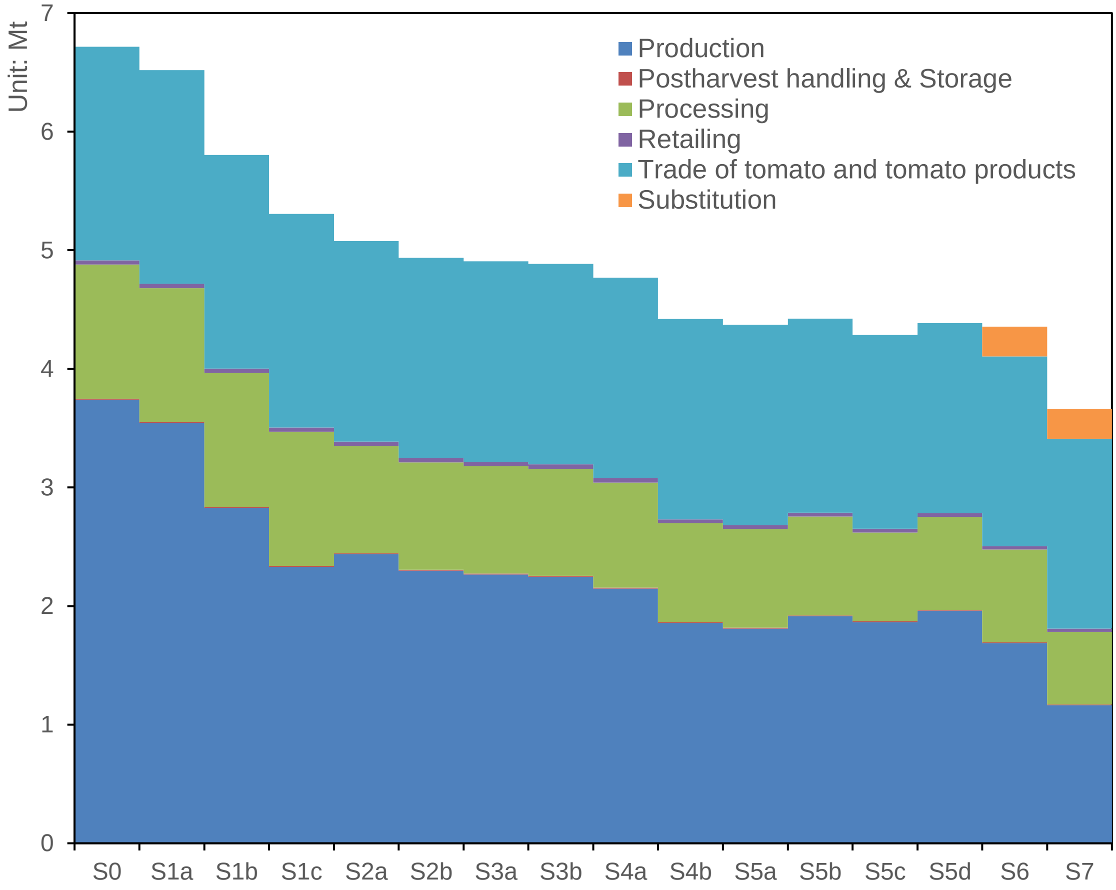


Figure 19. Combined scenario result of GHG emissions reduction in EU28.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

Figure A17-A27 show the varying potential of GHG emission reduction measures in different countries. Reducing consumption waste would be a universal measure to reduce GHG emissions for all countries. In Spain, reducing emission intensity of greenhouse production and shifting from greenhouse to open-field would contribute significantly to GHG emission reduction; likewise, those countries of which tomato production is greenhouse-dominant have the same characteristics. In Italy, improving the efficiency of process energy and reducing the export of tomato products are the two most significant measures. In Portugal, improving reducing emission intensity of open-field production has the most significant potential for GHG emission reduction. For countries where emission intensity of tomato production is higher than other vegetables for substitution, reducing tomato or tomato products consumption would backfire on the GHG emissions reduction it contributes.

5.3.3 Environmental benefits of waste valorisation

Figure 20 presents the GHG emissions from different sources by considering credits from the substitution of resources and energy (e.g., fertilisers, electricity, and heat). In the top 10 countries, the majority of GHG emissions in the waste management came from landfills, with tomato wastes from the consumption stage contributing 79 kt CO_2-eq, while tomato wastes from the consumption stage in the other 18 countries contributed 15 kt CO_2-eq. In the top 10 countries, anaerobic digestion contributed 14 kt CO_2-eq to the GHG emission saving. According to Table 8, most of the tomato wastes generated from the consumption stage end up in landfills, due to the low capture rate of household bio-wastes. Compared to the overall emissions coming from the whole tomato supply chain, the GHG emissions of waste management are negligibly small.

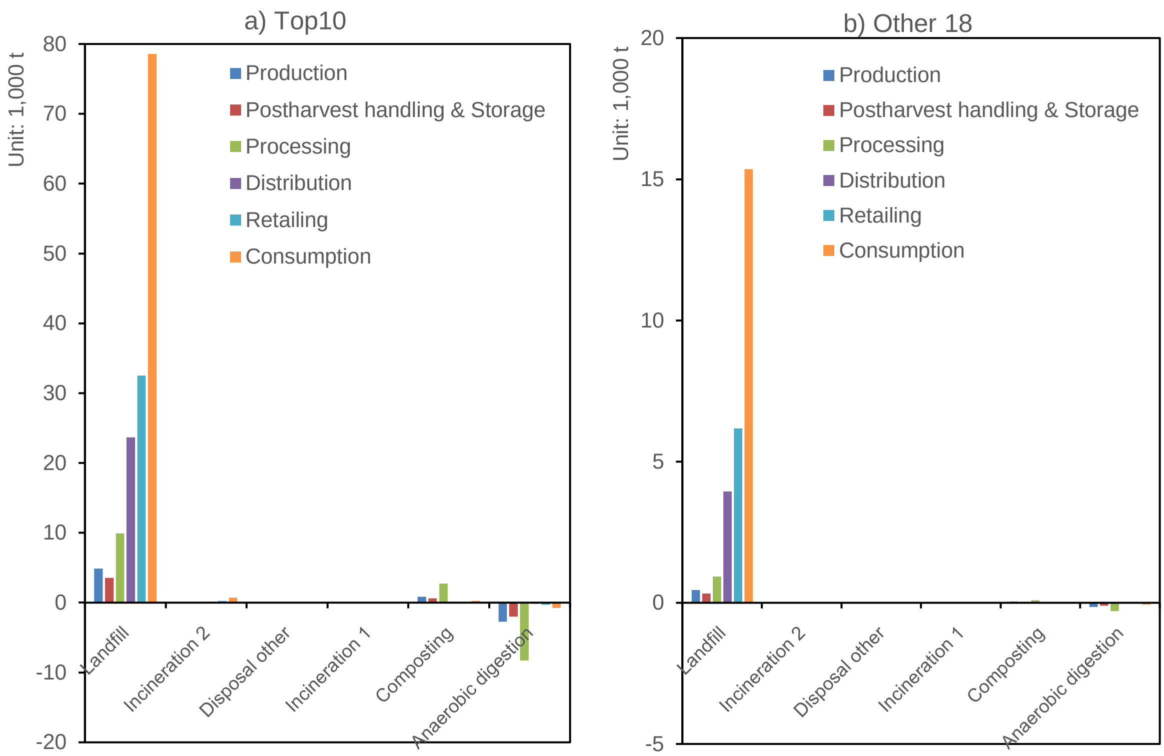


Figure 20. GHG emissions or benefits resulted from different waste treatment measures along the tomato supply chain.

5.4 Economic impacts

This section presents the results of a qualitative analysis aimed at evaluating the potential economic impacts of outlined strategies for tomatoes. Since modelled scenarios and related percentages were not associated to a specific intervention (i.e. a precise innovation reducing emission intensity or preventing food waste), a full life cycle costing was not carried out. Therefore, secondary data and literature on possible examples of strategies and scenarios was collected and analysed, aiming at providing generic indications of the possible outcomes, in terms of costs for various stakeholders affected by proposed changes.

5.4.1 Production efficiency

The S1d scenario reducing by 20% the greenhouse production emission intensity, has the second-best reduction potential. The scenario could be reached by applying different and simultaneous approaches. On one hand, it can be achieved by improving greenhouse efficiency production, higher yield with the same or fewer resources. On the other hand, it can be accomplished by less resource intensive technologies.

A study analysed the environmental and economic cost of rooftop greenhouses compared with industrial greenhouse systems (multi-tunnel) (Sanyé-Mengual et al., 2015). Results revealed that 1kg of tomato produced in a rooftop greenhouse, at the production level has a lower environmental impact (10–19%) but a higher economic cost (24%) than in a multi-tunnel system. At consumption level, environmental and cost savings in rooftops represent 42% and 21% respectively as opposed to the conventional tomatoes with multi-tunnel techniques. The study also showed that crop efficiency is a key input to determine environmental and cost impact. If this scenario needs to be implemented, investments on crop efficiency are also necessary. This needs to be considered alongside the appropriate greenhouse system or structure. Additionally, properties related to urban food schemes and social cohesion should be taken into account when certain production techniques are chosen. Tomato production under rooftop systems might help small cities to become more self-sufficient, while encouraging the development of local / short food supply chains, with positive societal values.

Focusing on production costs, studies published in Turkey and California (USA) highlighted the main items involved in tomato production. A study analysed the tomato production in Turkey, and revealed that labour cost is the highest contributor to the final figure, followed by land rent, pesticides, and fuel. It is calculated that farmers spent about 3 469.9 $/ha to obtain 4 082.2 $/ha (Çetin and Vardar, 2008). The cost for irrigation was 30.2 $/ha, which is lower the irrigation and energy share (0.87% and 8.45%). The energy use efficiency was found to be 0.80. In addition, the benefit-cost ratio of tomato production was determined to be 0.85. On the other hand, the share of direct energy input was 47.3% in the total energy compared to 52.7% for indirect energy. The research results showed that on average the non-renewable form of energy input was 87.6% compared to 12.4% for renewable energy. It is relevant to point that this study was performed in 2008, when renewable energies were not developed as much as they are in the current decade. An analysis between the investments needed to move towards renewable energy and their economic return could be made from an environmental and cost perspective.

A study (Long et al., 2018) focusing on a processing tomato case in Southern San Joaquin Valley, California (USA), analysed the expenses to produce 1 ha. Data from each costing item is shown in Table 10.

Table 10. Expenses to produce one ha of tomatoes for processing products.

Item	€/ha
Preplant cost	294.54
Cultural cost	7216.56
Harvest cost	1673.61
Post-harvest cost	358.54
Assessment cost	78.82
Operating interest capital (5%)	131.21
Cash overhead	927.12
Non-cash overhead	2326.69
Total cost	13007.34
Gross returns	11922.58
Total cost	224.61
Net returns above total cost	-1084.77

In the original work, the cost units were presented in USD. The currency exchange utilized was 1USD-1.18EUR.

Note that a price of 83.19EUR per ton was applied in the USA study, as usually growers produce tomatoes under annual contracts with various tomato processors.

The cultivation costs, representing typical production operations and materials for a well-managed farm in the region, represented the highest value followed by non-cash overhead cost items. This last item was calculated as the capital recovery cost for equipment and other farm investments. Hence, it can be changed according to farmer’s risk aversion to investing in certain equipment.

In both cases, although the prices may vary from European countries, the percentage associated with each cost item might be similar to other tomato producing countries.

Farming practices are subject to unrecognised payment due to familiar support or other working deals. Guaranteeing a solid framework to allow farmers earning a fair salary should be the core of the economic and social development of the food supply chain, thus the efforts to deal with this cost item should be focused on building adequate policy frameworks to stimulate fair labour conditions as well as training more sustainable practices.

5.4.2 Process optimization

From a food loss approach, a report[26] from REFRESH recognises tomato (pomace, including seed, skin and pulp) as one of the top 20 food waste streams appropriate for valorisation, mainly for its high level of lycopene. Therefore, beyond the first option which is a minimization of food loss and waste, valorisation routes seem to be appropriate options to manage tomato sub products and waste.

When focusing on processing phases, at the manufacturing level, the residual mass of tomato pastes accounts for about 2–5% of the processed product, often involving an added cost for disposal management. This residual could be sold at a low price for animal feeding or given for free to companies which utilized it as organic fertilizer. Researchers are trying to find a better use for these residues because, on one hand, their management involves a high amount of methane emissions, while, on the other hand, their carotenoid content is rather interesting for other industries (such as pharmaceutics) and their energy content can be recovered through anaerobic digestion. This last option usually has improved environmental performances than animal feeding and organic fertilizer production, and it can benefit from public subsides (Bacenetti et al., 2015). However, a report[27] from REFRESH pointed out that, due to the high-water content of tomato pomace, both valorisation routes (animal feed and anaerobic digestion) might be only convenient when the product travels short distances and it usually involves intermediaries (between the producer and the farmer using pomace).

The cold chain maintenance is key to avoid product damage. The cost of providing it depends on the energy cost and the utilization efficiency of the facilities during the year. Figures from one study conducted in India showed that about 30% of fruits and vegetables grown in India were wasted due to the gap between the energy cost to maintain the cold chain along the different steps of the supply chain and the price obtained by the product (Prusky, 2011). The study highlights the fact that longer distance transportation is a challenge in the fresh tomato market. Beyond food waste measures, meeting high food safety standards are essential. Promoting initiatives to conserve in better conditions the food transported (including the storage) should be the pillar to fight against foodborne issues while reducing waste.

Tomato carotenoids from industry residues, such as lycopene, α-carotene and β-carotene, have been employed for encapsulation and are being sold in food

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[26] https://eu-refresh.org/top-20-food-waste-streams

[27] https://eu-refresh.org/sites/default/files/D6.10%20REFRESH%20_FORKLIFT_Annexes%20.pdf

antioxidant and supplement applications. The investment costs of these technologies are key to stimulate or reject the adoption.

When considering tomatoes as substitute of other ingredients in animal feed, such as in the diet of dairy goat, it implies a reduction in the methane production keeping the same milk yield (Molina-Alcaide et al., 2017). In an internalization of environmental cost, the role of environmental emissions in managing residues will be also included in the decision-making.

As cited literature shows, there is a strong link between better production and processing performance and food waste reduction. When this reduction is not possible, alternatives that guarantee economic profit without compromising environmental issues should be found.

5.4.3 Food waste reduction

Analysing S4 (food waste reduction at the retail/consumer level), some figures from a study conducted in different Swedish supermarket reveals that about 743 tons of this product are sold while about 6.75 tons are wasted in-store (Eriksson et al., 2012). The study highlights the fact that data about sold and wasted figures in some vegetables and fruit products are missing. It also indicates the rejection of delivered goods as the main source of waste at pre-store level. This involves not only a waste of the product and its value but the associated impacts of the resources needed at the pre-store level such as electricity, storage management, labour, as well as waste management taxes. That additional cost might be highlighted when measures to reduce food waste wants to be implemented, as well as the embedded environmental impact of food waste and the ethical concern it represents.

A study analysing the food waste flow along the tomato supply chain in Cali (Colombia) revealed that farmers donate about 72% of the unsold fresh tomatoes, traders 69%, and retailers 44% (Chaboud, 2017). Home-consumption is the second preferred option by retailers to avoid throwing away unmarketable tomatoes. Most of the unsold tomatoes (due to market standards and other ascetical reasons) are placed in other products as processing tomato. At the consumer level, data from USA[28] emphasized that 31% of fresh tomatoes bought by the USA country are wasted, involving a direct cost of over 2.7 billion EUR a year. Measures beyond raising awareness about the economic cost and the number of resources involved in food production were not found. Studies report that up until the retail level, food waste associated with tomato production can be managed by applying a variety of valorisation options. However, at consumer level practices beyond reducing the waste were not found. The policy options pointed out in this report also highlight that the major issue in the tomato supply chain resides in the retailing and consumption stages. This could imply that a focus on these sections of the value chain should be considered.

[28] https://www.ers.usda.gov/publications/pub-details/?pubid=37428

5.4.4 Trade pattern change

If trade patterns are analysed, the price of the tomato in Europe suffers high volatility, as it depends on weather conditions and a strong trade market. In a 5-years analysis, the price of tomato has ranged from 144€/100kg to 93€/100kg[29].

In 2017, the balance between export and imports in the European countries' aggregation accounted for 1,262,551 thousand EUR (fresh tomato)[30]. Table 11 and Table 12 show the top 10 countries imported/exported accruing to its trade value[31].

The negative value indicates that the aggregation spends in importing tomatoes more than what earned in the exporting.

Table 11. Top tomato exporter countries according to the trade value in 2018. Sourced by UN Comtrade 2018.

Country	Type of tomato	Trade value (EUR)
Mexico	Fresh	2 667 974 765
Portugal	Fresh	75 265 238
Belarus	Fresh	63 365 410
United Kingdom	Sauces	42 195 995
Mexico	Sauces	33 925 462
Portugal	Sauces	33 354 283
Sweden	Sauces	28 984 349
Greece	Vegetable preparations	24 850 474
Greece	Fresh	17 706 291
Portugal	Vegetable preparations	16 171 776

Note: currency exchange used 1USD-1.18EUR

[29] https://ec.europa.eu/agriculture/sites/agriculture/files/dashboards/tomato-dashboard_en.pdf
[30] https://www.trademap.org/Index.aspx
[31] https://comtrade.un.org/data/

Table 12. Top tomato importer countries according to the trade value in 2018. Sourced by UN Comtrade 2018.

Country	Type of tomato	Trade value (EUR)
United Kingdom	Fresh	825 927 645
United Kingdom	Vegetable preparations	306 380 459
United Kingdom	Sauces	225 475 011
Sweden	Fresh	200 713 808
Belarus	Fresh	137 534 546
Switzerland	Fresh	101 535 127
Denmark	Fresh	87 590 045
Finland	Fresh	74 724 789
Ireland	Fresh	64 095 065
Switzerland	Sauces	54 381 963
Mexico	Sauces	53 602 949
Portugal	Fresh	51 967 124

Note: currency exchange used 1USD-1.18EUR

S5d scenario, involving a 50% reduction of tomato products import from countries other than EU28 has a negative impact in territory base and consumption base. When looking at the Europe aggregate value indicated in Figure 17, there is a clear demand for tomato by Europe, which cannot be satisfied by European production. This means that if Europe wants to keep the consumption level, it is not feasible nowadays to reduce the import of tomato. Data from Comtrade 2018 reveals that 8 of the most exported products in terms of EUR are from European countries in the top 10 of tomato exporters, while 9 out of 10 most imported products are from European countries.

Another source indicates that EU production of fresh tomatoes is expected to remain relatively stable between 2017 and 2030 (-1.4%), compared to the average for 2014-2016. While the production area is expected to decrease, the average yields of fresh tomatoes are increasing, driven by an extension of productive seasons in all regions of production. Fresh tomato consumption in Europe is expected to go slightly down while processed tomatoes are expected to marginally grow due to the higher demand under the rise of the Mediterranean diet[32].

5.4.5 Dietary structure change

Starting from the best reduction scenario, the greatest difference compared to the base scenario was reported in S7, which comprises a dietary change by decreasing the tomato product consumption by 20%. Tomato consumption in Europe accounts for about 34.2 kg per capita in 2017[33]. In particular, this product is quite important in the Mediterranean diet followed by some of the most important producing countries.

From a nutritional perspective, finding a vegetable/fruit with the same nutritional value and cooking versatility as tomato might be difficult. Tomatoes are very rich in Vitamin C and carotenoids, a combination not easy to find in a single product. Medical studies have found some shreds of evidence between lycopene consumption, an antioxidant carotenoid abundant in tomatoes, and certain cancer reduction or better treatment performances. The properties of lycopene have been also discussed in a report[34] from REFRESH, highlighting its potentials in reducing risks of cardiovascular disease, hypertension, and epithelial cancer. Additionally, tomato is the most consumed product in Europe under the "fruit vegetables" categories, including peppers, chillies, aubergines, legumes, squashes, and pumpkins[35].

If the price is analysed, the cost of 1kg of tomato in the European Countries for 2016-2018 was about 0.89 EU[36], similar to substitute products such as mandarins (a product with high content of vitamin C) or watermelon (a product with a high level of lycopene). Thus, if the cooking versatility (and properties) of tomato are not considered but only its nutritional profile is, other products could behave as substitute products without having any effect at costing level for consumers. On the other hand, analysis of the performance of those products fulfilling the tomato substitution should be made, as tomato is strongly present in certain diets. The fact that tomatoes are often grown in greenhouses is an element which should be considered, as some top tomato countries producers (as Netherlands or Belgium) would not be able to currently compete with the mentioned substitute products. This element should be considered if the scenario S7 is adopted.

Finally, beyond the need to substitute several nutritional benefits of tomatoes, also cultural constraints might hinder the achievement of the modelled scenario (S7).

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[32] https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/farming/documents/agricultural-outlook-2017-30_en.pdf
[33] https://ec.europa.eu/agriculture/sites/agriculture/files/dashboards/tomato-dashboard_en.pdf
[34] https://eu-refresh.org/sites/default/files/D6.10%20REFRESH%20_FORKLIFT_Annexes%20.pdf
[35] http://www.fruitnet.com/live/article/175295/what-next-for-the-european-tomato-trade
[36] https://ec.europa.eu/agriculture/markets-and-prices/price-monitoring/monthly-prices_en

5.5 Policy implications

Our mapping of the mass flow of EU tomato supply chain provides a detailed understanding of the whole system efficiency of fresh tomatoes and tomato products and the generation and destination (e.g., waste valorisation) of tomato losses and waste. The study also presents the comparison of the effects of different GHG emissions mitigation strategies based on different scenario analysis covering production efficiency, process optimization, food waste reduction, trade pattern change, and diet structure change. The mapping also reveals the magnitude of the main tomato-production countries, data gaps to be addressed, and future research directions.

Our results on mass flows show that the largest contributor of tomato losses and waste were the processing and consumption stages. It can be explained by that a large number of fresh tomatoes are used for processing (57%). The production of tomato products relates to sorting, peeling, steaming, dicing, and canning stages, which would result in peels and some pulp discarded. Tomato waste at the consumption stage should also be paid attention to, especially for fresh tomatoes, which accounted for about 60% of the total tomato waste at this stage.

Our results on GHG emissions show that reducing the consumption of tomato or tomato products, improving tomato cultivation efficiency, and shifting from greenhouse to open-field would be the three most promising measures to mitigate GHG emissions along the entire tomato supply chain. EU28's tomato production greatly relies on greenhouse. This means halting import of tomato or tomato products would not reduce GHG emissions, because this would lead to an increase in domestic tomato production. Therefore, reducing export of tomato or tomato products could significantly contribute to GHG emission reduction as well.

Furthermore, a moderate GHG reduction potential is observed at reducing tomato waste from the retailing and consumption stages. A reduced amount of waste from these stages could be achieved by waste prevention measures, such as buying on demand, better planning or changed storage conditions. A further improvement potential is observed in the different waste management strategies of the countries. Tomato waste from retailing and consumption stages is often mixed with other municipal solid waste; thus, they are still sent to landfills in most of the EU-28 countries. Separate collection is the precondition for fostering high-quality recycling, especially for tomato wastes generated from the retailing and consumption stages. A door-to-door collection system, especially with a separate collection container of biodegradables, could significantly improve the separation rate of tomato wastes. This measure could also prevent cross-contamination with other materials (e.g., plastics, glass, and metals).

6 Conclusions

This report addressed mass, energy, and GHG emissions along the entire supply chain of two agri-food products. We identified five major reduction measures: production efficiency, process optimisation, food waste reduction, trade pattern change, and dietary structure change. Our results highlight that waste reduction could significantly reduce GHG emissions along the entire supply chain of an agri-food product.

In addition, the following specific key conclusions could be listed based on the scenarios assessed:

i) Our results highlight that waste reduction could significantly reduce GHG emissions along the entire supply chain. A reduction of food waste from retailing and consumption stages by half, as recommended in the SDGs, would reduce GHG emissions by approximately 11% in both case studies (Germany's meat supply chain and EU28's tomato supply chain). In addition, our results also show that if production can be decreased and resources can be used more efficiently, the considerable potential to Global Warming Mitigation could be achieved.

ii) Regarding tomatoes, Figure 16 shows that a majority of the GHG emissions of the EU tomato supply chain comes from greenhouse tomatoes. For meat, the majority of GHG emissions were also found in the production sector.

iii) Although GHG emissions of waste management are rather neglectable compared to emissions of the entire supple chain, large variations in GHG emissions exist within the different options of waste management (disposal versus recycling options). Landfilling is next to incineration with energy recovery the most used option for household and similar waste from commerce. Considering the fact that the capture rate of separate collection of bio-degradable is still low in EU-28, most of the biodegradable waste that has been lost is suitable for recycling (composting or anaerobic digestion). From an economic point of view, landfilling is furthermore linked with costs for the waste owner (e.g. landfill tax), which would also favour the opportunity to reduce the amount of waste going to landfill. The capture rate of biodegradable waste needs to be increased in order to prevent them from being landfilled.

iv) Dietary structure change leading to a reduced meat or tomato consumption is the most promising scenario to reduce GHG emissions if assumed that a reduced consumption of meat or tomato means a reduced production of them. However, the market consequences of a dietary structure change can have multiple effects, which are not easy to predict.

v) The assumptions made in this report and related conclusions are subject to several limitations which needs to be taken into consideration and further looked into:
   - In practice, a reduced consumption does not necessarily imply a reduced production. It leads to a better distribution or decrease in price.
   - Effects on other systems are not included since a static background system has been assumed.
   - Nutritional aspects are not taken into account. It is uncontroversial that meat or tomato products are of nutritional value for humans. Yet, it is controversial that we need meat on a daily basis and fresh tomatoes all year round. Further, if we consider how much GHG emissions come together with the production of one kg meat, we shall use the resource meat with more caution.
   - It would be beneficial to know what the driver of the production in greenhouses is. Is it due to controlled conditions, which allow a more

efficient production, or is it due to the demand of fresh tomatoes in Europe all year round? It is probably a combination of both. However, it can be recommended that heated greenhouses shall be supplied with renewable energy instead of fossil energy and that the consumption of fresh tomatoes shall be limited to seasonal supply.

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8 Annex

8.1 Additional figures of German meat case

8.1.1 Data uncertainty

Stages	Data type	Description	Cattle	Pork	Poultry
Production	Statistic	Carcass weight (CW) in production			
	Statistic	Average weight of animal (CW)			
	Coefficient	Relation of CW to LW			
	Coefficient	Relation of offal to LW			
	Coefficient	Animal death ratio			
	Coefficient	Lifetime of animal			
	Coefficient	Manure production per animal			
	Coefficient	Water content of meat			
	Coefficient	Water content of byproducts			
	Coefficient	Ratio of the feed input energy to meat product			
	Coefficient	Ratio of feed in total energy input in animal husbandry			
	Coefficient	Energy equivalent for CW			
	Coefficient	Energy equivalent for offal			
	Coefficient	Energy equivalent for byproducts			
	Coefficient	Energy equivalent of manure (MJ/t)			
	Coefficient	Meat production emission intensity of Germany			
Animal market	Statistic	Trade of animal in CW			
	Coefficient	Meat production emission intensity of trade countries			
Slaughtering	Statistic	CW in slaughtering			
	Statistic	CO_2 emission factor for the electricity mix			
	Coefficient	Energy use in slaughtering (MJ/t)			
	Coefficient	CO_2 emission factor for natural gas			
	Coefficient	CO_2 emission factor for fossil fuel			
Meat processing	Coefficient	Relation of LW to meat for human consumption			
	Coefficient	Energy use in meat processing (MJ/t)			
	Coefficient	Energy equivalent of meat products			
Meat products market	Statistic	Trade of meat products			
	Coefficient	Energy equivalent of meat products			
	Coefficient	Emission intensity of meat products in trade countries			
Retailing	Coefficient	Meat waste rate in retailing			
	Coefficient	Energy use in retailing (MJ/t)			
Consumption	Coefficient	Meat consumption ratio in household			
	Coefficient	Meat consumption ratio out-of-home			
	Coefficient	Meat waste rate in household			
	Coefficient	Meat waste rate out-of-home			
	Coefficient	Energy use in household (MJ/t)			
	Coefficient	Energy use out-of-home (MJ/t)			
Valorization and Waste management	Coefficient	Ratio of manure for agriculture utilization			
	Coefficient	Ratio of manure for biogas production			
	Coefficient	Ratio of meat waste for incineration			
	Coefficient	Ratio of meat waste for composting			
	Coefficient	Ratio of meat waste for biogas production			
	Coefficient	Ratio of 3 animal byproducts categories			
	Coefficient	Protein/fat content in 3 animal byproducts categories			
	Coefficient	Utilization rate of byproducts protein/fat in rendering			
	Coefficient	Biogas yield from manure (m^3/t)			
	Coefficient	Biogas density (kg/m^3)			
	Coefficient	Biogas energy equivalent (MJ/m^3)			
	Coefficient	Efficiency of biogas plant			
	Coefficient	Yield from by-products fat to biodiesel			
	Coefficient	Biodiesel energy equivalent (MJ/L)			
	Coefficient	Energy content of fat			
	Coefficient	Energy content of protein			
	Coefficient	CO_2 emission factor for soybean meal			
	Coefficient	CO_2 emission factor for palm oil			
	Coefficient	CO_2 emission factor for fossil fuel			
	Coefficient	CO_2 emission factor for incineration			
	Coefficient	CO_2 emission factor for composting			
	Coefficient	Electricity energy yield from byproducts incineration (MJ/kg)			
	Coefficient	Heating energy yield from byproducts incineration (MJ/kg)			
	Coefficient	Electricity energy yield from biogas (MJ/kg)			
	Coefficient	Heating energy yield from biogas (MJ/kg)			

Figure A1. Qualitative uncertainties of the data used in the paper based on three levels (low, medium, and high).

Note: Low uncertainty is shown in dark green, medium uncertainty is shown in light green, while high uncertainty is shown in yellow.

Stages		Mass flow	Cattle	Pork	Poultry	Energy flow	Cattle	Pork	Poultry
Production	A0,1a					Energy equivalent of Feed			
	A1,2	Live animal				Energy equivalent of live animals (DM equivalent)			
	A1,8	Manure production in total				Energy equivalent of manure			
	A1,9	Dead animal				Energy equivalent of dead animals (DM equivalent)			
	A1,0a	Animal respiration				Animal respiration			
Animal market	A0,2	Imported live animals				Energy equivalent of imported live animal (DM equivalent)			
	A2,0	Exported live animals				Energy equivalent of exported live animal (DM equivalent)			
Slaughtering	A3,4	CW				Energy equivalent of CW (DM basis)			
	A3,9	Animals byproducts in slaughtering				Energy equivalent of animals byproducts in slaughtering			
Meat processing	A4,5	Meat products for human consumption				Energy equivalent of meat byproducts for human consumption			
	A4,9	Meat byproducts in processing				Energy equivalent of meat byproducts in processing			
Meat products market	A0,5	Imported meat products				Energy equivalent of imported meat byproducts			
	A5,0	Exported meat products				Energy equivalent of exported meat byproducts			
Retailing	A6,7	Meat products for consumption				Energy equivalent of meat products for consumption			
	A6,10	Wasted meat products in retailing				Energy equivalent of wasted meat products in retailing			
Consumption	A7,0a	Meat consumption in household				Energy equivalent of meat products consumed in household			
	A7,0b	Meat consumption out-of-home				Energy equivalent of meat products consumed out-of-home			
	A7,10a	Wasted meat in household				Energy equivalent of wasted meat in household			
	A7,10b	Wasted meat out-of-home				Energy equivalent of wasted meat out-of-home			
Valorization and Waste management	A8,11	Manure for agriculture use				Energy equivalent of manure for agriculture use			
	A8,18	Manure for biogas production				Energy equivalent of manure for biogas production			
	A9,12	Byproducts for food production				Energy equivalent of byproducts for food production			
	A9,13	Byproducts for feed production				Energy equivalent of byproducts for feed production			
	A9,14	Byproducts for industry use				Energy equivalent of byproducts for industry use			
	A9,15	Byproducts for biodiesel production				Energy equivalent of byproducts for biodiesel production			
	A9,16	Byproducts for incineration				Energy equivalent of byproducts for incineration			
	A10,16	Meat waste for incineration				Energy equivalent of wasted meat for incineration			
	A10,17	Meat waste for composting				Energy equivalent of wasted meat for composting			
	A10,18	Meat waste for biogas prodcution				Energy equivalent of wasted meat for biogas production			
	A15,0a	Biodiesel production				Energy equivalent of biodiesel			
	A15,0b	Mass loss in biodiesel production				Lost energy in biodiesel production			
	A18,0h	Biogas from manure				Energy equivalent of biogas from manure			
	A18,0i	Biogas from meat waste				Energy equivalent of biogas from meat waste			
	A18,0b	Mass loss in biogas production				Lost energy in biogas production			

Figure A2. Qualitative uncertainties associated to mass flow and energy flow based on three levels (low, medium, and high).

Note: Low uncertainty is shown in dark green, medium uncertainty is shown in light green, while high uncertainty is shown in yellow.

Stages	GHG emissions	Cattle	Pork	Poultry	Valorization and Waste management	
Production	GHG emissions in production				Rendering emissions from food production	
Animal market	GHG emissions embedded in animal trade				Reduction of emissions from feed production	
Slaughtering	GHG emissions in slaughtering				Rendering emissions from biodiesel production	
Meat processing	GHG emissions in meat processing				Reduction of emissions from biogas production	
Meat products market	GHG emissions embedded in meat products trade				Rendering emissions from incineration	
Retailing	GHG emissions in meat retailing				Rendering emissions from composting	
Consumption	GHG emissions in household				GHG emissions from soymeal production	
	GHG emissions out-of-home				GHG emissions from palm oil production	
Live animals Trade	Embodied emissions in import				GHG emissions from fossil fuel production	
	Embodied emissions in export				Avoided emissions from biogas production	
Meat products trade	Embodied emissions in import				Avoided emissions from incineration	
	Embodied emissions in export				Avoided emissions from composting	

Figure A3. Qualitative uncertainties associated to GHG emissions based on three levels (low, medium, and high).

Note: Low uncertainty is shown in dark green, medium uncertainty is shown in light green, while high uncertainty is shown in yellow.

8.1.2 Scenarios for CW reduction

As to the total meat carcass weight (CW) produced, the greatest difference to the base scenario can be seen in the scenario was the reduction of meat consumption by 50% (S6) with 42% reduction of the original CW. The next best scenario was reducing meat waste in retailing as well as consumption (S4c) by 50%, consequently, 13.1% reduction of the original CW was produced. When less offal was thrown away by 50% and consumed as food (S8), 13% of reduction of the original CW. Improving the efficiency by 20% in slaughtering and meat processing (S3c) would result in 74, 185, and 58 kt cattle, pig and poultry CW less produced, respectively. When the process of slaughtering and processing were optimized and less energy was consumed (S2c), there was no impacts on the production of meat but has significant impacts on the GHG emissions. Live animal and meat products trade are important in the meat supply chain. However, when stopping the import of these goods (S5a, S5d) from the top 3 GHG emissions partners, the production of meat would increase by 7% and 19% to the base scenario, respectively. Reducing beef consumption (S7) by 25% would result in reducing the total CW by 1% when the total energy consumed was kept constant. Consequently, pork and poultry production would increase by 2% and 3%, respectively (Figure A4, A5).

Reduction scenarios		Low					Medium					High				
		%	Cattle	Pork	Poultry	Total	%	Cattle	Pork	Poultry	Total	%	Cattle	Pork	Poultry	Total
S1	Emission intensity	-5	0	0	0	0	-10	0	0	0	0	-20	0	0	0	0
S2a	Slaughtering PE	-5	0	0	0	0	-10	0	0	0	0	-20	0	0	0	0
S2b	Processing PE		0	0	0	0		0	0	0	0		0	0	0	0
S2c	S2a + S2b		0	0	0	0		0	0	0	0		0	0	0	0
S3a	Slaughtering byproducts	-5	-4	-2	-2	-2	-10	-7	-3	-4	-4	-20	-14	-6	-8	-7
S3b	Processing byproducts		-3	-2	-1	-1		-5	-3	-2	-3		-10	-6	-3	-6
S3c	S3a + S3b		-6	-3	-3	-3		-12	-6	-5	-7		-22	-11	-10	-13
S4a	Retail waste	-10	0	0	0	0	-25	-1	-1	-1	-1	-50	-2	-1	-2	-1
S4b	Consumption waste		-3	-2	-3	-3		-8	-6	-8	-6		-14	-11	-14	-12
S4c	S4a + S4b		-4	-3	-4	-3		-8	-6	-8	-7		-15	-12	-16	-13
S5a	Animal import	-25	0	2	1	2	-50	0	5	2	3	-100	0	9	4	7
S5b	Animal export		-3	0	-7	-2		-3	0	-7	-2		-4	0	-7	-2
S5c	S5a + S5b		-3	2	-6	0		-3	4	-5	1		-3	9	-4	5
S5d	Meat products import		6	3	9	5		13	6	17	9		26	12	34	19
S5e	Meat products export		-1	-4	-2	-3		-3	-8	-4	-6		-5	-17	-7	-13
S5f	S5d + S5e		5	-1	7	1		10	-2	14	3		20	-5	27	6
S5g	S5c + S5f		2	1	1	1		7	2	8	4		17	4	24	10
S6	Meat consumption	-10	-10	-7	-10	-8	-25	-25	-19	-25	-21	-50	-49	-37	-50	-42
S7	Beef consumption	-5	-5	0	1	0	-10	-10	1	1	0	-25	-25	2	3	-1
S8	Offal thrown away	-10	-6	-2	-1	-3	-25	-14	-6	-3	-6	-50	-28	-12	-6	-13

Figure A4. Different scenarios of the production of CW changes.

Note: Negative values mean the reduction percentage compared to the reference scenario, positive values mean the increase to the baseline.

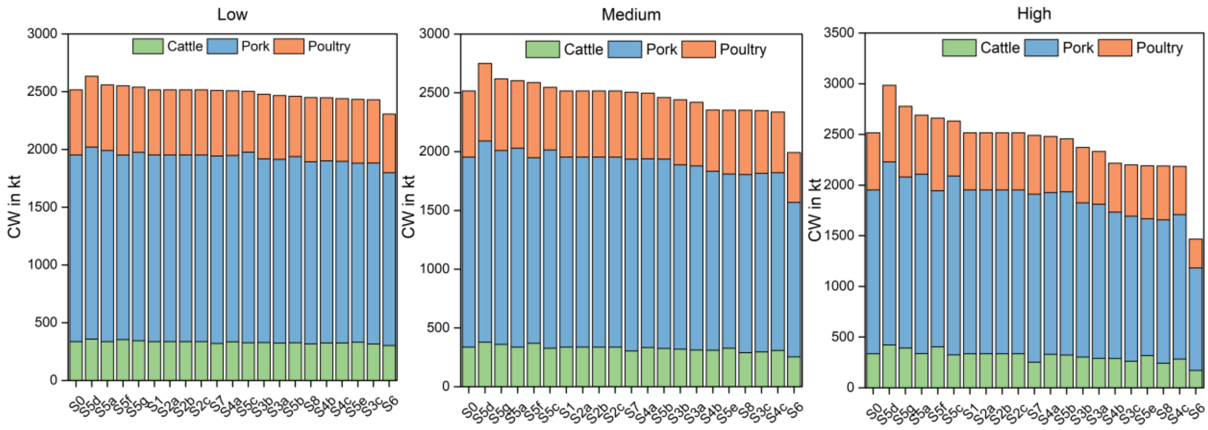

Figure A5. The changes of the amount of CW production under three levels (low, medium, and high).

Note: S0: Baseline scenario, S1: Production emission intensity, S2a: Slaughtering PE , S2b: Processing PE, S2c: Slaughtering and processing PE, S3a: Slaughtering byproducts, S3b: Processing byproducts, S3c: Slaughtering and processing byproducts, S4a: Retailing waste, S4b: Consumption waste, S4c: Retailing and consumption waste, S5a: Animals import from the top 3 GHG emission partners, S5b: Animals export to non-EU countries, S5c: S5a + S5b, S5d: Meat products import from the top 3 GHG emission partners, S5e: Meat products export to non-EU countries, S5f: S5d + S5e, S5g: S5c + S5f, S6: Meat consumption, S7: Beef consumption, S8: Offal consumed as food less thrown away. PE: process energy.

8.1.3 Territory-based accounting of GHG emissions reduction of German meat case

Figure A6 shows the changes of total GHG emissions along the whole meat supply chain based on the territory-based accounting. The greatest difference to the base scenario was reducing meat consumption by 50% (S6), which resulted in a 44% reduction of the emissions (12% higher than the consumption-base accounting). When reducing offal that was throw away by 50% and consumed as food (S8), it showed the second largest reduction potential or 18.8% of the original GHG emissions (5% higher than the consumption-base accounting). Reducing GHG emissions intensity in production (S1) by 20% (S1) almost had the same reduction potential or 18.6% of the original GHG emissions (6% higher than the consumption-base accounting). Different from the consumption-based accounting, halting the import of live animals from the top 3 GHG emission countries (S5a) showed an increase of GHG emissions by 4% (decreasing in consumption-based accounting), due to the increase of domestic meat production. When halting the trade of animals and meat products (importing from the top 3 GHG partners and exporting to non-EU 28 countries), the GHG emissions would increase by 11%. The other scenarios showed a similar trend in both accounting.

Reduction scenarios		Low %	Low Cattle	Low Pork	Low Poultry	Low Total	Medium %	Medium Cattle	Medium Pork	Medium Poultry	Medium Total	High %	High Cattle	High Pork	High Poultry	High Total
S1	Emission intensity	-5	-5	-5	-4	-5	-10	-10	-9	-8	-9	-20	-20	-18	-16	-19
S2a	Slaughtering PE	-5	0	0	0	0	-10	0	0	-1	0	-20	0	-1	-1	0
S2b	Processing PE		0	0	0	0		0	0	-1	0		0	-1	-1	-1
S2c	S2a + S2b		0	0	-1	0		0	-1	-1	0		0	-1	-2	-1
S3a	Slaughtering byproducts	-5	-4	-1	-2	-3	-10	-7	-3	-3	-5	-20	-14	-6	-7	-9
S3b	Processing byproducts		-3	-1	-1	-2		-5	-3	-1	-4		-10	-6	-3	-7
S3c	S3a + S3b		-6	-3	-2	-4		-12	-6	-5	-8		-22	-11	-9	-16
S4a	Retail waste	-10	0	0	0	0	-25	-1	-1	-1	-1	-50	-2	-1	-2	-1
S4b	Consumption waste		-3	-2	-3	-3		-8	-6	-8	-7		-14	-11	-15	-13
S4c	S4a + S4b		-4	-3	-4	-3		-8	-6	-9	-8		-15	-12	-16	-14
S5a	Animal import	-25	0	2	1	1	-50	0	4	1	2	-100	0	9	3	4
S5b	Animal export		-3	0	-6	-2		-3	0	-6	-2		-4	0	-6	-2
S5c	S5a + S5b		-3	2	-5	-1		-3	4	-4	0		-3	8	-3	2
S5d	Meat products import		6	3	8	5		13	6	16	10		25	11	32	20
S5e	Meat products export		-1	-4	-2	-3		-3	-8	-3	-5		-5	-16	-7	-10
S5f	S5d + S5e		5	-1	6	2		10	-2	13	5		20	-5	26	9
S5g	S5c + S5f		2	1	1	2		7	2	8	5		17	4	23	11
S6	Meat consumption	-10	-10	-7	-10	-9	-25	-25	-19	-25	-22	-50	-49	-37	-50	-44
S7	Beef consumption	-5	-5	0	1	-2	-10	-10	1	1	-4	-25	-25	2	3	-10
S8	Offal thrown away	-10	-6	-2	-1	-4	-25	-14	-6	-3	-9	-50	-28	-12	-6	-19

Figure A6. Different scenarios of GHG emissions in a territory-based accounting.

Note: Negative values mean the reduction percentage compared to the reference scenario, and positive values mean the increase percentage relative to the baseline.

8.2 Data used in the German meat case

Table A1: Animals production, trade & meat products trade

	Live animals			Meat and meat products		
	Production	Import	Export	Import	Export	Average CW per animal
	1000t			1000t		kg
Cattle	1186.4	19.0	66.0	460.0	443.8	337.1
Pig	4984.8	665.2	74.5	1050.0	2500.0	94.9
Chicken	1312.6	69.5	370.6	670.0	580.0	1.3
Turkey	408.7	80.0	1.6	180.5	163.5	12.9
Duck	49.5	0.0	3.7	49.0	16.7	2.2
Goose	5.1	0.0	0.0	36.5	4.6	5.0

Data sources	Federal Agency for Agriculture and Food (BLE)[37]

Note: The amount of meat production given in carcass weight (CW).

Table A2: Relation of CW to Live weight (LW)

Animal	Relation in %	Reference
Cattle	60.0	(Lesschen et al., 2011)
Pig	70.0	
Chicken	66.0	(Hahn, 2008)
Turkey	73.5	
Duck	68.6	
Goose	67.0	

Table A3: Relation of innards to LW

Animal	Relation in %	Reference
Cattle	16.0	(Schmidt, 2011)
Pig	15.0	
Chicken	4.0	(Hahn, 2008)
Turkey	3.3	
Duck	5.2	
Goose	6.2	

Table A4: Water content of meat products and by-products

Animal	Meat products (%)	Reference	By-products (%)	Reference
Beef	71.7	European Food	38	Servicegesellschaft Tierische Nebenprodukte mbH[39]
Pork	67.6		38	
Chicken	67.3		38	

[37] https://www.ble.de/DE/BZL/Daten-Berichte/Fleisch/fleisch_node.html?cms_gts=9091262_list%253DdateOfIssue_dt%252Basc/

[39] http://www.stn-vvtn.de/fakten_zahlen.php/

Turkey	72.1	Information Resource[38]	38
Duck	63.7		38
Goose	52.4		38

Table A5: Death rate of each animal

Animal	Death rate (%)	Reference
Cattle	2.5	(Heinrich-Böll-Stiftung, 2014)
Pig	3.3	
Chicken	3.9	
Turkey	3.5	
Duck	3.0	
Goose	3.5	

Note: Here we only considered the death rate in animal rearing.

Table A6: Lifespan of animals

Animal	lifespan (yr)	Reference
Cattle	1.58	Swissveg website[40]
Pig	0.42	
Chicken	0.11	
Turkey	0.21	
Duck	0.29	
Goose	0.31	

Table A7: Manure production of animals

Animal	Kg (DM)/day	kg (DM)/yr	Reference
Cattle	2.71		(Haenel et al., 2018)
Pig	0.3		(Haenel et al., 2018)
Chicken		5	(FAO Nutrients in livestock wastes) [41]

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38 http://www.eurofir.org
40 http://www.swissveg.ch/life_expectancy?language=en/
41 http://www.fao.org/docrep/004/x6518e/x6518e01.htm/

Turkey	8.5	(Haenel et al., 2018)
Duck	5	(FAO Nutrients in livestock wastes)
Goose	8.5	(Haenel et al., 2018)

Table A8: Share of each by-product category in slaughtering

By-products	Cat 1	Cat 2	Cat 3	EAF	Reference
Cattle	43.5	0.0	51.1	5.4	(Schmidt, 2011)
Pig	0.0	17.4	74.7	7.9	
Poultry	0.0	0.0	90.4	9.6	

Note: The share of different by-products categories was calculated based on the share of three categories from (Schmidt, 2011) and the quantity of three by-products categories and EAF from STN (https://www.stn-vvtn.de/fakten_zahlen.php), assuming that EAF was a part of cat 3.

Table A9: Relation of meat for human consumption to LW

Animal	Meat for human consumption to LW (%)	Reference
Cattle	38.0	(Schmidt, 2011)
Pig	62.0	(Schmidt, 2011)
Chicken	58.0	(Heinrich-Böll-Stiftung, 2014)
Turkey	66.0	(Schmidt, 2011)
Duck	62.0	(Heinrich-Böll-Stiftung, 2014)
Goose	62.0	(Heinrich-Böll-Stiftung, 2014)

Table A10: Meat waste rate in retailing

Reference	Meat wasted ratio (%)
(Noleppa and Cartsburg, 2015)	4.0
(Kreyenschmidt, 2013)	4.0
(EHI Retail Institute, 2011)	2.1
Average	3.4

Table A11: Separation of meat consumption for household and out-of-home

Reference	Household	Out of home

(Noleppa and Cartsburg, 2015)	68.0	32.0
(Kranert et al., 2012)	78.0	22.0
(Eberle and Fels, 2016a)	81.0	19.0
Average	75.7	24.3

Table A12: Meat waste rate in consumption

	Meat wasted ratio (%)	Reference
Household	21.7	(Göbel et al., 2015)
Out-of-home	34.6	(Göbel et al., 2015)

Table A13: Ratio of protein, fat and other content from by-products

Byproducts	Protein %	Fat %	Other %	Reference
Cat 1	61.9	34.3	3.8	(Dienstleister zur Sicherung des Gesundheits- und Umweltschutzes, 2016)
Cat 2	62.5	33.6	3.9	
Cat 3	57.8	39.2	3.0	
EAF	28.9	69.7	1.4	

Table A14: Utilization rate of protein and fat for different industries

Byproducts	Food production	Feed production	Industry use	Biodiesel production	Incineration	Reference
Cat 1 Protein	0.00	0.00	0.00	0.00	100.00	(Dienstleister zur Sicherung des Gesundheits- und Umweltschutzes, 2016)
Cat 2 Protein	0.00	0.00	100.00	0.00	0.00	
Cat 3 Protein	0.01	82.41	17.57	0.00	0.00	
EAF Protein	0.01	82.41	17.57	0.00	0.00	
Cat 1 Fat	0.00	0.00	3.49	95.53	0.98	
Cat 2 Fat	0.00	0.00	0.00	100.00	0.00	
Cat 3 Fat	0.00	20.02	47.45	32.51	0.02	
EAF Fat	8.89	49.89	23.03	18.19	0.00	

Table A15: Biogas yield from manure

	Unit	Cattle	Pig	Poultry	Reference

Biogas/manure	m³/t	25	30	80	(Gülzow and Fermentervolumens, 2005)
Biogas density	kg/m³		1.125		(Wojciechowski and Ueth, 2012)
Energy equivalent of biogas	kwh/m³		6		(Gülzow and Fermentervolumens, 2005)

Table A16: Biodiesel coefficient

	Beef	Pork	Poultry	Reference
Yield from by-products fat to biodiesel (%)	90.8	91.4	76.8	(Mata et al., 2014)
Heating value (MJ/kg)	40	39.9	39.4	

Table A17: Efficiency of incineration, biodiesel production and biogas production

	Efficiency in %	Reference
Incineration	35	Berliner Abfallacheck website[42]
Biogas production	43	(Biogasanlagen Völklingen, 2008)

Table A18: Share of feed in energy input of animal production

	Beef	Pork	Poultry	Reference
Feed in %	88	69	71	(Woods et al., 2010)

Table A19: Energy equivalent of manure

Animal	Energy equivalent in MJ/t (Gross calorific value, DM basis)	Reference
Cattle	13261	Manure as Fuel Homepage[43]
Pig	16603	eXtension website[44]

42 http://www.berliner-abfallcheck.de/node/36/
43 http://large.stanford.edu/courses/2010/ph240/birer1/
44 http://articles.extension.org/pages/27469/energy-and-nutrient-recovery-from-swine-manures/

Poultry	6400	Livestock manure to energy[45]

Table A20: Energy equivalent of CW

Animal	Energy equivalent in MJ/t	Reference
Cattle	27150	(Holttinen, 2011)
Pig	27550	(Holttinen, 2011)
Poultry	25732	(Wiersnusz, C.J.; Park, B.C.; Teeter, n.d.)

Table A21: Energy equivalent of innards

Animal	Energy equivalent in MJ/t	Reference
Cattle	5810	Nährwertrechner.de website[46]
Pig	4880	
Chicken	8120	Kalorientabelle.net website[47]
Turkey	5400	
Duck	5690	
Goose	5570	

Table A22: Energy equivalent of meat products

Animal	Energy equivalent in MJ/t	Reference
Cattle	5785	(Fries et al., 2001)
Pig	7350	
Chicken	4850	
Turkey	5020	
Duck	5510	
Goose	6760	

45 https://www.agropark.dk/admin/public/download.aspx?file=/Files/Files/ecom/products/Biogas-Go-Global/Livestock-Manure-to-Energy.pdf
46 https://www.naehrwertrechner.de/naehrwerte/Schwein+Innereien+frisch/
47 http://www.kalorientabelle.net/fleisch/innereien/

Table A23: Energy equivalent of protein and fat

	Energy equivalent in MJ/t	Reference
Protein	17000	(Gehring, 2017)
Fat	37000	

Table A24: Process energy in slaughtering and meat processing

	Animal	Fossil fuel (MJ/t)	Natural gas (MJ/t)	Electricity (MJ/t)	Total (MJ/t)	Reference
Slaughtering	Beef	15	596	390	1001	BMEL website[48]
	Pork	15	596	390	1001	
	Poultry	69	488	947	1504	
Processing			867	759	1627	
Retail			300	400	700	(Eberle and Fels, 2016b)
Household					519	(Beretta et al., 2017)
Food service					3470	

Table A25: GHG emissions factor in production in Germany

	CO_2 eq/kg CW	Reference
Beef	26.4	(Lesschen et al., 2011)
Pork	5.0	
Poultry	2.5	

Table A26: GHG emissions factor for energy

	Unit	CO_2 eq	Reference
Fossil fuel	g/L	3178	IINAS website[49]
Natural gas	g/kWh	264	Ditto

48 https://ec.europa.eu/food/safety/animal-by-products/eu-rules_en/
49 http://iinas.org/gemis-download.html

Electricity	g/kWh	527	Statista, 2018[50]

Table A27: The share of imported live animals and GHG emission factors in production

Cattle			Pig			Poultry		
Country	Percentage	kg CO_2 eq/kg	Country	Percentage	kg CO_2 eq/kg	Country	Percentage	kg CO_2 eq/kg
Czech Republic	38.15	29.60	Netherlands	70.88	6.30	Denmark	28.30	1.87
France	15.12	25.52	Denmark	24.21	3.43	Netherlands	26.31	3.52
Netherlands	13.45	37.33	Belgium	2.23	4.68	Poland	16.83	2.89
Luxembourg	9.99	22.60	Czech Republic	0.75	3.82	France	9.77	1.77
Austria	8.18	25.03	Luxembourg	0.74	3.50	Czech Republic	9.72	1.24
Estonia	3.70	39.68	Poland	0.56	3.50	Austria	4.62	1.56
Latvia	2.89	25.97	France	0.46	3.74	Hungary	1.89	2.29
Belgium	2.54	27.53	Hungary	0.14	5.51	Belgium	1.55	1.24
Poland	2.08	36.20	Slovakia	0.01	2.66	Switzerland	0.81	1.60
Lithuania	1.80	21.68	Croatia	0.01	3.50	Sweden	0.17	1.32
Romania	0.65	25.36	Spain	0.01	3.63	UK	0.03	1.90
UK	0.64	28.18	Austria	0.00	3.12	Italy	0.00	1.80
Denmark	0.48	19.64	Italy	0.00	4.78	Spain	0.00	1.44

[50] https://de.statista.com/statistik/daten/studie/38897/umfrage/co2-emissionsfaktor-fuer-den-strommix-in-deutschland-seit-1990/

Switzerland	0.19	22.60	Switzerland	0.00	3.50
Slovakia	0.07	23.14	Norway	0.00	3.50
Italy	0.05	29.27			
Croatia	0.03	22.60			

Note: The share of imported live animals are calculated based on the UN-Comtrade database. The GHG emission factors are adopted from (Lesschen et al., 2011).

Table A28: The GHG emission factors for the imported meat products from the top 3 GHG emission partners and other countries

	The top 3 GHG emissions and other countries	Animal production (kg CO_2 eq/kg)	Reference	Meat processing (kg CO_2 eq/kg)	Reference
Beef	Brazil	48.0	(Bellarby et al., 2013)	0.49	(Scherhaufer et al., 2018)
	Netherlands	37.3	(Lesschen et al., 2011)		
	Poland	36.2			
	Others	28.0	(Scherhaufer et al., 2018)		
Pork	Netherlands	6.3	(Lesschen et al., 2011)	0.20	
	Italy	4.8			
	Belgium	4.7			
	Others	5.9	(Scherhaufer et al., 2018)		
Poultry	Netherlands	3.5	(Lesschen et al., 2011)	0.21	
	Poland	2.9			
	Hungary	2.3			
	Others	3.0	(Scherhaufer et al., 2018)		

Table A29: GHG emission factors for byproducts and waste treatment

Waste management	Rendering emissions	Reference	Substitution	Avoided emissions factor	Reference

	factor (kg CO_2-eq/kg)			(kg CO_2-eq/kg)	
Food production	0.26	(European Commission, 2006b)	Palm oil	0.98	(Reijnders and Huijbregts, 2008)
Feed production	0.26		Soybean meal	1.08	(Dalgaard et al., 2008)
Biodiesel production	1.07	(Barber et al., 2007)	Fossil fuel	3.80	(Barber et al., 2007)
Incineration	0.26	(European Commission, 2006b)	Electricity	0.19	(Beretta et al., 2017)
			Heating	0.18	
Biogas from manure	0.24	(Börjesson and Berglund, 2006)	Electricity	0.48	(Schleiss, 2008)
Biogas from waste	0.35		Heating	0.72	
Composting	0.12	(California Environmental Protection Agency, 2011)	Fertilizer	0.42	(California Environmental Protection Agency, 2011)

Table A30: Share of live animals and meat products exported to EU 28 and non-EU 28 countries

	EU 28 (%)	Non-EU 28 (%)
Live animals		
Cattle	65.0	35.0
Pig	95.9	4.1
Poultry	99.9	0.1
Meat products		
Beef	90.7	9.3
Pork	74.2	25.8
Poultry	86.1	13.9

Note: The share of exported live animals and meat products are calculated based on the UN-Comtrade database.

Table A31: The consumption, energy content, and GHG emission factor of soybeans and nuts in Germany

	Soybeans	Nuts	References
Consumption (kt)	554	72	FAOSTAT, 2013[51]
Energy content (kJ/100g)	601	2413	Vitamine homepage[52]
GHG emission factor (kg/kg)	0.49	1.2	(Clune et al., 2017)

8.3 Additional data and figures of EU tomato case

8.3.1 Emission factors

Table A32: Emission factors of tomato production and electricity mix

Country	Greenhouse	Field	Aggregate	Electricity mix
Austria	678.993797	80.69851692	675.5172309	0.164
Belgium	678.993797	80.69851692	678.9937969	0.226
Bulgaria	550.1711	80.69851692	243.554395	0.498
Croatia	550.1711	80.69851692	342.663072	0.233
Cyprus	537.574363	80.69851692	354.618841	0.649
Czechia	678.993797	80.69851692	80.69851692	0.521
Denmark	678.993797	80.69851692	678.9937969	0.174
Estonia	678.993797	80.69851692	678.9937969	1.026
Finland	678.993797	80.69851692	678.9937969	0.107
France	550.1711	80.69851692	435.3400385	0.046
Germany	678.993797	80.69851692	678.9937969	0.45

51 http://www.fao.org/faostat/en/
52 https://www.vitamine.com/lebensmittel/sojabohnen/

Greece	537.574363	80.69851692	223.7130029	0.584
Hungary	678.993797	80.69851692	80.69851692	0.274
Ireland	678.993797	80.69851692	678.9937969	0.418
Italy	537.574363	80.69851692	114.7934448	0.342
Latvia	678.993797	80.69851692	678.9937969	0.145
Lithuania	678.993797	80.69851692	518.3987481	0.186
Luxembourg	678.993797	80.69851692	678.9937969	0.281
Malta	537.574363	80.69851692	80.69851692	0.652
Netherlands	678.993797	80.69851692	678.9937969	0.489
Poland	678.993797	80.69851692	499.3009459	0.73
Portugal	537.574363	80.69851692	87.40926696	0.346
Romania	678.993797	80.69851692	219.1916233	0.34
Slovakia	678.993797	80.69851692	276.4410002	0.169
Slovenia	678.993797	80.69851692	276.4410002	0.265
Spain	546.581649	80.69851692	261.2160575	0.293
Sweden	678.993797	80.69851692	678.9937969	0.011
United Kingdom	678.993797	80.69851692	678.9937969	0.349

Note: Unit is kg CO_2/t

Table A33: Emission factors of tomato processing

Processing electricity (Unit: kWh/t)			Processing fuel (Unit: kg CO_2/t)		
Tomato sauce	Tomato whole or in pieces	Tomato juice	Tomato sauce	Tomato whole or in pieces	Tomato juice
67.11252533	70.84539663	88.8	124.915199	109.929132	-

Table A34: Emission factors of Postharvest handling & storage and retailing stages

Postharvest handling & storage (Unit: KWh/t)	Retailing (Unit: Kwh/t)
1.283910004	14.88333333

Table A35: Emission factors of top 5 vegetables

Top 5 vegetables	Production %	Energy (KJ/100g)	GHG emission factors (g/kg)
Cabbages and other brassicas	28%	107	107
Onions, dry	25%	135	181
Carrots and turnips	22%	111	373
Cucumbers and gherkins	15%	52	965
Pumpkins, squash and gourds	10%	89	605
Aggregate	-	104	364
Equivalent tomato	-	-	274

8.3.2 Split of different waste treatment options

Table A36: Waste treatment options in Belgium

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	0%	0%	0%	0%	60%	40%
Postharvest	0%	0%	0%	0%	60%	40%
Processing	0%	0%	0%	0%	60%	40%

Distribution	1%	2%	0%	85%	7%	5%
Retailing	1%	2%	0%	85%	7%	5%
Consumption	1%	2%	0%	85%	7%	5%

Table A37: Waste treatment options in Germany

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	0%	0%	0%	11%	72%	17%
Postharvest	0%	0%	0%	11%	72%	17%
Processing	0%	0%	0%	11%	72%	17%
Distribution	0%	8%	0%	64%	22%	5%
Retailing	0%	8%	0%	64%	22%	5%
Consumption	0%	8%	0%	64%	22%	5%

Table A38: Waste treatment options in Spain

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	4%	0%	0%	3%	74%	19%
Postharvest	4%	0%	0%	3%	74%	19%
Processing	4%	0%	0%	3%	74%	19%

Distribution	76%	0%	0%	17%	5%	1%
Retailing	76%	0%	0%	17%	5%	1%
Consumption	76%	0%	0%	17%	5%	1%

Table A39: Waste treatment options in France

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	6%	0%	0%	1%	56%	37%
Postharvest	6%	0%	0%	1%	56%	37%
Processing	6%	0%	0%	1%	56%	37%
Distribution	34%	13%	0%	48%	3%	2%
Retailing	34%	13%	0%	48%	3%	2%
Consumption	34%	13%	0%	48%	3%	2%

Table A40: Waste treatment options in Italy

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	0%	0%	0%	3%	79%	18%
Postharvest	0%	0%	0%	3%	79%	18%
Processing	0%	0%	0%	3%	79%	18%

Distribution	5%	7%	0%	9%	65%	14%
Retailing	5%	7%	0%	9%	65%	14%
Consumption	5%	7%	0%	9%	65%	14%

Table A41: Waste treatment options in Netherlands

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	0%	0%	0%	2%	84%	14%
Postharvest	0%	0%	0%	2%	84%	14%
Processing	0%	0%	0%	2%	84%	14%
Distribution	1%	0%	0%	74%	21%	3%
Retailing	1%	0%	0%	74%	21%	3%
Consumption	1%	0%	0%	74%	21%	3%

Table A42: Waste treatment options in Portugal

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	10%	0%	0%	12%	62%	16%
Postharvest	10%	0%	0%	12%	62%	16%
Processing	10%	0%	0%	12%	62%	16%

Distribution	70%	0%	0%	30%	0%	0%
Retailing	70%	0%	0%	30%	0%	0%
Consumption	70%	0%	0%	30%	0%	0%

Table A43: Waste treatment options in Poland

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	0%	0%	0%	1%	79%	20%
Postharvest	0%	0%	0%	1%	79%	20%
Processing	0%	0%	0%	1%	79%	20%
Distribution	46%	1%	0%	18%	28%	7%
Retailing	46%	1%	0%	18%	28%	7%
Consumption	46%	1%	0%	18%	28%	7%

Table A44: Waste treatment options in UK

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	2%	1%	0%	0%	85%	11%
Postharvest	2%	1%	0%	0%	85%	11%
Processing	2%	1%	0%	0%	85%	11%

Distribution	37%	16%	0%	35%	11%	1%
Retailing	37%	16%	0%	35%	11%	1%
Consumption	37%	16%	0%	35%	11%	1%

Table A45: Waste treatment options in other 18 countries

Stages	Landfill	Incineration without energy recovery	Disposal other	Incineration with energy recovery	Composting	Anaerobic digestion
Production	5%	1%	0%	8%	69%	17%
Postharvest	5%	1%	0%	8%	69%	17%
Processing	5%	1%	0%	8%	69%	17%
Distribution	55%	0%	0%	34%	9%	2%
Retailing	55%	0%	0%	34%	9%	2%
Consumption	55%	0%	0%	34%	9%	2%

8.3.3 Mass flow mapping (country-specific)

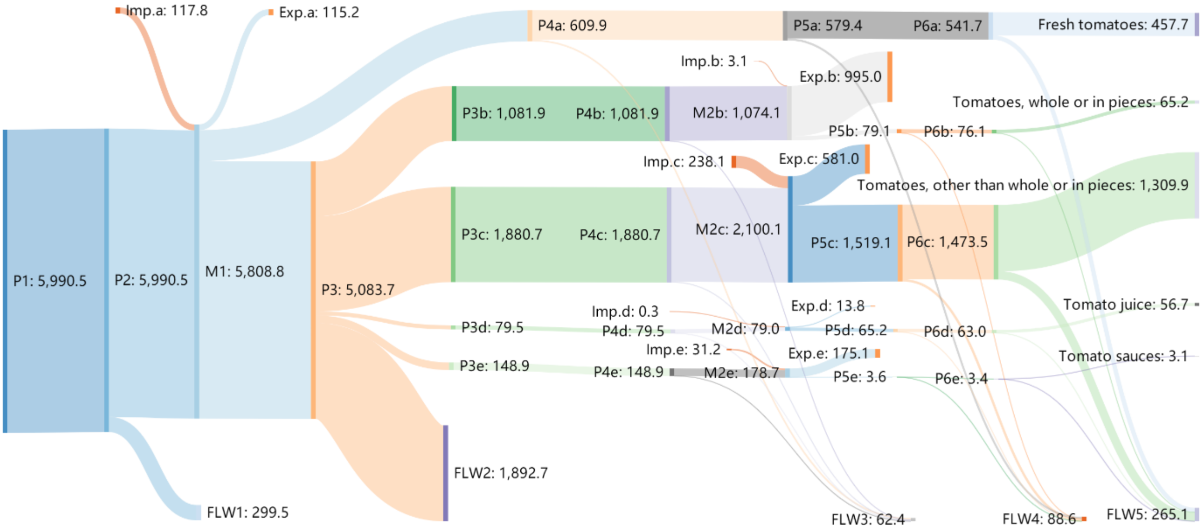

Figure A7. Mass flow of fresh tomatoes and tomato products in Italy.

Note: P1: Production, P2: Postharvest handling and storage, P3: Processing, P4: Distribution, P5: Retailing, P6: Consumption, M1: Fresh tomato market, M2: Tomato products market. a: Fresh tomato, b: Tomatoes, whole or in pieces, c: Tomato, other than whole or in piece, d: Tomato juice, e: Tomato sauces. FLW1: Tomato loss in postharvest handling and storage stage, FLW2: Tomato loss in processing stage, FLW3: Tomato loss in distribution stage, FLW4: Tomato loss in retailing stage, FLW5: Tomato waste in consumption stage.

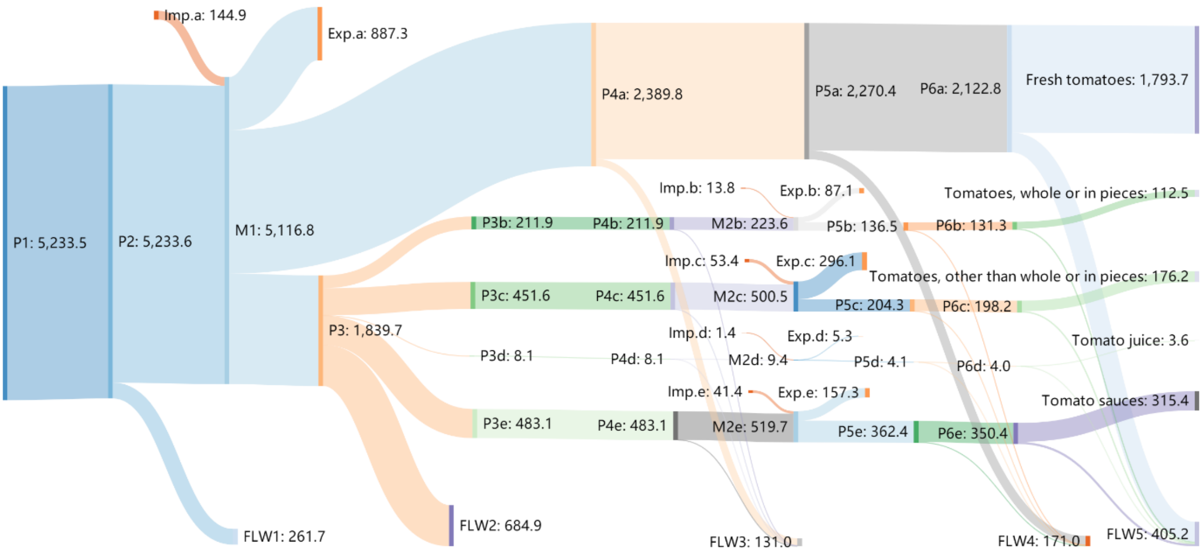

Figure A8. Mass flow of fresh tomatoes and tomato products in Spain.

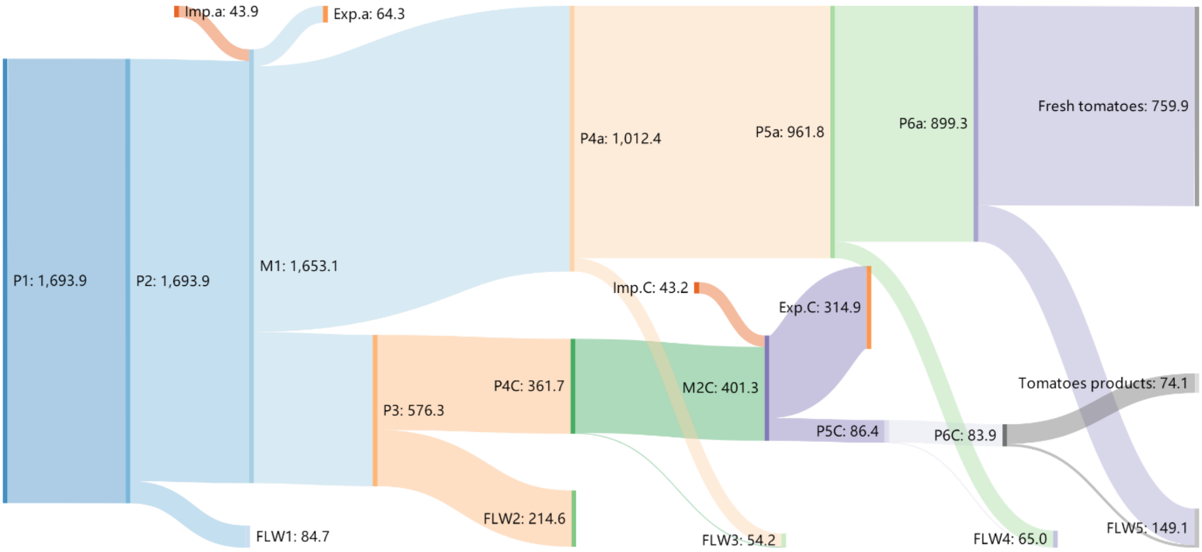

Figure A9. Mass flow of fresh tomatoes and tomato products in Portugal.

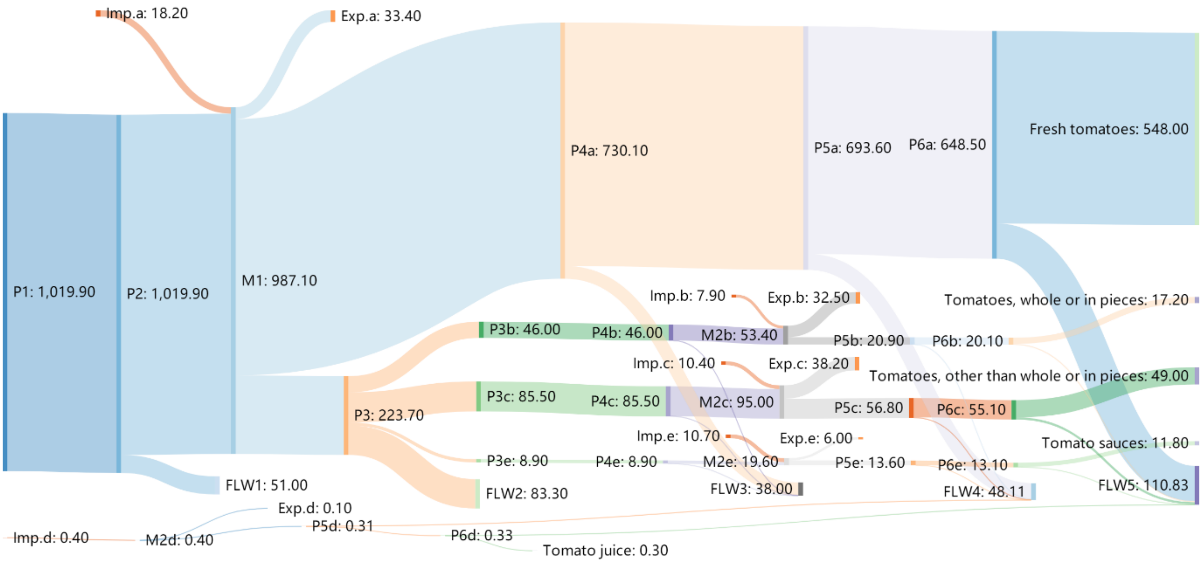

Figure A10. Mass flow of fresh tomatoes and tomato products in Greece.

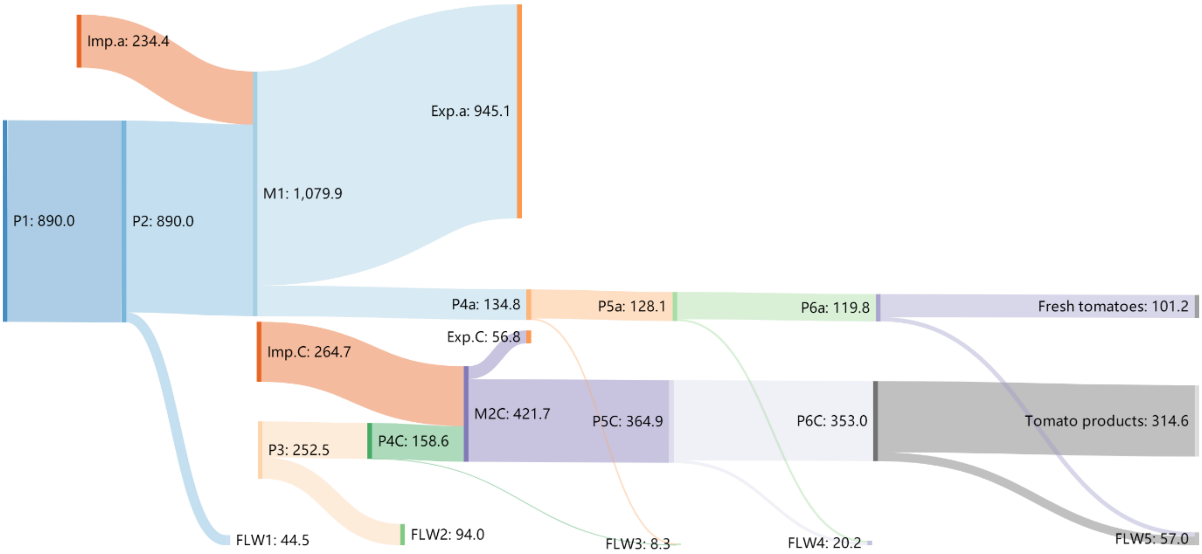

Figure A11. Mass flow of fresh tomatoes and tomato products in Netherlands.

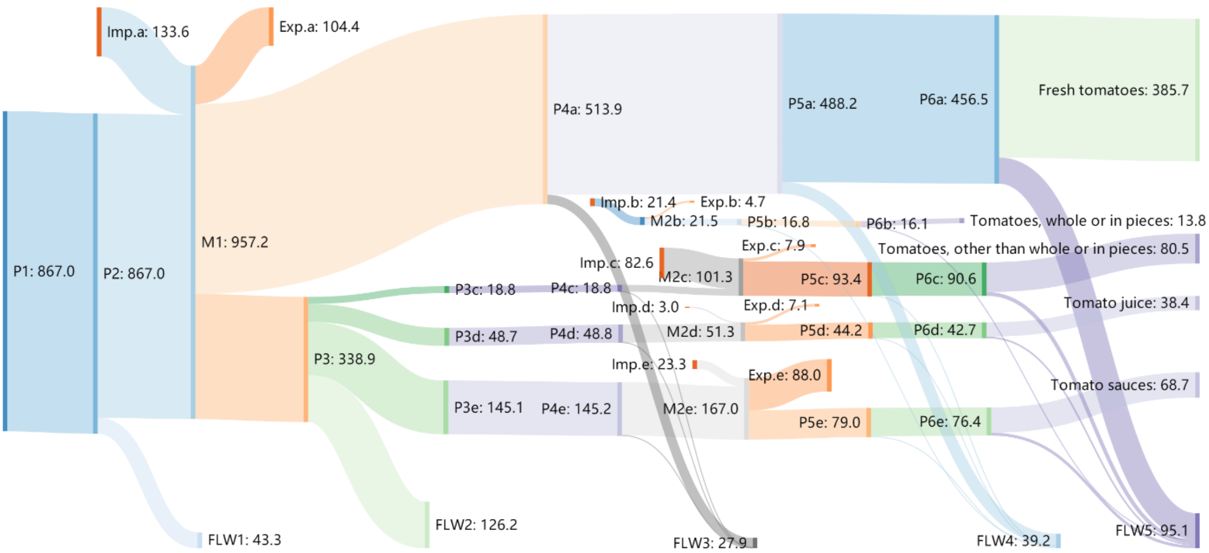

Figure A12. Mass flow of fresh tomatoes and tomato products in Poland.

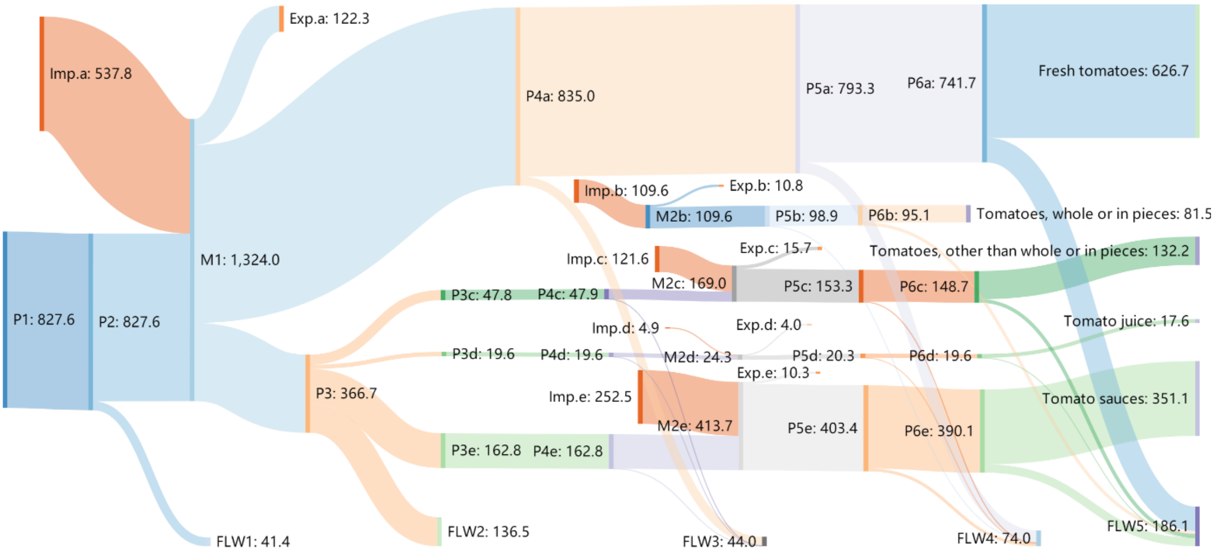

Figure A13. Mass flow of fresh tomatoes and tomato products in France.

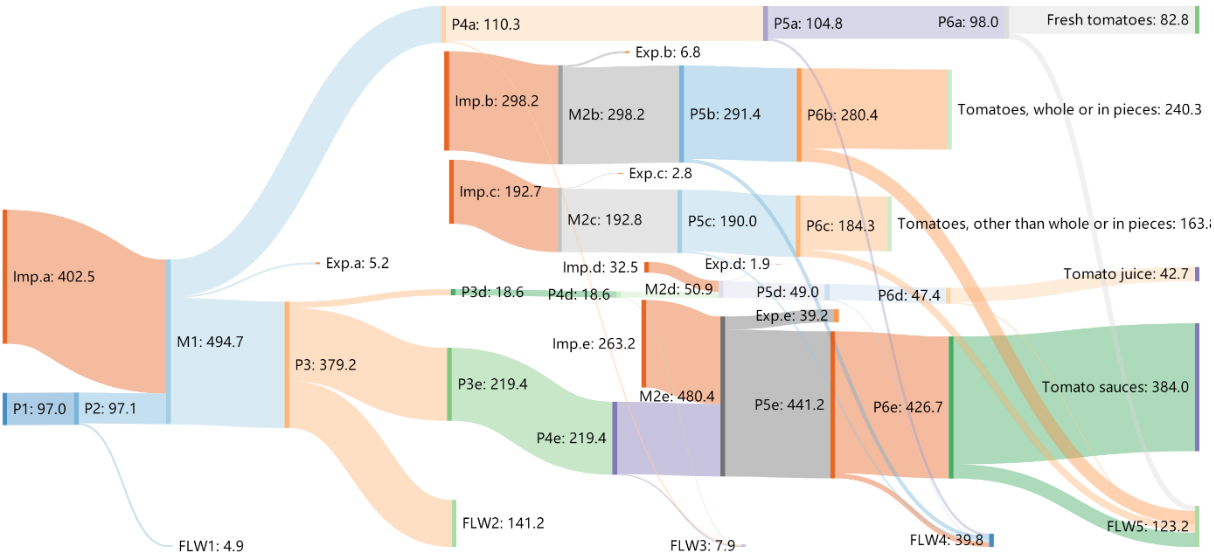

Figure A14. Mass flow of fresh tomatoes and tomato products in United Kingdom.

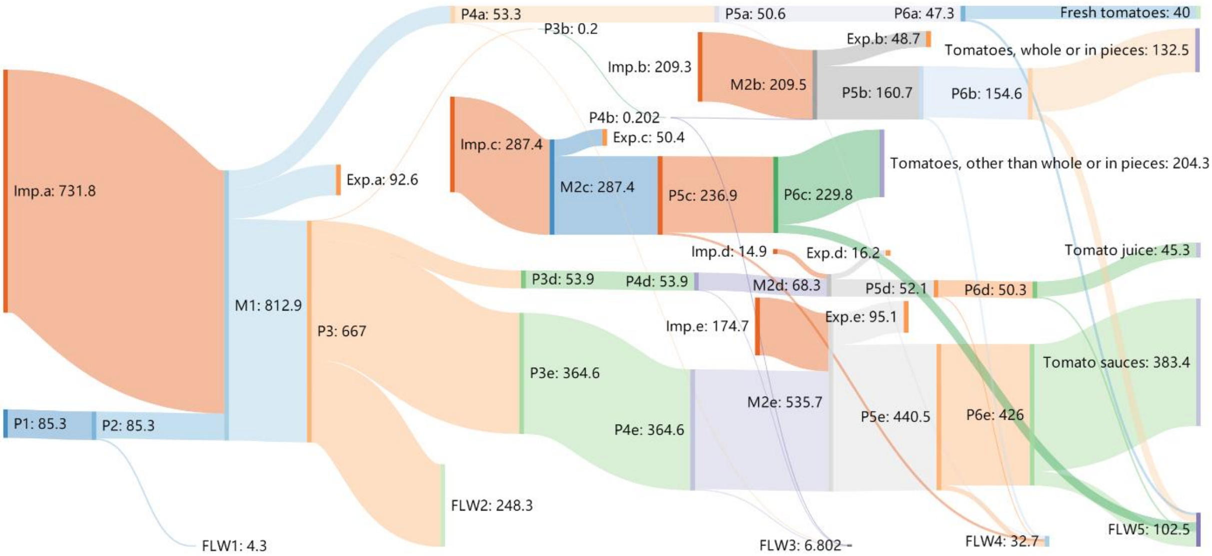

Figure A15. Mass flow of fresh tomatoes and tomato products in United Kingdom.

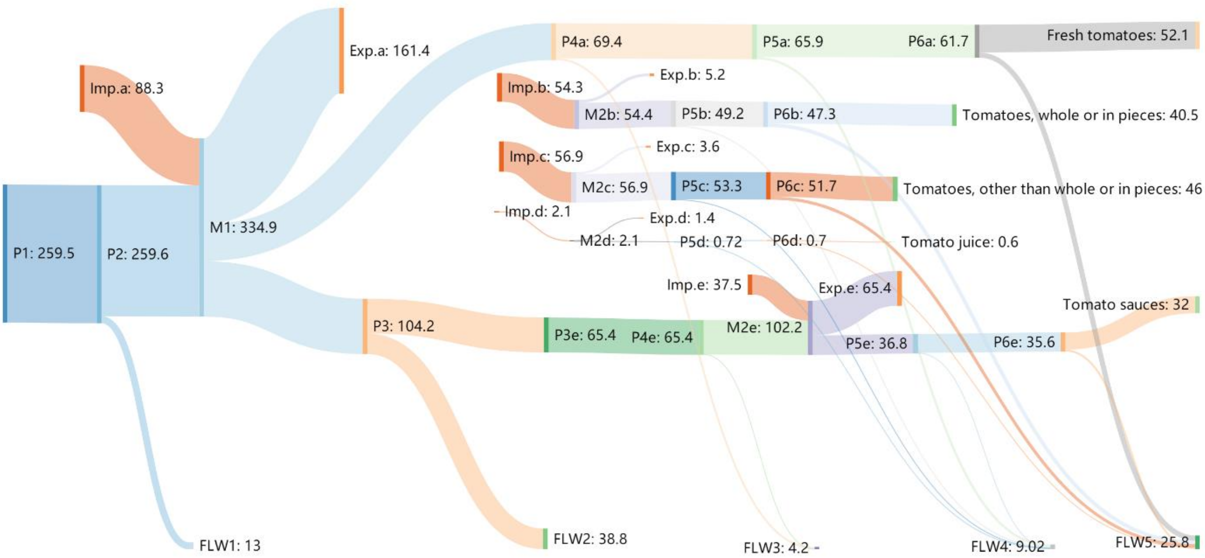

Figure A16. Mass flow of fresh tomatoes and tomato products in Belgium.

8.3.4 Combined scenarios (country-specific)

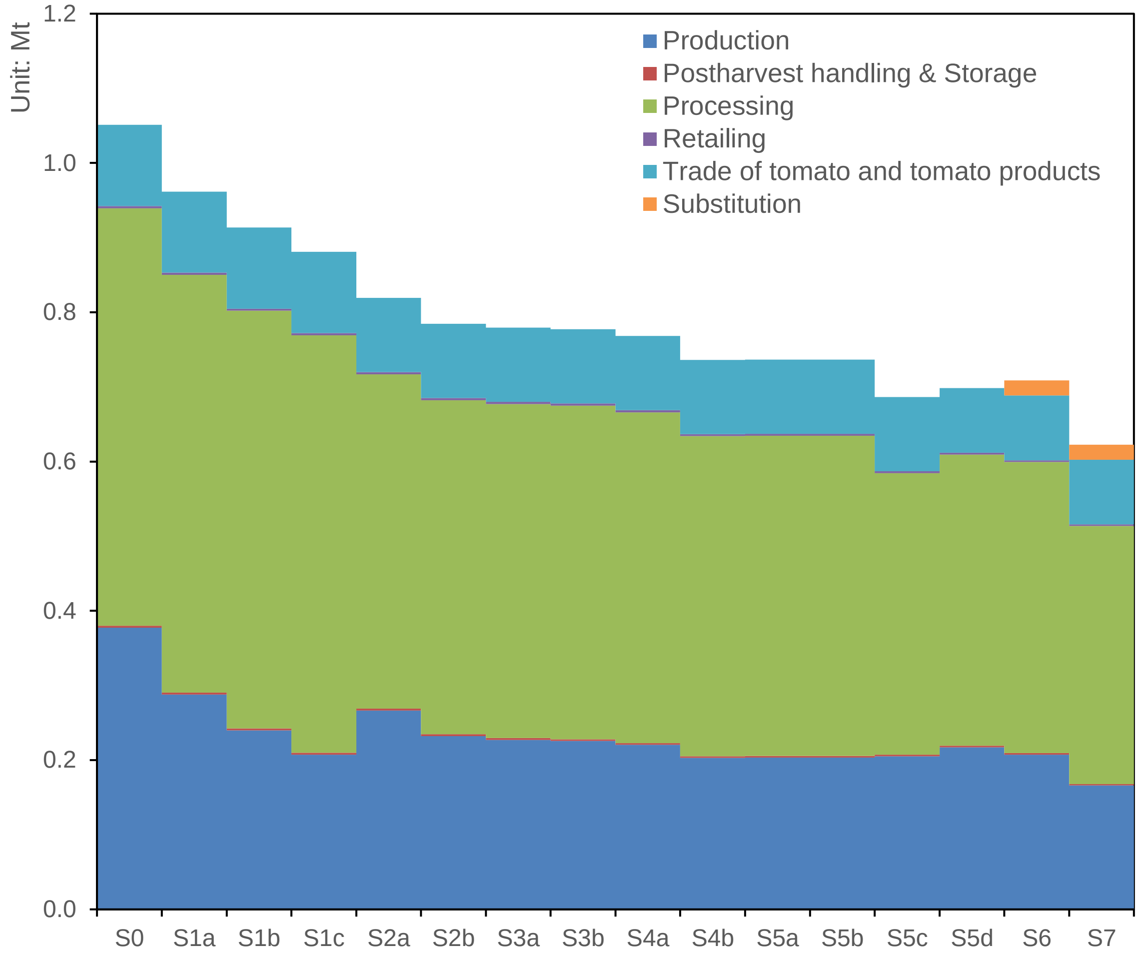

Figure A17. Combined scenario result of GHG emissions reduction in Italy.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

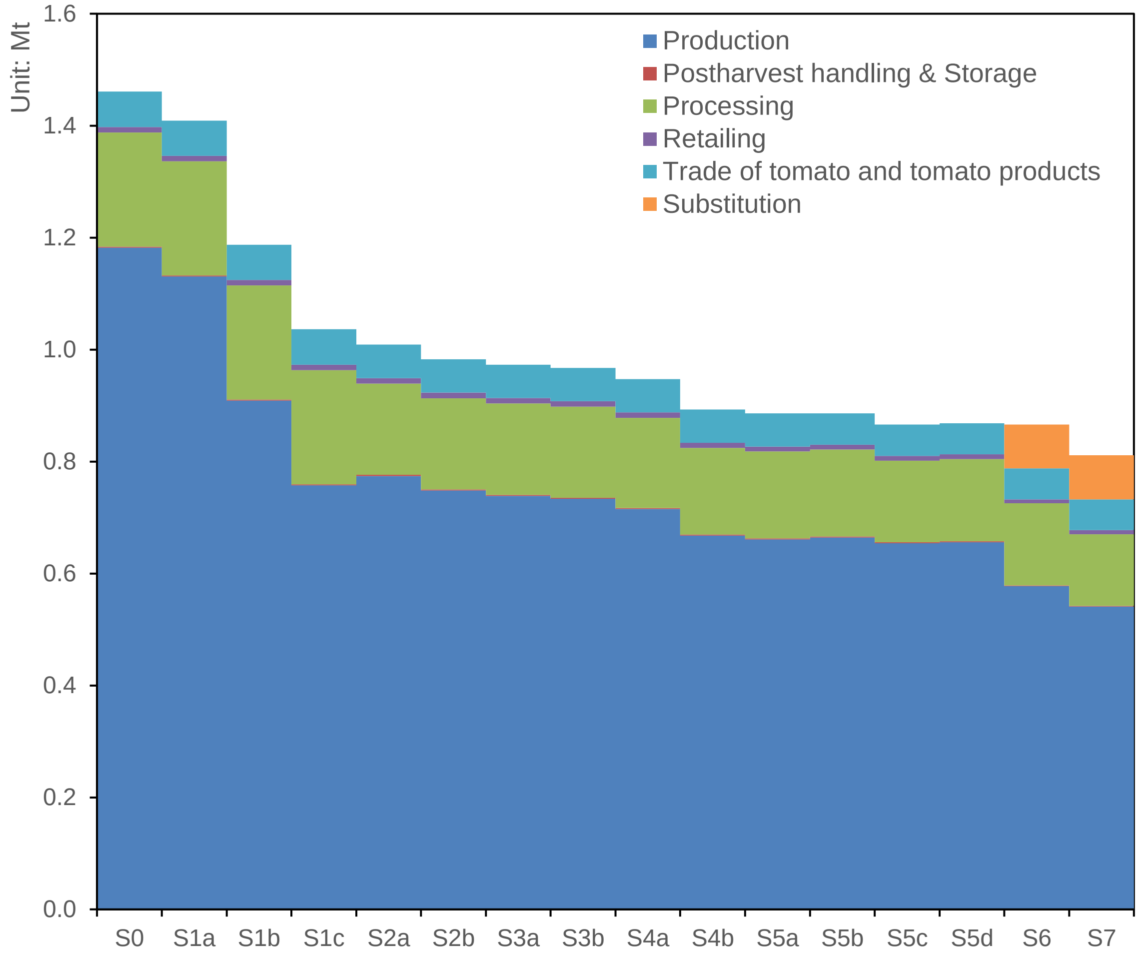

Figure A18. Combined scenario result of GHG emissions reduction in Spain.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

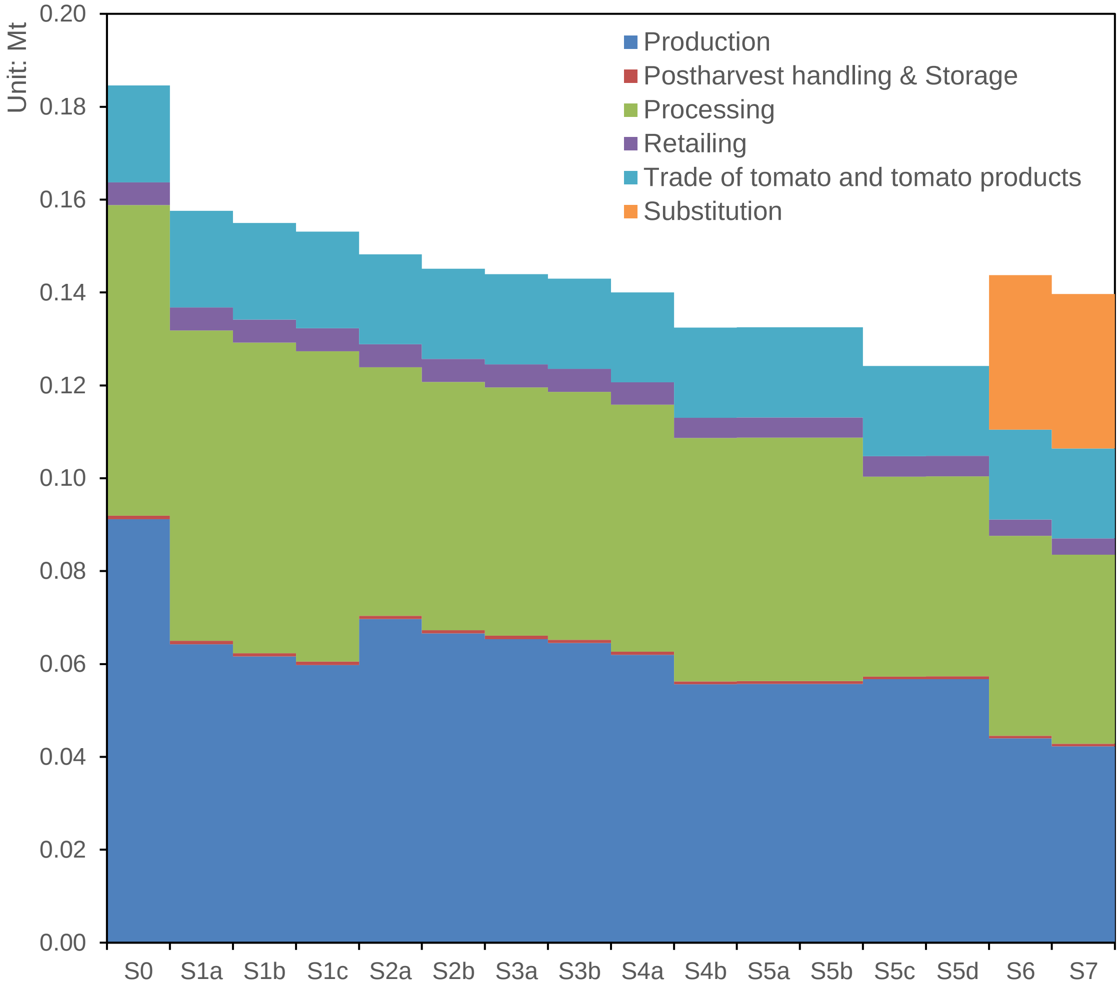

Figure A19. Combined scenario result of GHG emissions reduction in Portugal.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

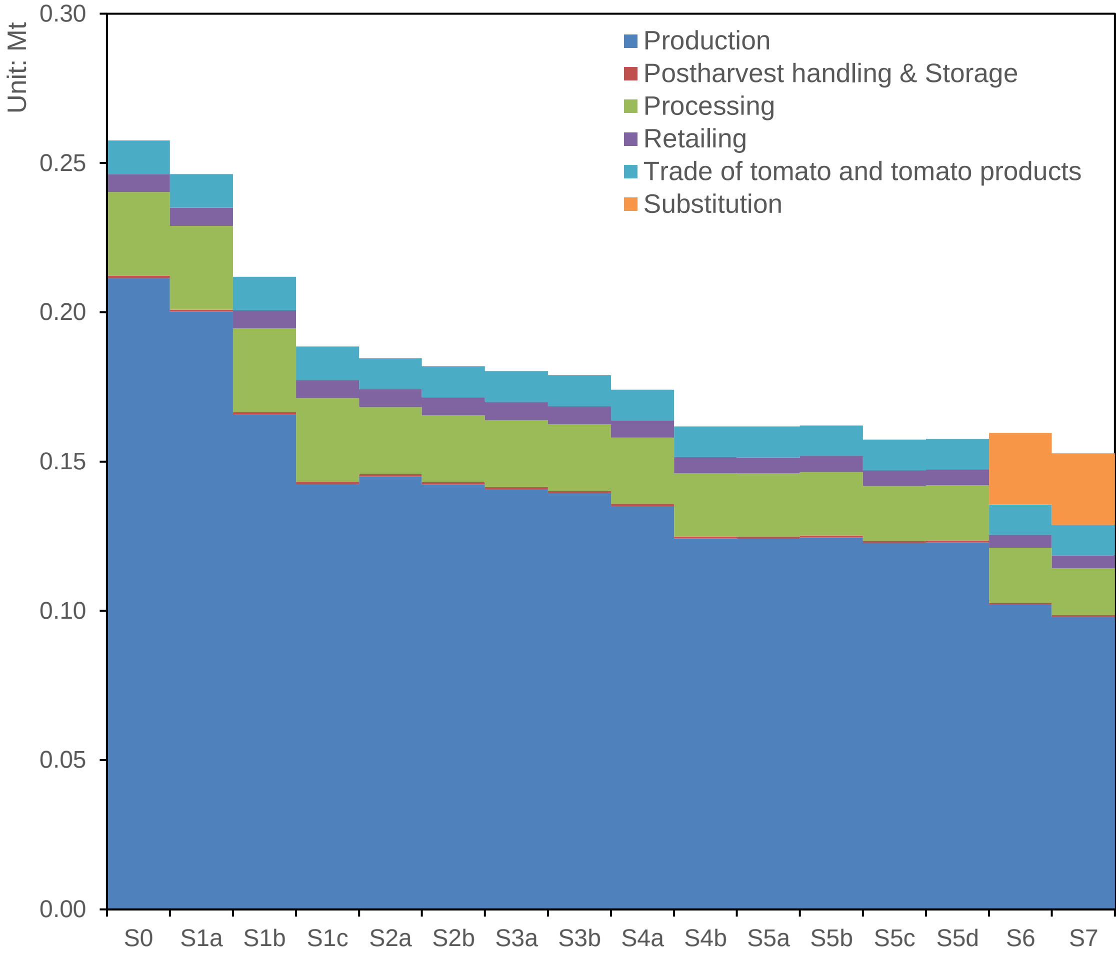

Figure A20. Combined scenario result of GHG emissions reduction in Greece.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

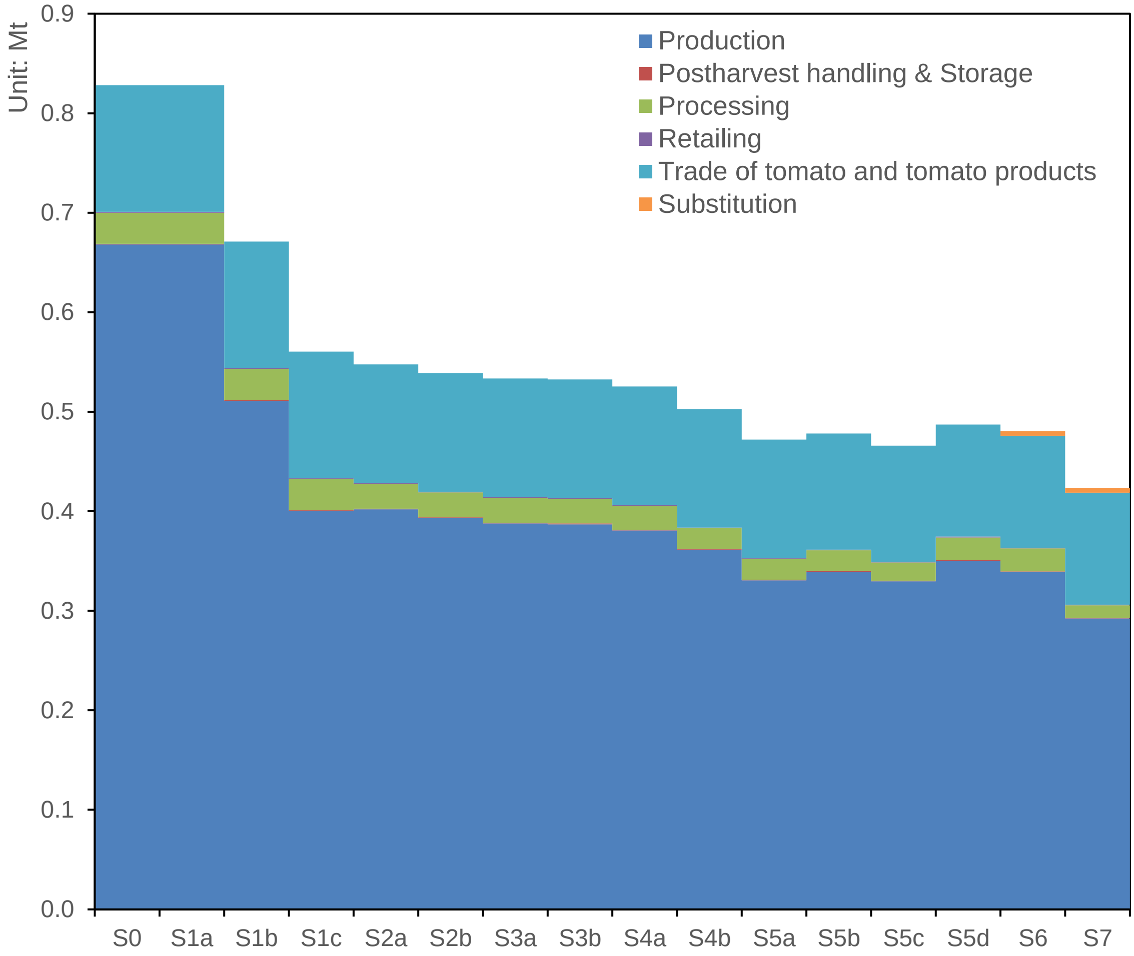

Figure A21. Combined scenario result of GHG emissions reduction in Netherlands.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

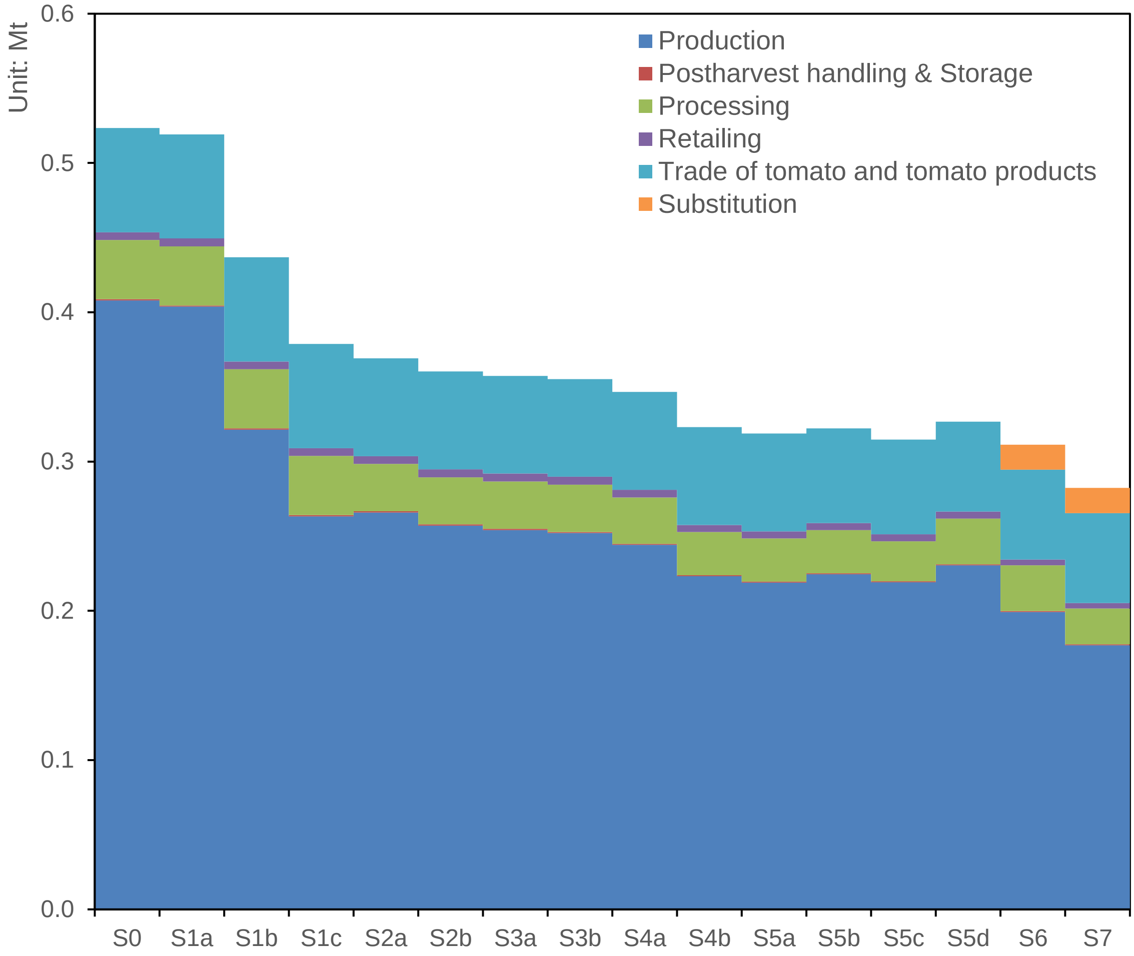

Figure A22. Combined scenario result of GHG emissions reduction in Poland.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

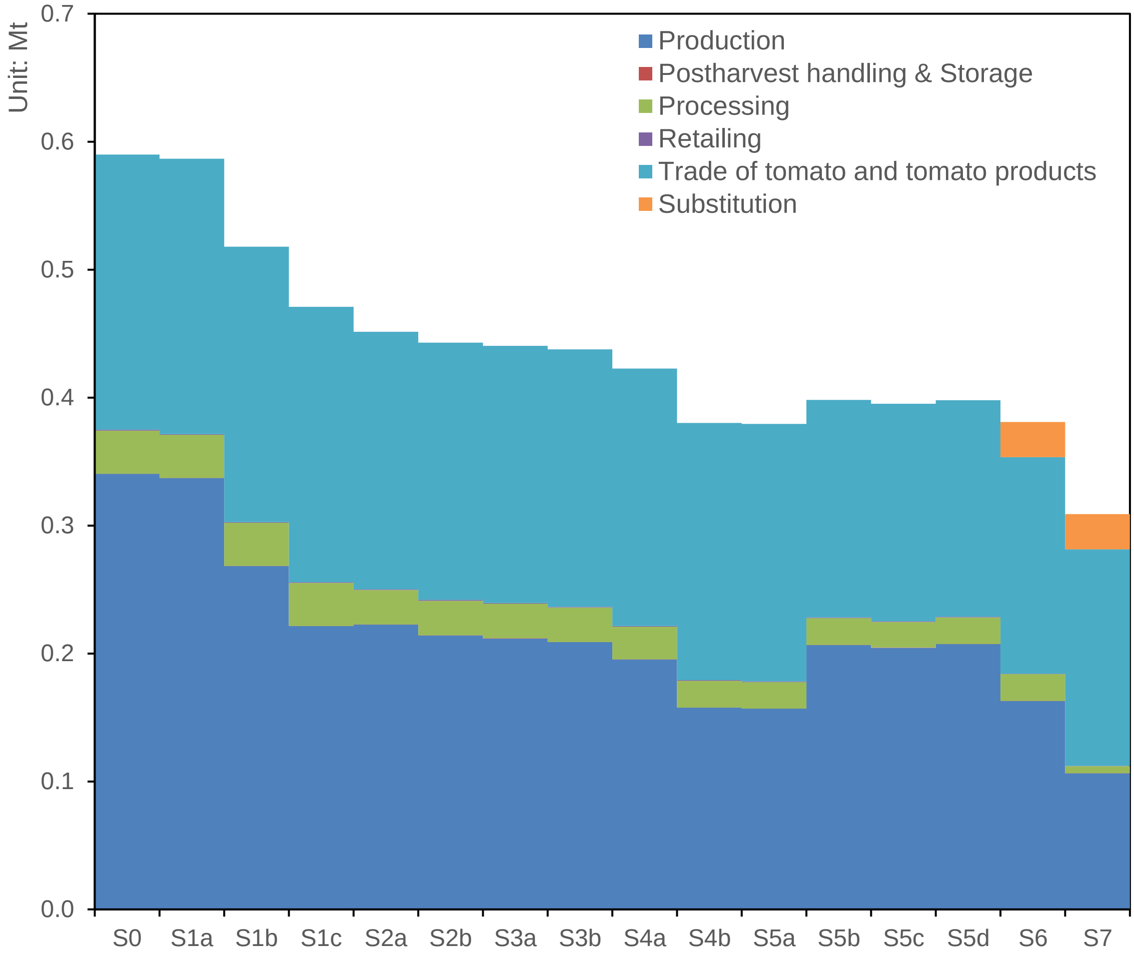

Figure A23. Combined scenario result of GHG emissions reduction in France.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

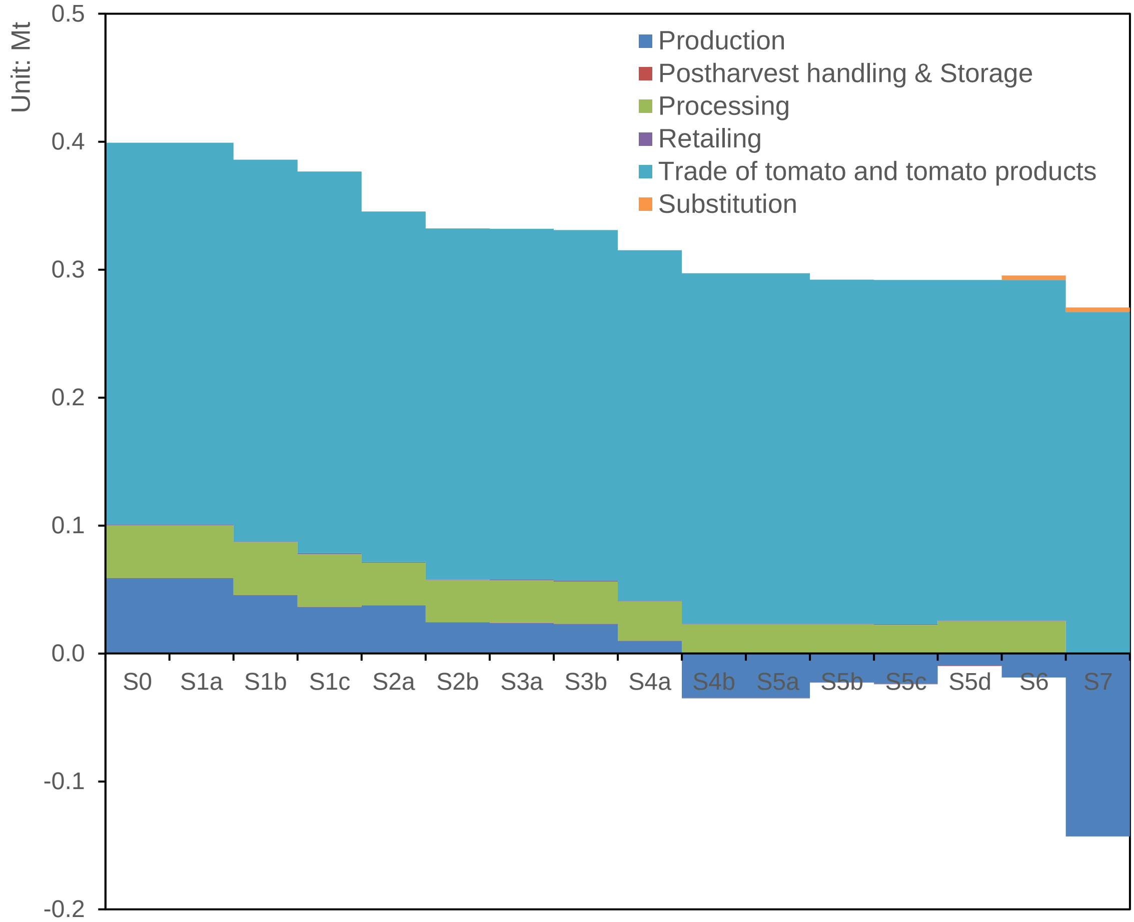

Figure A24. Combined scenario result of GHG emissions reduction in UK.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

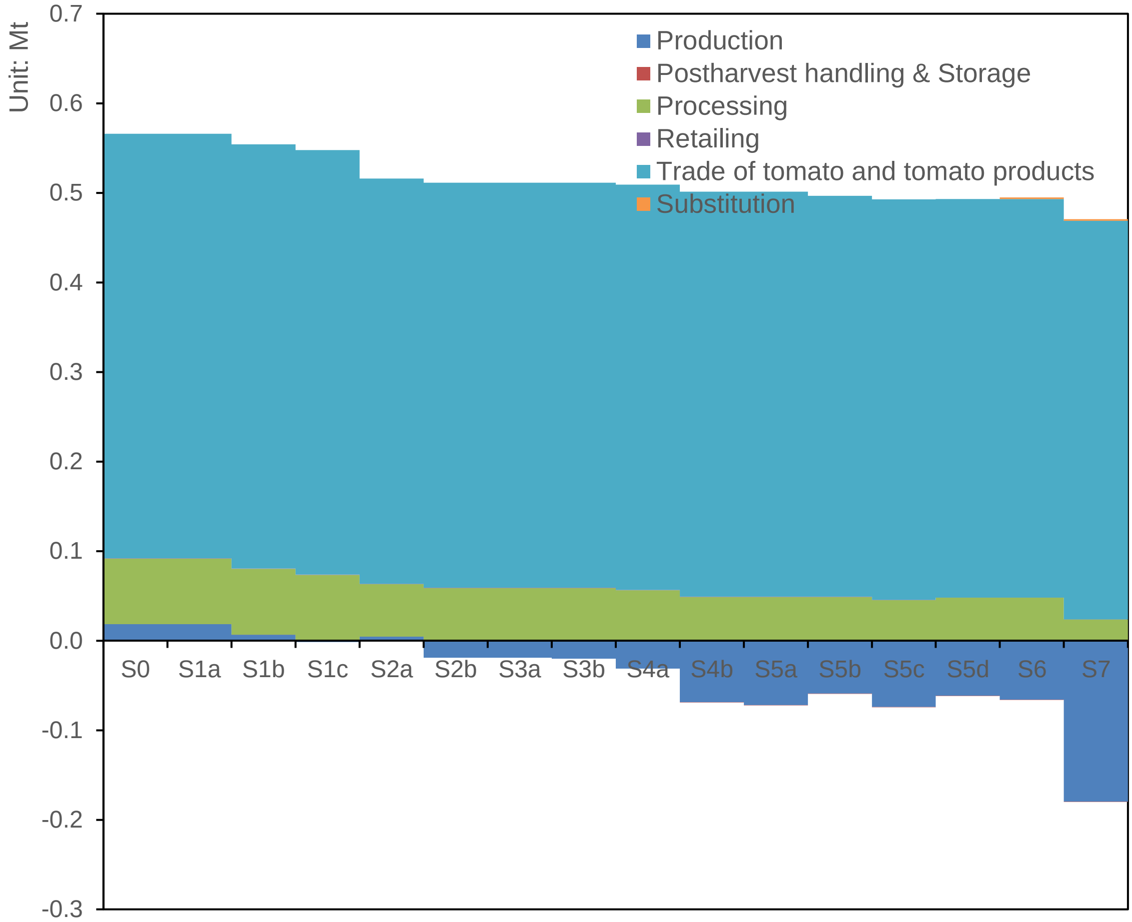

Figure A25. Combined scenario result of GHG emissions reduction in Germany.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

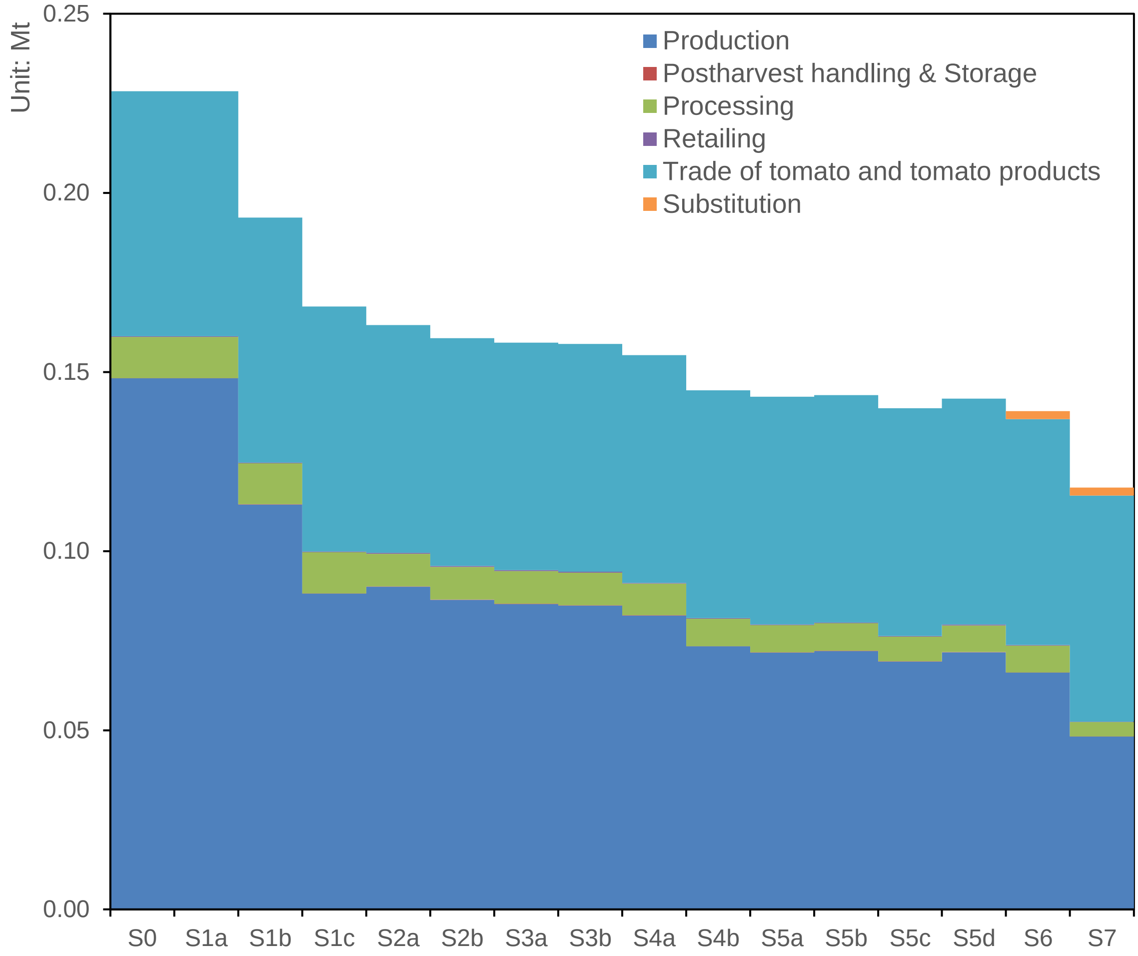

Figure A26. Combined scenario result of GHG emissions reduction in Belgium.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

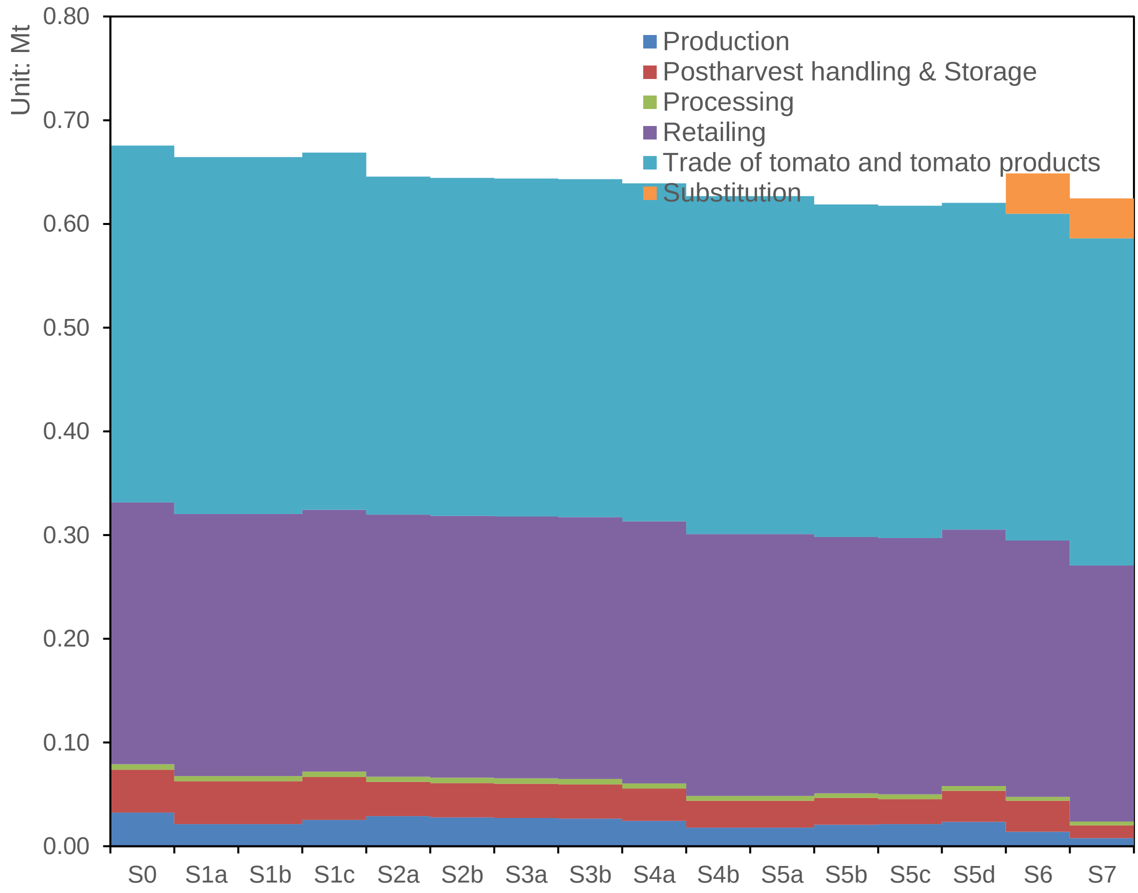

Figure A27. Combined scenario result of GHG emissions reduction in other 18 countries.

Note: results are calculated in the consumption-based accounting method. S0 is the baseline scenario.

8.4 Analytical solutions of German meat mass flow and energy flow

Table A46: Analytical solutions of mass flow

Flow	Flow name	Equation
A1,2	Live animals	$(CW_p + Innards_p) \times DM_c + Byproducts_p \times DM_c$
A1,8	Manure	$(\text{Number of animals}_p + \text{Number of animals}_d) \times \text{lifetime of animals} \times \text{Manure production per animal}$

A1,9	Dead animals	[Number of animals$_p$ × Death ratio/ (1 - Death ratio) × Average weight of animal (CW) + Number of animals$_p$ × Animal death ratio/ (1 - Animal death ratio) × Average weight of animal (LW) × Relation of innard to LW] × DM$_c$ + Byproducts$_p$ × DM$_c$
A0,2	Imported live animals	(CW$_i$+ Innards$_i$) × DM$_c$ + Byproducts$_i$ × DM$_c$
A2,0	Exported live animals	(CW$_e$ + Innards$_e$) × DM$_c$ + Byproducts$_e$ × DM$_c$
A2,3	Live animals after Imp/Exp	A1,2 + A0,2 - A2,0
A3,4	CW for processing	(CW$_p$ + CW$_i$ - CW$_e$) × DM$_c$
A3,9	Animals byproducts in slaughtering	A2,3 - A3,4 + (Innards$_p$ + Innards$_i$ - Innards$_e$) × DM$_c$
A4,5	Meat products for human consumption	A3,4 × Relation of LW to meat for human consumption (MHC)/Relation of CW to LW
A4,9	Meat byproducts in processing	A3,4 - A4,5
A0,5	Imported meat products	Given × DM$_c$
A5,0	Exported meat products	Given × DM$_c$
A5,6	Meat products after Imp/Exp	A4,5 + A0,5 - A5,0
A6,7	Meat products for consumption	A5,6 - A6,9
A6,10	Wasted meat products in retailing	A5,6 × Meat waste rate in retailing
A7,0	Meat consumption	A7,0a + A7,0b
A7,0a	Meat consumption in household	A6,7 × Meat consumption ratio in household
A7,0b	Meat consumption out-of-home	A6,7 × Meat consumption ratio out-of-home
A7,10	Wasted meat at consumption stage	A7,10a + A7,10b
A7,10a	Wasted meat in household	A7,0a× Meat waste rate in household
A7,10b	Wasted meat out-of-home	A7,0b × Meat waste rate out-of-home
A8,11	Manure for agriculture use	A1,8 × Ratio of manure for agriculture utilization

A8,18	Manure for biogas production	A1,8 × Ratio of manure for biogas production
A9,12	**Byproducts for food production**	A9,12a + A9,12b + A9,12c
A9,12a	Byproducts cat 3 protein for food production	(A3,9 + A4,9) × Cat 3% × Protein % × Protein utilization rate
A9,12b	Byproducts EAF protein for food production	(A3,9 + A4,9) × EAF% × Protein % × Protein utilization rate
A9,12c	Byproducts EAF fat for food production	(A3,9 + A4,9) × EAF% × Fat % × Fat utilization rate
A9,13	**Byproducts for feed production**	A9,13a + A9,13b
A9,13a	Byproducts protein for feed production	A9,13h + A9,13i
A9,13h	Byproducts cat 3 protein for feed production	(A3,9 + A4,9) × Cat 3% × Protein % × Protein utilization rate
A9,13i	Byproducts EAF protein for feed production	(A3,9 + A4,9) × EAF% × Protein % × Protein utilization rate
A9,13b	Byproducts fat for feed production	A9,14j + A9,14k
A9,13j	Byproducts cat 3 fat for feed production	(A3,9 + A4,9) × Cat 3% × Fat % × Fat utilization rate
A9,13k	Byproducts EAF fat for feed production	(A3,9 + A4,9) × EAF% × Fat % × Fat utilization rate
A9,14	**Byproducts for industry use**	A9,14a + A9,14b
A9,14a	Byproducts protein for industry use	A9,14h + A9,14i + A9,14j
A9,14h	Byproducts cat 2 protein for industry use	(A1,9 + A3,9 + A4,9) × Cat 2% × Protein % × Protein utilization rate
A9,14i	Byproducts cat 3 protein for industry use	(A3,9 + A4,9) × Cat 3% × Protein % × Protein utilization rate
A9,14j	Byproducts EAF protein for industry use	(A3,9 + A4,9) × EAF% × Protein % × Protein utilization rate
A9,14b	Byproducts fat for industry use	A9,14l + A9,14m + A9,14n
A9,14l	Byproducts cat 1 fat for industry use	(A1,9 + A3,9 + A4,9) × Cat 1% × Fat % × Fat utilization rate

A9,14m	Byproducts cat 3 fat for industry use	(A3,9 + A4,9) × Cat 3% × Fat % × Fat utilization rate
A9,14n	Byproducts EAF fat for industry use	(A3,9 + A4,9) × EAF% × Fat % × Fat utilization rate
A9,15	**Byproducts for biodiesel production**	A9,15a + A9,15b + A9,15c + A9,15d
A9,15a	Byproducts cat 1 fat for biodiesel production	(A1,9 + A3,9) × Cat 1% × Fat % × Fat utilization rate
A9,15b	Byproducts cat 2 fat for biodiesel production	(A1,9 + A3,9) × Cat 2% × Fat % × Fat utilization rate
A9,15c	Byproducts cat 3 fat for biodiesel production	(A3,9 + A4,9) × Cat 3% × Fat % × Fat utilization rate
A9,15d	Byproducts EAF fat for biodiesel production	(A3,9 + A4,9) × EAF% × Fat % × Fat utilization rate
A9,16	**Byproducts for incineration**	A9,16a + A9,16b + A9,16c + A9,16d
A9,16a	Byproducts cat 1 protein for incineration	(A1,9 + A3,9 + A4,9) × Cat 1% × Protein % × Protein utilization rate
A9,16b	Byproducts cat 1 fat for incineration	(A1,9 + A3,9 + A4,9) × Cat 1% × Fat % × Fat utilization rate
A9,16c	Byproducts cat 3 fat for incineration	(A3,9 + A4,9) × Cat 3% × Fat % × Fat utilization rate
A9,16d	Byproducts other content for incineration	A9,16h + A9,16i + A9,16j + A9,16k
A9,16h	Byproducts cat 1 other content for incineration	(A1,9 + A3,9 + A4,9) × Cat 1% × Other %
A9,16i	Byproducts cat 2 other content for incineration	(A1,9 + A3,9 + A4,9) × Cat 2% × Other %
A9,16j	Byproducts cat 3 other content for incineration	(A3,9 + A4,9) × Cat 3% × Other %
A9,16k	Byproducts EAF other content for incineration	(A3,9 + A4,9) × EAF% × Other %
A10,16	Meat waste for incineration	(A6,10 + A7,10) × Ratio of meat waste for incineration
A10,17	Meat waste for composting	(A6,10 + A7,10) × Ratio of meat waste for composting
A10,18	Meat waste for biogas production	(A6,10 + A7,10) × Ratio of meat waste for biogas production
A15,0a	Biodiesel	A9,15 × Yield from by-products fat to biodiesel

A15,0b	Mass loss in biodiesel production	A9,15 - A15,0a
A18,0a	Biogas	A18,0h + A18,0i
A18,0h	Biogas from manure	A8,18 × Biogas yield from manure × Biogas density
A18,0i	Biogas from meat waste	A10,18 × Biogas energy equivalent × Efficiency of biogas plant × Biogas density
A18,0b	Mass loss in biogas production	A8,18 + A10,18 - A18,0a

Note: CW_p = Carcass weight in production, CW_d = Dead animal carcass weight, CW_i = Carcass weight of imported animals, CW_e = Carcass weight of exported animals, DM_c = Dry matter content, $Innards_p$ = Innards in production, $Byproducts_p$ = Byproducts in production, Number of $animals_p$ = Number of animals in production, Number of $animals_d$ = Number of dead animals. PE = Process energy.

Table A47: Analytical solutions of energy flow

Flow	Flow name	Equation
A0,1a	Energy equivalent of feed	(A1,2 + A1,9)/Ratio of the feed input energy to meat products
A1,2	Energy equivalent of live animals	Number of animals × (A2,3/Number of animals after trade)
A1,8	Energy equivalent of manure	Flow M A1,8 × Ec of manure
A1,9	Energy equivalent of dead animals	Number of $animals_p$ × Animal death ratio / (1 - Animal death ratio) × (A2,3/Number of animals after trade)
A1,0	Animal respiration energy	A0,1a - A1,2 - A1,8 - A1,9
A0,2	Energy equivalent of imported animals	Number of animals in import × (A2,3/Number of animals after trade)
A2,0	Energy equivalent of exported animals	Number of animals in export × (A2,3/Number of animals after trade)
A2,3	Energy equivalent of live animals after Imp/Exp	A3,4 + A3,9
A3,4	Energy equivalent of CW for processing	$(CW_p + CW_i - CW_e) \times DM_c$
A3,9	Energy equivalent of animal byproducts in slaughtering	Flow M A3,9 × E_c of byproducts + E_c of CW + $(Innards_p + Innards_i - Innards_e) \times DM_c \times E_c$ of innards
A4,5	Energy equivalent of meat products	Flow M A4,5 × E_c of meat products

A4,9	Energy equivalent of meat byproducts in processing	A3,4 - A4,5
A0,5	Energy equivalent of imported meat products	Flow M A0,5 × E_c of meat products
A5,0	Energy equivalent of exported meat products	Flow M A5,0 × E_c of meat products
A5,6	Energy equivalent of meat products after Imp/Exp	Flow M A5,6 × E_c of meat products
A6,7	Energy equivalent of meat products for consumption	Flow M A6,7 × E_c of meat products
A6,9	Energy equivalent of wasted meat products in retailing	Flow M A6,9 × E_c of meat products
A7,0	Energy equivalent of meat products for consumption	A7,0a + A7,0b
A7,0a	Energy equivalent of meat products consumed in household	Flow M A7,0a × E_c of meat products
A7,0b	Energy equivalent of meat products consumed out-of-home	Flow M A7,0b × E_c of meat products
A7,10	Energy equivalent of wasted meat at consumption stage	A7,10a + A7,10b
A7,10a	Energy equivalent of wasted meat in household	Flow M A7,10a × E_c of meat products
A7,10b	Energy equivalent of wasted meat out-of-home	Flow M A7,10b × E_c of meat products
A8,11	Energy equivalent of manure for agriculture use	A1,8 × Ratio of manure for agriculture utilization
A8,18	Energy equivalent of manure for biogas production	A1,8 × Ratio of manure for biogas production
A9,12	**Energy equivalent of byproducts for food production**	A9,12a + A9,12b + A9,12c
A9,12a	Energy content of byproducts cat 3 protein for food production	Flow M A9,12a × E_c of protein
A9,12b	Energy content of byproducts EAF protein for food production	Flow M A9,12b × E_c of protein
A9,12c	Energy content of byproducts EAF fat for food production	Flow M A9,12c × E_c of fat
A9,13	**Energy equivalent of byproducts for feed production**	A9,13a + A9,13b
A9,13a	Energy content of byproducts protein for feed production	A9,13h + A9,13i

A9,13h	Energy content of byproducts cat 3 protein for feed production	Flow M A9,13h × E_c of protein
A9,13i	Energy content of byproducts EAF protein for feed production	Flow M A9,13i × E_c of protein
A9,13b	Energy content of byproducts fat for feed production	A9,13j + A9,13k
A9,13j	Energy content of byproducts cat 3 fat for feed production	Flow M A9,13j × E_c of fat
A9,13k	Energy content of byproducts EAF fat for feed production	Flow M A9,13k × E_c of fat
A9,14	**Energy equivalent of byproducts for industry use**	A9,14a + A9,14b
A9,14a	Energy content of byproducts protein for industry use	A9,14h + A9,14i + A9,14j
A9,14h	Energy content of byproducts cat 2 protein for industry use	Flow M A9,14h × E_c of protein
A9,14i	Energy content of byproducts cat 3 protein for industry use	Flow M A9,14i × E_c of protein
A9,14j	Energy content of byproducts EAF protein for industry use	Flow M A9,14j × E_c of protein
A9,14b	Energy content of byproducts fat for industry use	A9,14l + A9,14m + A9,14n
A9,14l	Energy content of byproducts cat 1 fat for industry use	Flow M A9,14l × E_c of fat
A9,14m	Energy content of byproducts cat 3 fat for industry use	Flow M A9,14m × E_c of fat
A9,14n	Energy content of byproducts EAF fat for industry use	Flow M A9,14n × E_c of fat
A9,15	**Energy equivalent of byproducts for biodiesel production**	A9,15a + A9,15b + A9,15c + A9,15d
A9,15a	Energy content of byproducts cat 1 fat for biodiesel production	Flow M A9,15a × E_c of fat
A9,15b	Energy content of byproducts cat 2 fat for biodiesel production	Flow M A9,15b × E_c of fat
A9,15c	Energy content of byproducts cat 3 fat for biodiesel production	Flow M A9,15c × E_c of fat
A9,15d	Energy content of byproducts EAF fat for biodiesel production	Flow M A9,15d × E_c of fat

A9,16	**Energy equivalent of byproducts for incineration**	A9,16a + A9,16b + A9,16c + A9,16d
A9,16a	Energy content of byproducts cat 1 protein for incineration	Flow M A9,16a × E_c of protein
A9,16b	Energy content of byproducts cat 1 fat for incineration	Flow M A9,16b × E_c of fat
A9,16c	Energy content of byproducts cat 3 fat for incineration	Flow M A9,16c × E_c of fat
A9,16d	Energy equivalent of byproducts other content for incineration	A9,16h + A9,16i + A9,16j + A9,16k
A9,16h	Energy content of byproducts cat 1 other content for incineration	(A1,9 + A3,9) × Cat1% - A9,14l - A9,15a - A9,16a - A9,16b
A9,16i	Energy content of byproducts cat 2 other content for incineration	(A1,9 + A3,9) × Cat2% - A9,14h - A9,15b
A9,16j	Energy content of byproducts cat 3 other content for incineration	(A3,9 + A4,9) × Cat3% - A9,12a - A9,13h - A9,13j - A9,14i - A9,14m - A9,15c - A9,16c
A9,16k	Energy content of byproducts EAF other content for incineration	(A3,9 + A4,9) × EAF% - A9,12b - A9,12c - A9,13i - A9,13k - A9,14j - A9,14n - A9,15d
A10,16	Energy equivalent of wasted meat for incineration	Flow M A10,16 × E_c of meat products
A10,17	Energy equivalent of wasted meat for composting	Flow M A10,17 × E_c of meat products
A10,18	Energy equivalent of wasted meat for biogas production	Flow M A10,18 × E_c of meat products
A15,0a	Energy equivalent of biodiesel	A9,15 × Biodiesel heating value
A15,0b	Lost energy in biodiesel production	A9,15 - A15,0a
A18,0a	Energy equivalent of biogas	A18,0h + A18,0i
A18,0h	Energy equivalent of biogas from manure	Flow M A18,0h × Efficiency of biogas production
A18,0i	Energy equivalent of biogas from meat waste	A10,18 × Efficiency of biogas production
A18,0b	**Lost energy in biogas production**	A8,18 - A18,0h + A10,18 - A18,0i
A0,1b	Animals husbandry PE	A0,1a/ Feed ratio in total energy input in animal production - A0,1a
A0,3	Slaughtering PE	Flow M A2,3 × Energy use in slaughtering (MJ/t)

A0,4	Meat processing PE	Flow M A3,4 × Energy use in processing (MJ/t)
A0,6	Retailing PE	Flow M A5,6 × Energy use in retailing (MJ/t)
A0,7a	Household PE	Flow M A6,7 × Energy use in household (MJ/t)
A0,7b	Out-of-home PE	Flow M A6,7 × Energy use out-of-home (MJ/t)

Note: CW_p = Carcass weight in production, CW_d = Dead animal carcass weight, CW_i = Carcass weight of imported animals, CW_e = Carcass weight of exported animals, DM_c = Dry matter content, $Innards_p$ = Innards in production, $Byproducts_p$ = Byproducts in production, Number of $animals_p$ = Number of animals in production, Number of $animals_d$ = Number of dead animals. PE = Process energy.