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D 2.6 Report on Life Cycle Assessment of five large scale anaerobic digesters employing nutrient recovery and reuse technologies

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Content

List of Abbreviations

AD	Anaerobic digestion
AeS	Acqua & Sole
AMP	AM-Power
BAT	Best Available Technology
Bio-LNG	Bio-liquid natural gas
Bio-CNG	Bio-compressed natural gas
CHP	Combined heat and power
CO_2	Carbon dioxide
CSTR	Continuous stirred-tank reactor
DAF	Dissolved air flotation
DCB-eq	Dichlorobenzene equivalents
GHG	Greenhouse gases
GLO	Global level
GZV	Groot Zevert Vergisting
kg	kilogramme
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^3	Cubic meter
MJ	Megajoule
MPF	Mixed plug-flow
N	Nitrogen
NRR	Nutrient Recovery and Recycling
P	Phosphorus
RER	Regional Code for Europe (in contrast to other global regions)
SO_2	Sulphur dioxide
tkm	Tonne-kilometre
UNFCC	United Nations Framework Convention on Climate Change
WNE	Waterleau NewEnergy

Preface

The objective of WP2 was to develop economic and environmental KPI's and to integrate these into business models in order to create economically viable business cases for nutrient recovery and recycling from biowaste. Information from the five demonstration plants (collected in WP1) was used to derive economic KPI's and environmental KPI's (impact categories). Environmental effects expressed in numeric values in different impact categories were derived in order to compare the sustainability of recovered products with their synthetic counterparts. The Life Cycle Impact Assessment (LCIA) assesses the impact of all processes at the AD plants (material and energy inputs, greenhouse gas emissions, waste and transport). Products are assessed in terms of replacing conventional fertilisers from cradle-to-farmgate. The impact of using the products in the field (risks for eutrophication, spreading of contaminants, greenhouse gas emissions) was assessed in an environmental impact assessment (EIA) in WP3.

The SYSTEMIC Description of Action (DoA) stipulates

- *Systemic will demonstrate at five Demonstration Plants the effective **combination of anaerobic digestion with novel nutrient recovery technologies** (TRL 7) for producing valuable fertilizers and soil amendments from EU's most abundant biowaste streams (manure, sewage sludge and food waste).*
- *Using **existing business cases and logistic chains as a starting point**, SYSTEMIC will develop enhanced Circular Economy business models and will demonstrate their commercial viability.*
- *To evaluate the environmental sustainability of the **eco-innovative systems compared** to the current common approach.*

These objectives have several implications on the performance of the LCA which are explained below:

a. The eco-innovative system to be assessed in comparison to conventional fertiliser production necessarily includes the biogas plant from which the fertilising product manufacturing cannot be separated. The biogas plant is the reaction chamber where chemical reactions take place providing the material composition for downstream nutrient separation. Biogas provides all the energy necessary for downstream processes – without biogas primary energy would be consumed that would have a relevant negative effect on the Life Cycle Impact Assessment. Evaluating the effect of NRR from, for instance, animal houses, would be a different project with certainly different results. Yet, this was not in the terms of reference for SYSTEMIC. On the contrary, the starting point of SYSTEMIC was that biogas plants concentrate substrate and consequentially nutrient flows in one plant which offers an opportunity for implementing nutrient recovery and recycling (NRR) systems. Also, it provides renewable energy for the involved processes. The critical question for the Life Cycle Assessment (LCA) was if the implementation of NRR systems would not eliminate the benefits of renewable energy production.

b. Comparison of plants, processes and products requires functional units that are present in all plants. All plants process substrate and all plants produce biogas, unanimously supported reason for referring all impacts to these functional units alternatively. Also, LCA standards and handbooks (e.g., ILCD Handbook [1]) recommend selecting functional units in regard to the main function of the assessed system. Yet, the selection of the functional unit does not hamper comparison of the various processes and recycled products with conventional mineral fertilisers. Also in other comparative LCA studies of recovered fertilisers like the most comprehensive one on behalf of the German Environmental Protection Agency [2], person equivalents (PE) were chosen as functional unit for comparing the environmental impact of recovered fertilisers from wastewater treatment plants due to the fact that the main function of a sewage plant is treating wastewater and not producing fertilisers. In this study, comparison of biogas plant operation with and without nutrient recycling is provided as is the environmental effect of processes and products in comparison with conventional mineral products. All obligations as stipulated in the DoA are therefore fulfilled.

c. The impact of products in the field depends primarily on the timing and method of application and on external factors – weather, temperature, soil. Influence is more pronounced on organic fertilisers than on mineral products. The EIA of the only pure mineral product of SYSTEMIC, ammonium sulphate, showed at least equivalent or superior emission characteristics in comparison to conventional mineral N fertilisers. The EIA of recovered organic fertilisers showed, as expected, an inclination to higher losses. Yet, as losses of nutrients from organic fertilisers depend on the application and external factors, ammonia N (NH_3) losses can range between 5% and 95%. High, application-related variability of nutrient losses makes comparison of products impossible, except for the general – EIA-based – outcome that organic fertilisers have a higher inclination (risk) to nutrient losses compared to mineral ones. Adequate handling avoids losses, but handling is not a product and process feature and was not subject to the research in SYSTEMIC. To exclude handling and external factors from influencing the result of the LCA, the system boundaries were unanimously set with cradle-to-farm gate. Consequently, the LCA covers transports but does not cover nutrient losses from the field.

The core element of a Life Cycle Assessment (LCA, representing the entire study) is the Life Cycle Impact Assessment (LCIA), providing information on the environmental effect of processes and products on different environmental spaces – air, soil, water and humans called impact categories, representing the key performance indicators of an LCIA. The impacts are measured in numeric units while several substances or gases are transferred to one specific unit, such as all greenhouse gas emissions are expressed in kg carbon dioxide-equivalents ($CO_{2\text{-eq}}$) or all chemical substances with potential toxic effects are expressed in kg Dichlorobenzene-equivalents (kg DCB-eq).

A LCA does not give absolute answers to critical questions in regard to the environmental impact of certain processes or products. It is a decision support tool, most useful to provide comparative greenhouse gas emission indicators and indicators for other environmental effects such as toxicity effects on various environment systems and humans. In regard to recycled nutrient carriers, studies have exhibited that certain products have a much higher impact than their conventional equivalent [2]. It makes clear that the corresponding processes should either be substantially improved or abandoned. Yet, this is rather an exception. In most cases, LCAs exhibit a trade-off between various impacts and parties taking the LCA as a decision support tool must weigh advantages and disadvantages to draw conclusions. Also, decision makers must seriously consider the true origin of the impact. In this study, road transport has a relevant impact in several categories. The critical question is, if road transport is due to the assessed system or, for instance, to the high livestock density in a region. If livestock density is the true cause of transport, its impact in the LCIA must be put into perspective. Putting the results into perspective is an essential element of the interpretation stage within the LCA. Consequently, do not expect general answers but rather a tool for better assessment of the environmental effects of an activity.

Introduction

After assessing and reporting the regulatory framework in EU28 and across member states, evaluating the business cases of five demonstration plants and one outreach plant project (accessible at www.systemicproject.eu and https://library.wur.nl/) and developing key performance indicators the team eventually started working on the Life Cycle Assessment (LCA) of the processes and products of our SYSTEMIC partner plants.

Whereas evaluation of the legal framework and the business case has become an accepted requirement for starting a new business – the first for acting in compliance with legislation and the second for having access to finance and generating a return – Life Cycle Assessment is mostly performed by scientists in the course of joint research and innovation projects. Permitting authorities and banks do not ask for an LCA and only large projects with a relevant local impact are subject to an environmental impact assessment – a systematic process that assesses the local and regional impact of a (manufacturing or waste treatment) facility but not the potential environmental impact that a product may have during its life cycle. In addition, the environmental impact assessment does not take into account the impact the feedstock may have had at the place of its origin.

Since 2015, when the Paris Agreement (COP21) (UNFCCC, 2015) [3] and the Sustainable Development Goals (SDGs) (United Nations, 2018) [4] were adopted by virtually all United Nations, the focus is gradually shifting, and greenhouse gas emissions of new processes get more attention. Indeed, the LCA can tell investors and operators if a new process is more or less beneficial in terms of several environmental impact categories including greenhouse gas emissions, eutrophication and acidification. Performing an LCA in an early stage of process and product development would avoid being led astray and save millions of Euros assigned to research and development projects by private equity and public funding agencies. Past LCAs have produced unambiguous evidence that processes causing high environmental impacts usually turn out to be complicated and expensive, high impact feed materials are usually rather costly and high greenhouse gas emissions are typically associated with high fossil energy consumption.

Of capital importance is, of course, that the new process / product has lower impacts than the process / product to be replaced. When dealing with relevant mass fractions of effluents, regardless of being considered a waste or a by-product, the initial focus may be reducing the flows and saving handling, storage and disposal costs. Costs may be distorted by elements that have nothing to do with environmental impacts and processes may become commercially viable that have a much higher impact than the old practices. However, even if such process were commercially viable, its footprint should either be improved, or the process not be financed and developed.

In the context of a Circular Economy, recycling processes are generally promising, but they are in competition with processes which have been adjusted towards higher efficiency for decades and consequently may not have a substantial environmental impact in new plants using the best available technology (BAT). In comparison to conventional processes a trade-off between higher resource efficiency – the minimum you can expect from a recycling process – and higher energy consumption may be encountered. Normalisation of the LCA results, i.e. calculating the per capita share of the resulting impact, can show if the resource efficiency gains are justifying or not higher energy expenses. This is of course more likely if renewable energy can be used, if not now, than in a near future. Producing phosphate fertilisers is a good example for this – no substantial impact during production, only use has relevant impacts due to eutrophication and cadmium, if present. Eutrophication can be abated by smart use and pollutants can be avoided by removing them, regardless of virgin or recycled products.

As for many nutrient recycling activities, technologies are driven by reducing the mass flows and saving handling, storage and transportation costs. Business case evaluation has provided clear evidence that SYSTEMIC technologies improve the financial results of the digestion plants. D2.6 reports sustainability indicators for the produced secondary products by means of a LCA study which includes possible positive and negative side-effects and risks, such as those associated with CO_2 emissions and toxicity effects of transport or potentially harmful substances present in digestates, derived products and chemicals used for their production.

Summary

This report, conducted within the Work Package 2 'Business Case Innovation' of the EU-funded project SYSTEMIC, intends to display the status-quo of the overall work performed within Task 2.4: 'Life Cycle Assessment'. At the end of this task, Deliverable 2.6 'Final report on LCA assessment and sustainability indicators' will provide LCAs of the five demonstration plants participating in the project, as well as their nutrient recovery and recycling technologies. A detailed risk and environmental impact assessment of using the products of these processes is part of WP3.

Life Cycle Assessment is a method developed to assess the possible environmental impacts of processes and products. It is defined in the International standard ISO 14040/44 (2006) [5] [6] and consists of four phases: i) goals and scope, ii) inventory assessment, iii) impact assessment and iv) interpretation.

Goals and scope, reference flows, system boundaries and impact categories were unanimously decided within the consortium.

This report displays the overall positive Life Cycle Impact of biogas plants and their Nutrient Recovery and Recycling (NRR) processes and provides an assessment of their contribution to a more sustainable and green future. All demonstration plants have a positive effect in all impact categories except terrestrial ecotoxicity which shows a negative effect for all plants, essentially due to transporting either the substrates or the digestate and derived products. Not surprisingly, the energy related impacts are gradually less positive after consideration of NRR systems – they consume energy – while the transport related effect is less negative correspondingly.

The environmental effects of NRR systems are always small in relation to the overall positive effect of biogas plants, mainly due to the effect of converting waste to renewable energy carriers. To put the effects into context: the average CO_2 footprint of a European citizen is 7-10 tons $CO_{2\text{-}eq}$ per year. The annual $CO_{2\text{-}eq}$ savings are 40,000-44,000 $CO_{2\text{-}eq}$ per year. Consequently, CO_2 emissions of 4,000-6,000 Europeans are saved every year. Alternatively, one could also say that biogas plants could save the equivalent of 1-2% of the emissions of an average European citizen if all biowaste generated by the person is used for energy conversion and nutrient recovery. Even if the individual impacts of NRR systems are quite small, their overall effect could be important: NRR systems frequently enable the whole plant which may not be feasible without an NRR system, as shown by the Acqua & Sole plant. In these cases, NRR is responsible for the whole positive impact of the plant, even if its environmental effect is small.

1. Goals and Scope

1.1 Goals

The goal of the Life Cycle Assessments conducted under Task 2.4 of WP2 of the SYSTEMIC project funded from the European Union's Horizon 2020 Framework Programme for Research and Innovation under Grant Agreement no. 730400 is the assessment of the environmental impacts of the Nutrient Recovery and Recycling (NRR) installations of the 5 Demonstration plants that are part of the consortium of the SYSTEMIC project. The environmental impacts of nutrient recovery installations and products are exhibited separately to investigate their environmental benefit in addition to the economic impacts and benefits that are investigated in Task 2.2 and Task 2.3 of WP2 and that are usually the driver and main reason for owners and operators to invest in advanced nutrient management systems. Therefore, each AD plant is assessed with and without implemented NRR systems to investigate the Life Cycle Impact (LCI) of NRR solutions.

The targeted audience of this Deliverable are stakeholders in the biogas and waste management industry who may implement NRR solutions in existing or future Anaerobic Digestion (AD) operations as well as policy makers that may use the results as a decision support to foster the development of NRR in the biogas sector or biogas in general.

1.2 Scope

1.1.1 Function and functional unit

The systems that are investigated within this report are Anaerobic Digestion plants that have their primary purpose in transforming biodegradable substrates into Methane, which is either i) sold directly, ii) upgraded to higher value products (purified Methane, bio-LNG or bio-CNG) or iii) directly transformed to electric energy and heat via combustion on site. A large variety of substrates are being used for this purpose and can be divided into two separate groups: i) primary sources or energy crops, produced exclusively for energy generation and ii) secondary sources or biowastes, like livestock manure, food waste and sewage sludge, all of which having distinctive characteristics and challenges. NRR systems are installed mainly for three reasons: i) to improve the efficiency of methanation, ii) to enable the use of N-rich substrates (e.g.: chicken litter) or iii) to reduce (transport) costs related to the disposal of nutrient rich digestates.

Looking at input substrates and motivation behind NRR systems implementation, the secondary purpose of AD plants and the idea behind SYSTEMIC project comes into focus: biowaste management. The role of the AD technology as a holistic solution for biowaste treatment and recycling is to become the second main pillar of the biogas sector after Methane (energy) production.

The definition of the functional unit is essential for modelling a process / product system in an LCA. The functional unit should represent the main function of a system and – in comparative LCAs – must be present in every single unit of the systems to be compared. Also, the functional unit does not determine the subject of comparison, e.g., NRR systems. The environmental effect of bio-based fertilisers produced in the biogas plants is directly compared to the effect of conventional fertilisers, regardless of the functional unit chosen. Bio-based fertilisers produced in the plants cannot be selected as functional unit due to not being present in all plants. E.g., some plants produce ammonium sulphate, some nutrient depleted fibres, etc. Taking nutrients, N or P, as functional unit is not meaningful either. Supplying N or P is definitely not a function of the plants. In some cases, the objective of NRR systems is the contrary, separating nutrients to a concentrated stream and producing a nutrient depleted, solid or liquid fraction.

Based on the two pillars of anaerobic digestion plants and in compliance with the condition of being present in each individual system, two functional units are defined:

- The primary or "Energy Perspective" of biogas plants is the most efficient production of Methane as an energy carrier. The corresponding functional unit is **per cubic meter (m^3) of CH_4 produced for market or electricity generation for market (electricity to grid)**.
- The secondary or "Waste Management Perspective" of biogas plants is the most effective management of biowastes and their conversion into products or secondary raw materials. The corresponding functional unit is **per metric ton of substrate**.

1.1.2 Reference flows

Since the goal of this LCA is to investigate the impact of implemented NRR solutions, the reference scenario is the same AD plant without NRR systems installed. In most cases NRR systems were installed after the initial AD plant started operating, only Acqua & Sole was initially planned with an NRR system.

The reference flows for the products produced are described in table 1.1 below. Reference flows are the products / energy carriers replaced by renewable energy carriers, materials, products as an output of the assessed processes. 1 kg of P or N in fertilisers produced by the demonstration plant replaces 1 kg of P or N in reference flows. For P, the reference flow is P in superphosphate. For N, the reference flow is N in typically used inorganic nitrogen fertilisers. The environmental impact of reference products is defined in the ecoinvent database, release 3.7.1. Ecoinvent collects and hosts manufacturing data for a large number of industrial processes which are based on real industry data. Data for fertilisers are included in the sectors for Agriculture, Animal Husbandry, and Chemicals. Ecoinvent v3.7.1 includes new and updated data on mineral fertiliser production from Yara International ASA and Fertilizers Europe, submitted in collaboration with Quantis (WFLDB). Further, the markets and market mixes for the fertilisers sector have been generally restructured and updated, separating now the provision of organic and mineral fertilisers for nutrient supply. More detailed information on ecoinvent and its database background can be found at https://ecoinvent.org/.

Table 1.1 Table of reference flows of products

Product	Unit	Reference flow
Biogas (methane)	m^3	GLO: market for natural gas, high pressure ecoinvent 3.7.1
Electricity	MJ	RER: market group for electricity, medium voltage ecoinvent 3.7.1
Nutrient rich products, P	Kg	RER: triple superphosphate production ecoinvent 3.7.1
Nutrient rich products, N	Kg	RER: market group for inorganic nitrogen fertiliser, as N ecoinvent 3.7.1

The reference flows for chemicals, additives and transport are described in table 1.2. In contrast to renewable materials and energy produced by the biogas plants and replacing standardised industrial products, chemicals used in NRR processes are standardised industrial products. Their environmental impact is taken from the ecoinvent 3.7.1 database as defined in the table 1.2. For instance, the unit for transport is 1 ton per kilometre (1 t/km) in a EURO6 class truck with a transport capacity of 16-32 tons.

Table 1.2: Reference flows of chemicals, additives and transport

Substance	Unit	Reference flow
Sulphuric acid	Kg	RER: market for sulfuric acid ecoinvent 3.7.1
Polyacrylamide	Kg	GLO: polyacrylamide production ecoinvent 3.7.1
Transport	t/km	RER: transport, freight, lorry 16-32 metric ton, EURO6 ecoinvent 3.7.1

1.1.3 System boundaries

The boundaries of the conducted LCAs can be defined as 'Gate (including transport from cradle) to gate (including transport to grave). This unique approach was chosen due to the specific circumstances of investigate processes, where the main (economic) drivers for NRR is reduction of transport costs and/or the enablement of exploitation of closer markets.

Following processes are within the system boundaries:

- Anaerobic digestion plant (thermophilic/mesophilic, CSTR/MPF)
- CHP
- Solid/liquid separation facilities (centrifuge, screw press)
- Dryer (e.g.: rotary drum dryer)
- Stripper (Ammonium-stripper)
- Scrubbers
- Evaporators
- Reverse osmosis reactors
- Microfiltration reactors
- Biogas storage tanks
- Biogas Upgrading facilities (e.g.: bio-LNG, bio-CNG)
- Flotation reactors
- Acidification and struvite reactors
- Dissolved air flotation (DAF) reactors
- Auxiliary systems (e.g.: pumps, elevators)
- Transport (including transport from origin of substrate and to destination of product)

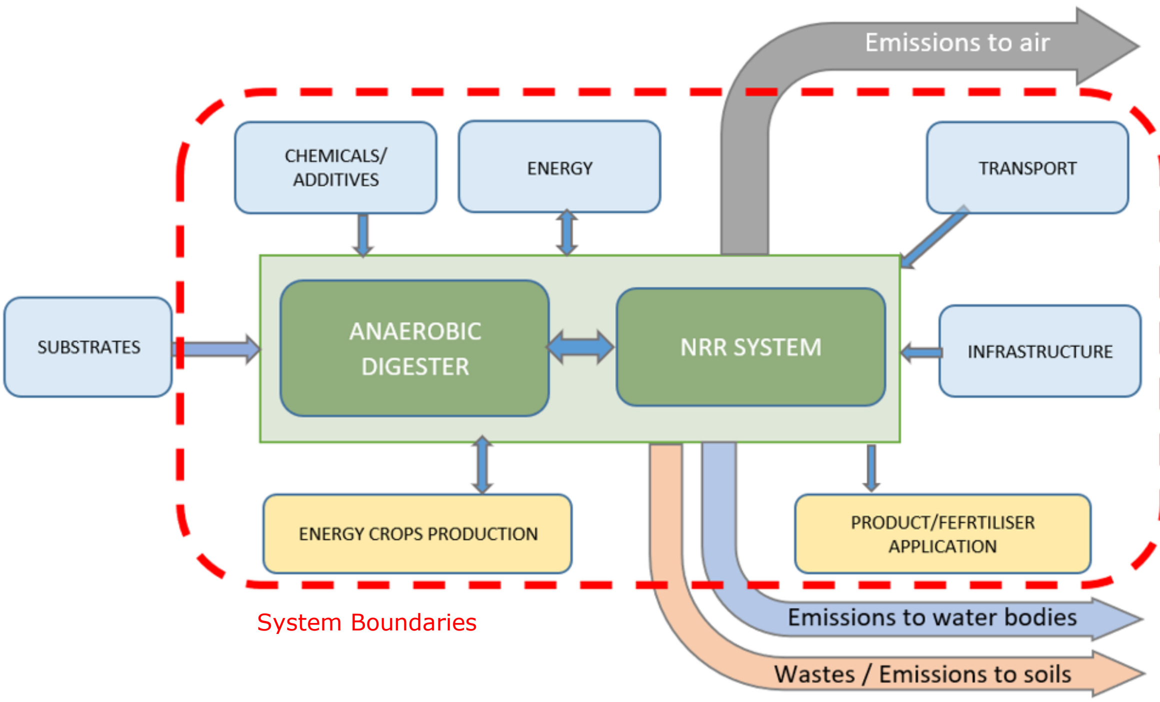


Figure 1.1 System boundaries

1.1.4 Impact categories and category indicators

The impact categories and corresponding environmental indicators were selected according to their relevance observed in comparable life cycle assessments. In this study, the indicators of the ReCiPe rating system (Huijbregts et al., 2017) are mainly taken into account for reasons of comparability and transferability of the results to other papers. In order to quantify and assess the impact of energy crop production, the impact category agricultural land use potential, defined as m^2/yr, is introduced. This allows a comparison to food/feed production or other possible utilisation of arable land.

Following environmental impact categories are investigated:

- Fossil depletion
- Climate change
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication
- Human toxicity, cancer
- Human toxicity, non-cancer
- Freshwater ecotoxicity
- Marine ecotoxicity
- Terrestrial ecotoxicity

During the Life Cycle Impact Assessment (LCIA) of an LCA, different emissions and environmental effects are converted into one indicator per impact category. Different emissions that cause the same impact- are converted into one unit that represents the impacts of different substances / compounds and makes them comparable.

For example, the impact category 'climate change' is expressed in kg CO_2 equivalents (kg CO_2-eq). Yet, other greenhouse gases such as methane (CH_4) or laughing gas (N_2O) also cause climate change. By converting the other greenhouse gas emissions to kg CO_2 equivalents, it is possible to have one single, comparable metric for climate change.

Similarly, all compounds causing freshwater eutrophication are expressed in kg P-eq, all compounds causing marine eutrophication are expressed in kg N-eq and all acidification causing compounds are converted and expressed in kg $SO_{2\text{-eq}}$. Eventually, all emissions and chemical compounds causing toxicity are expressed in 1,4 DCB-eq (dichlorobenzene-eq), an indicator based on a table with several thousand CAS-registered compounds which are all converted to and expressed in 1,4 DCB-eq.

Impact categories – KPIs for environmental effects

Impact categories have a similar function for environmental effects as KPIs for economic effects. They group complex data into accessible numbers – numbers that give a concrete picture of what the impact actually is.

These environmental impact categories each correspond to one environmental category indicator as displayed in table 1.3.

Table 1.3 Category indicators

Category indicators	Unit	Mostly generated by	Method/Model
Fossil depletion	kg oil eq.	Coal, gas, oil, uranium	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)
Climate change, default, excl. biogenic carbon	kg CO_2-eq	CO_2, CH_4, N_2O	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)
Terrestrial acidification potential TAP	kg SO_2-eq	SO_2, NO_X, NH_3	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)
Freshwater eutrophication potential FEP	kg P-eq	Phosphate	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)

Marine eutrophication potential MEP	kg N-eq	Nitrate	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)
Human toxicity, non-cancer	kg 1,4-DCB-Eq	Heavy metals and chemical compounds with an impact on the target system	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)
Human toxicity, cancer	kg 1,4-DCB-Eq	Heavy metals and chemical compounds with an impact on the target system	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)
Freshwater ecotoxicity potential FETP	kg 1,4-DCB-Eq	Heavy metals and chemical compounds with an impact on the target system	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)
Marine ecotoxicity potential METP	kg 1,4-DCB-Eq	Heavy metals and chemical compounds with an impact on the target system	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)
Terrestrial ecotoxicity potential TETP	kg 1,4-DCB-Eq	Heavy metals and chemical compounds with an impact on the target system	ReCiPe 2016 v1.1 Midpoint (H) (Huijbregts et al., 2017)

For reasons of comparability, relevance and transferability of results, the hierarchical perspective (H) of the ReCiPe Midpoint (Huijbregts et al., 2017) [7] approach is chosen, neglecting long-term emissions after more than 100 years. This time horizon is sufficient for strategic considerations over several generations and at the same time limited to a foreseeable period of time in regard to future developments.

1.1.5 Allocations and assumptions

Following rules for allocation are established and assumptions taken:

1. If nutrients (nutrient rich streams) are recovered / recycled for the sole purpose of converting / using / selling them as renewable fertiliser or other products, energy and / or any other impact will be allocated to the very process of nutrient recovery / recycling (recovered product respectively).
2. If nutrients are eliminated from the process for any other reason, like e.g.: enhancement of biogas production or enabling of a more profitable substrate input, the corresponding impact(s) is allocated to the process of methane (biogas) production.
3. All substrates, apart from energy crops, are considered as waste, and therefore do not have an environmental impact relevant to this report.

1.1.6 Types, sources and quality of data

The LCAs conducted within this report are based on data collected in WP1 of the SYSTEMIC project. This data is collected and / or measured directly at the participating Demonstration and Outreach AD plants and updated annually. The quality of this data is considered as 'high.'

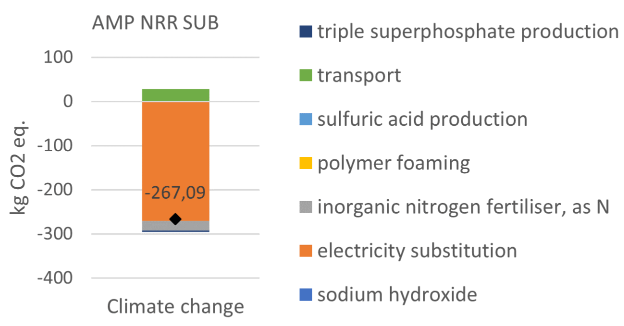
All other relevant data is provided by the ecoinvent v.3.57.1 and GABI databases, a commonly accepted dataset and state-of-the-art in the sector and is therefore classified as 'medium / high.'

2. RESULTS: LCIA (Life Cycle Impact Assessment) & Interpretation

Reading and understanding results:

Graphic representations as bar charts show positive and negative values and a numeric value indicating the result of the impact category assessed. Positive values stand for negative impacts whereas negative values stand for positive environmental impacts as all impacts are measured against reference scenarios. Zero would mean the same impact as the reference scenario. Higher positive value = higher environmental impact; lower positive or higher negative value = lower environmental impact compared to the reference scenario.

Example:



The bar goes from -300 to +100, the numeric value is -267.09 kg CO_2-eq showing savings of 267.09 kg CO_2-eq per ton of substrate treated compared to the reference scenario. The negative impact is transport, the main positive impacts are renewable electricity and substitution of mineral N and P fertilisers.

If the positive side of the bar exceeds the negative side, the activity has a negative impact in the corresponding category. If the negative side exceeds the positive side, the activity has a positive impact in the corresponding category.

As the following figures will show, electricity substitution, N-fertiliser replacement and transport are the AD+NRR based activities that have typically the highest, mostly positive environmental effect.

2.1 Acqua e Sole S.r.l. (AeS)

2.1.1 Introduction

Fig. 2.1: AES plant

Acqua e Sole S.r.l., a thermophilic anaerobic digestion plant in Vellezzo Bellini (30 km south of Milan), Pavia, Lombardy, Italy, in operation since 2016 with a total annual substrate processing capacity of 120,000 tonnes. Processing municipal sewage sludge and source separated domestic food waste.

2.1.2 Life Cycle Impact Assessment - LCIA

2.1.2.1 Acqua e Sole (AeS) with NRR, Functional Unit m³ CH_4

Fig. 2.2: LCIA – Acqua e Sole with NRR per m³ CH_4

2.1.2.2 Acqua e Sole (AeS) with NRR, Functional Unit t of Substrate

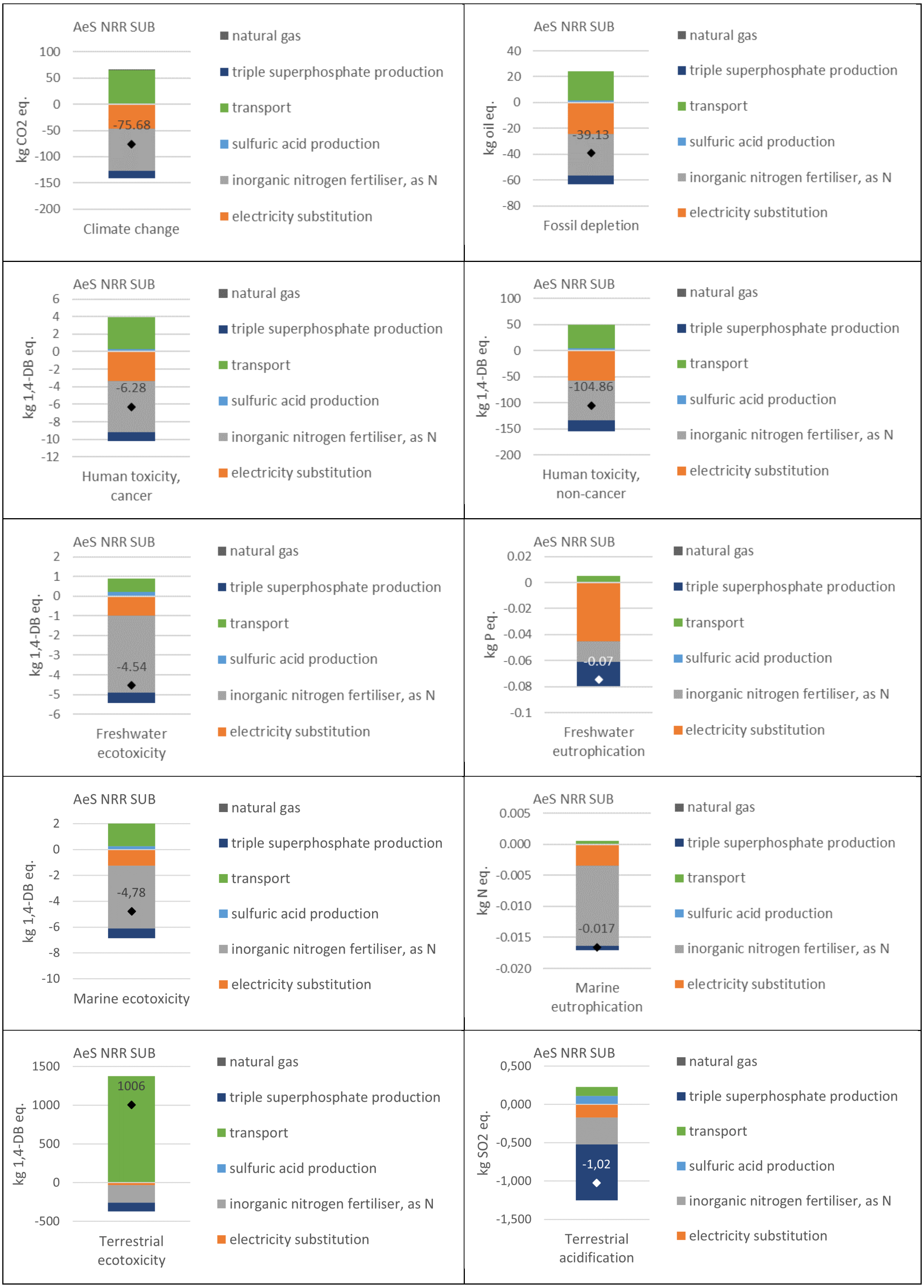


Fig. 2.3: LCIA – Acqua e Sole (AeS) with NRR per t substrate

2.1.2.3 Acqua e Sole (AeS) with NRR, total annual impact of the system

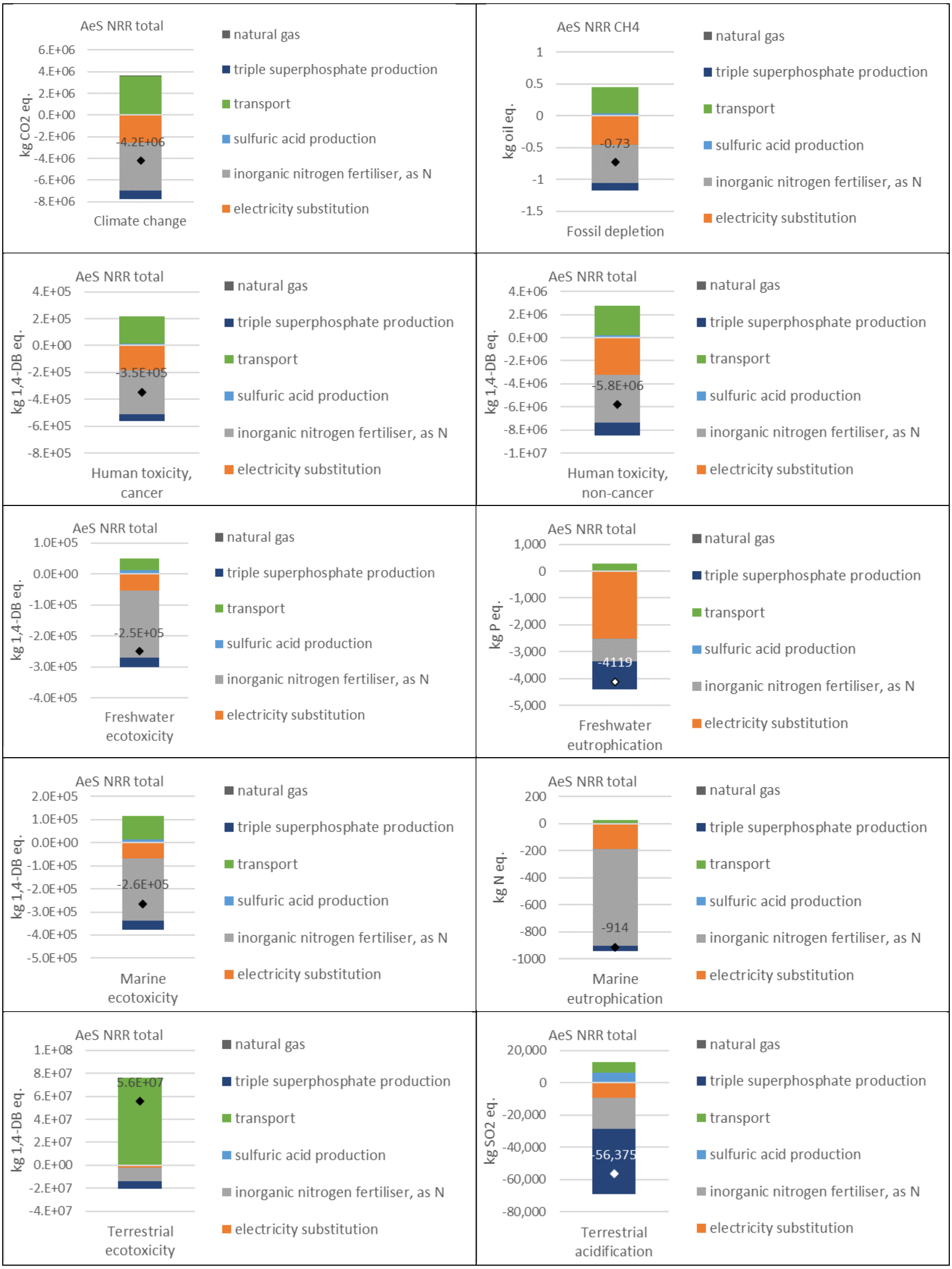


Fig. 2.4: LCIA – Acqua e Sole (AeS) with NRR total annual impact

2.1.3 Interpretation of the total annual impacts

Acqua & Sole is the only case where the NRR system was an integral part from the initial planning and construction phase onwards. This is due to the nature of the concept – to valorise sewage sludge as an energy and nutrient source. The high nitrogen content of sewage sludge would inhibit biogas-conversion (methanation) by anaerobic digestion by about 50% and therefore reduce biogas yield and – in this case – would hamper hygienisation. Therefore, the facility cannot be compared to a non NRR solution, which on the other hand makes a compelling case for NRR technologies.

However, there are interesting and important outcomes of the LCIA. The Acqua & Sole case has a highly positive environmental effect, i.e., negative numeric scores in all impact categories except terrestrial ecotoxicity due to the transport of substrates over comparatively large distances. The biogas + NRR system saves about 4,200 t/y CO_2-eq mainly due to replacement of mineral fertilisers and waste conversion to renewable electricity. 2,200 t/y oil equivalents are saved in regard to fossil depletion. Freshwater and marine indicators show benefits of up to several hundred tons/year N, P and DB-eq as are human toxicity indicators. Human toxicity scores stand out with benefits of 5,800 t/y DB-eq.

Rather large transport distances for the input substrates result in reduction of $CO_{2\text{-eq}}$ savings by almost half (3,500 t/y $CO_{2\text{-eq}}$) and in a comparatively high terrestrial ecotoxicity of about 56,000 t/y DB-eq. The corresponding impact is equivalent to about 25,000 t*km/y road transport in an EURO6 truck of 16-32 t capacity (1 t*km/y ~ 2.21 kg 1,4 DB-eq) [8]. The digestate and digestate derived products are used in the vicinity of the plant.

2.2 AM-Power

2.2.1 Introduction

Fig. 2.5: AM-Power plant

AM-Power BVBA, a thermophilic anaerobic digestion plant in Pittem (40 km west of Ghent), West-Flanders, Belgium, in operation since 2011 with a total annual substrate processing capacity of 180,000 tonnes. Processing source separated biowaste.

2.2.2 Life Cycle Impact Assessment - LCIA

2.2.2.1 AM-Power (AMP) without NRR, Functional Unit m³ CH_4

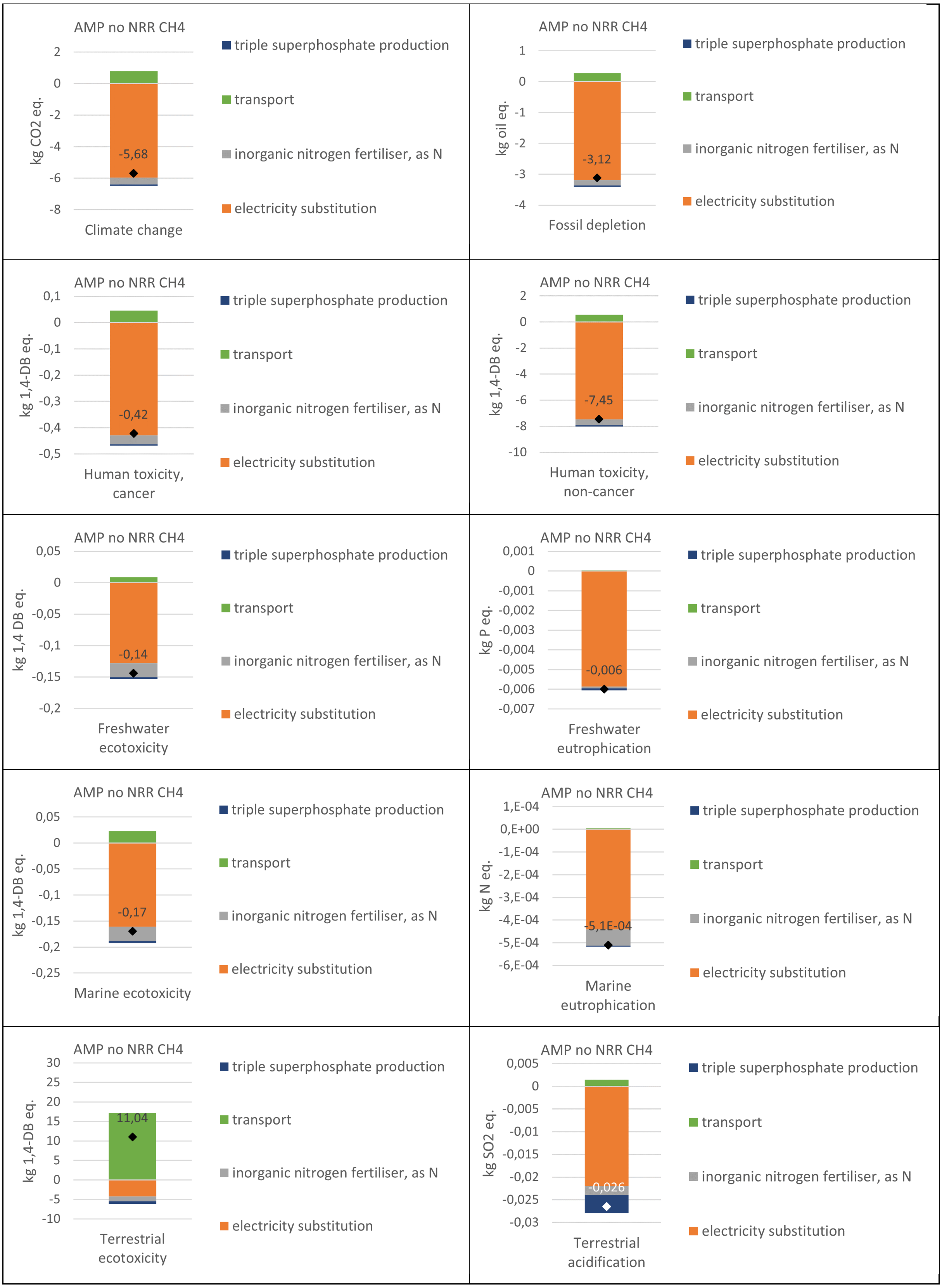


Fig. 2.6: LCIA - AM-Power (AMP) without NRR per m³ CH_4

2.2.2.2 AM-Power (AMP) with NRR, Functional Unit m³ CH_4

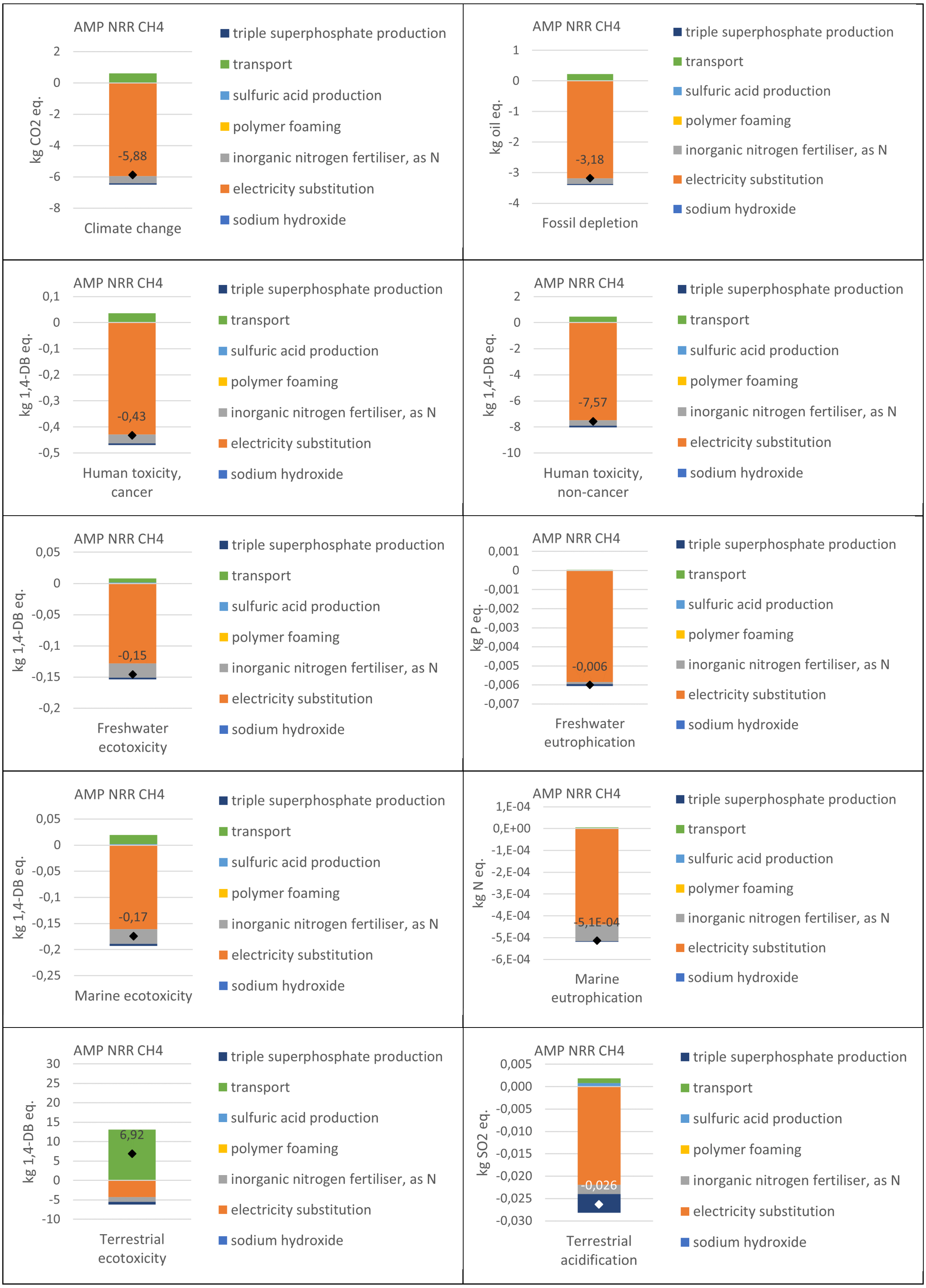


Fig. 2.7: LCIA - AM-Power (AMP) with NRR per m³ CH_4

2.2.2.3 AM-Power (AMP) without NRR, Functional Unit t of Substrate

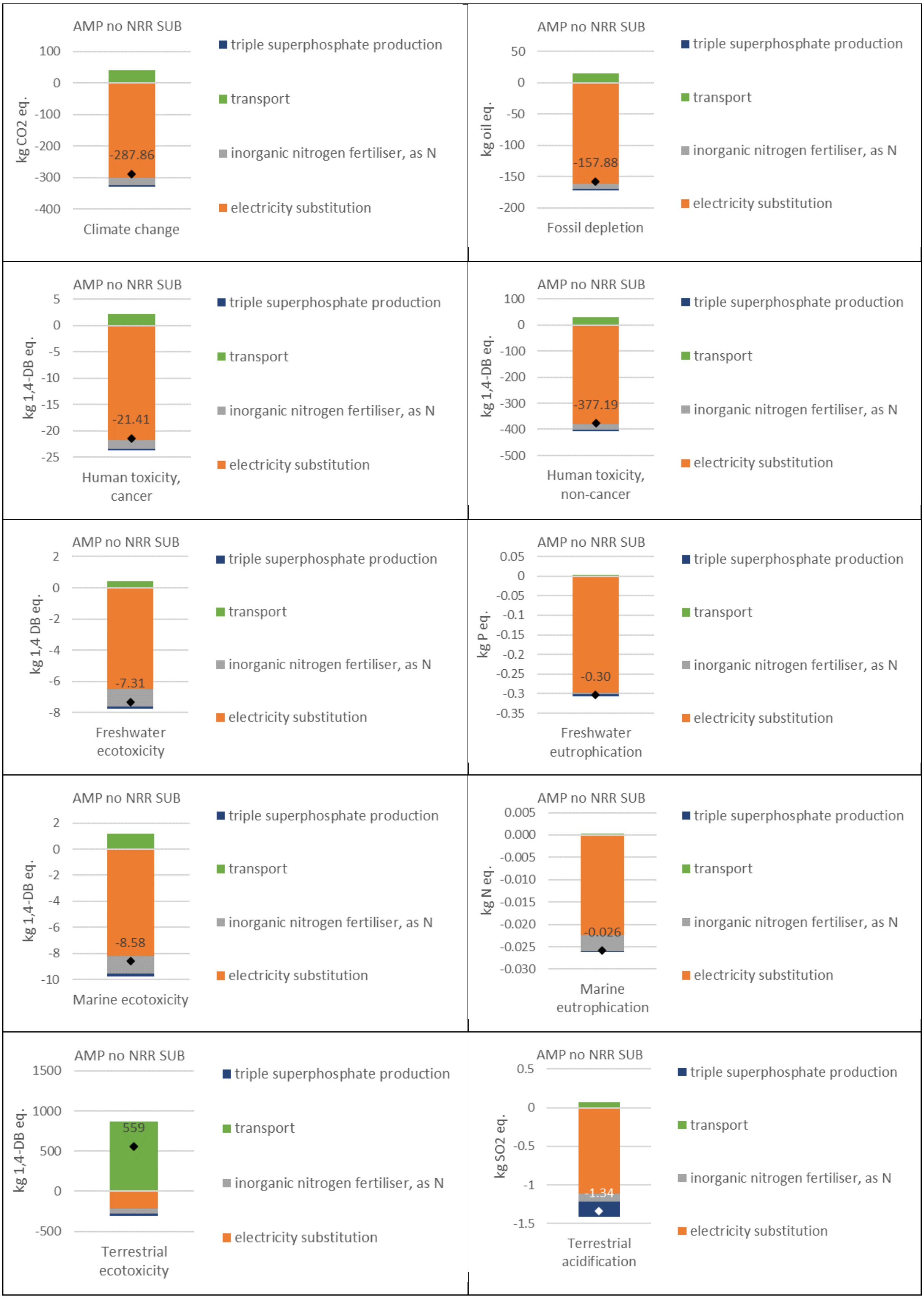


Fig. 2.8: LCIA - AM-Power (AMP) without NRR per ton of substrate

2.2.2.4 AM-Power (AMP) with NRR, Functional Unit t of Substrate

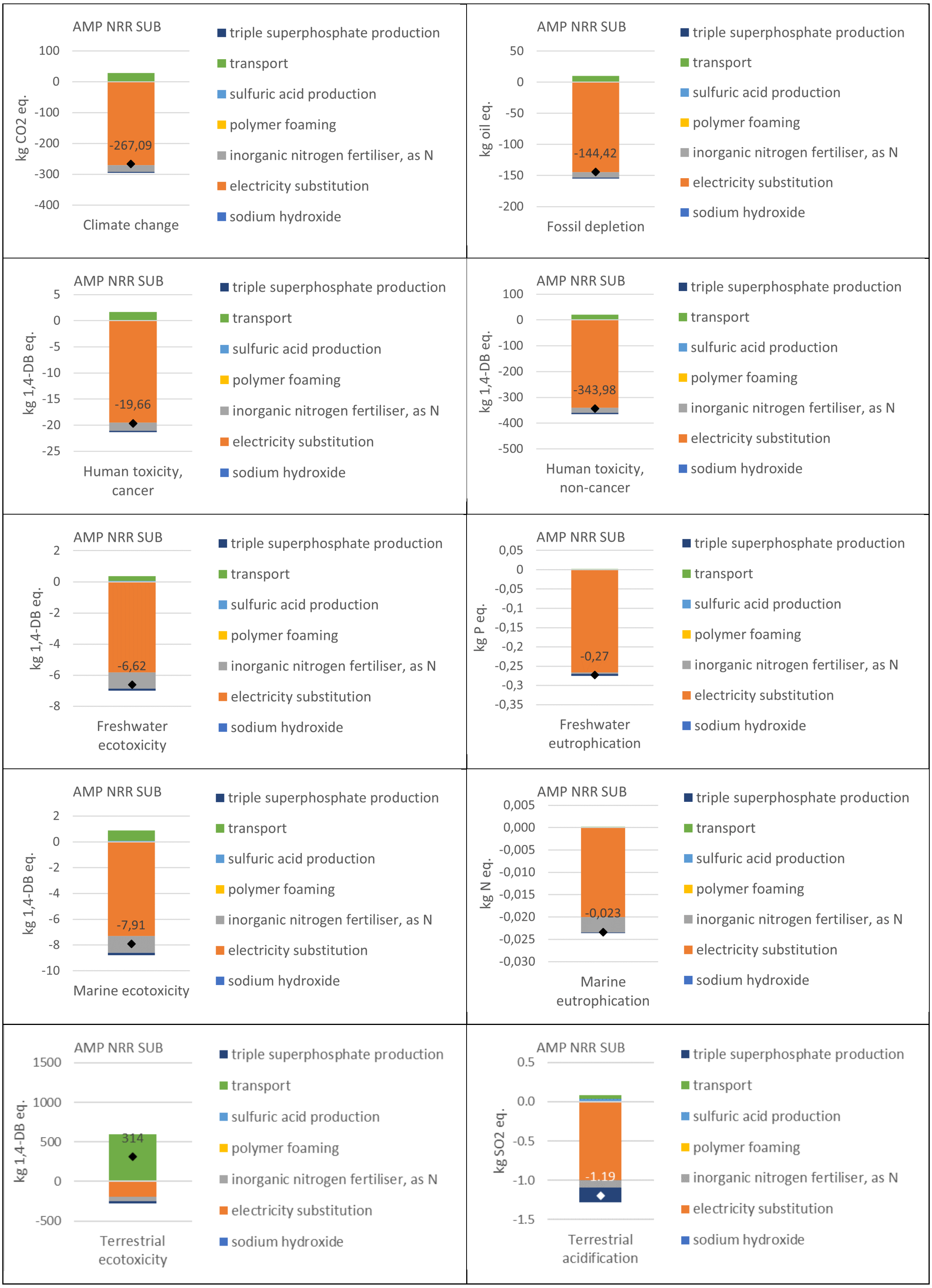


Fig. 2.9: LCIA - AM-Power (AMP) with NRR per ton of substrate

2.2.2.5 AM-Power (AMP) without NRR, total annual impact of the system

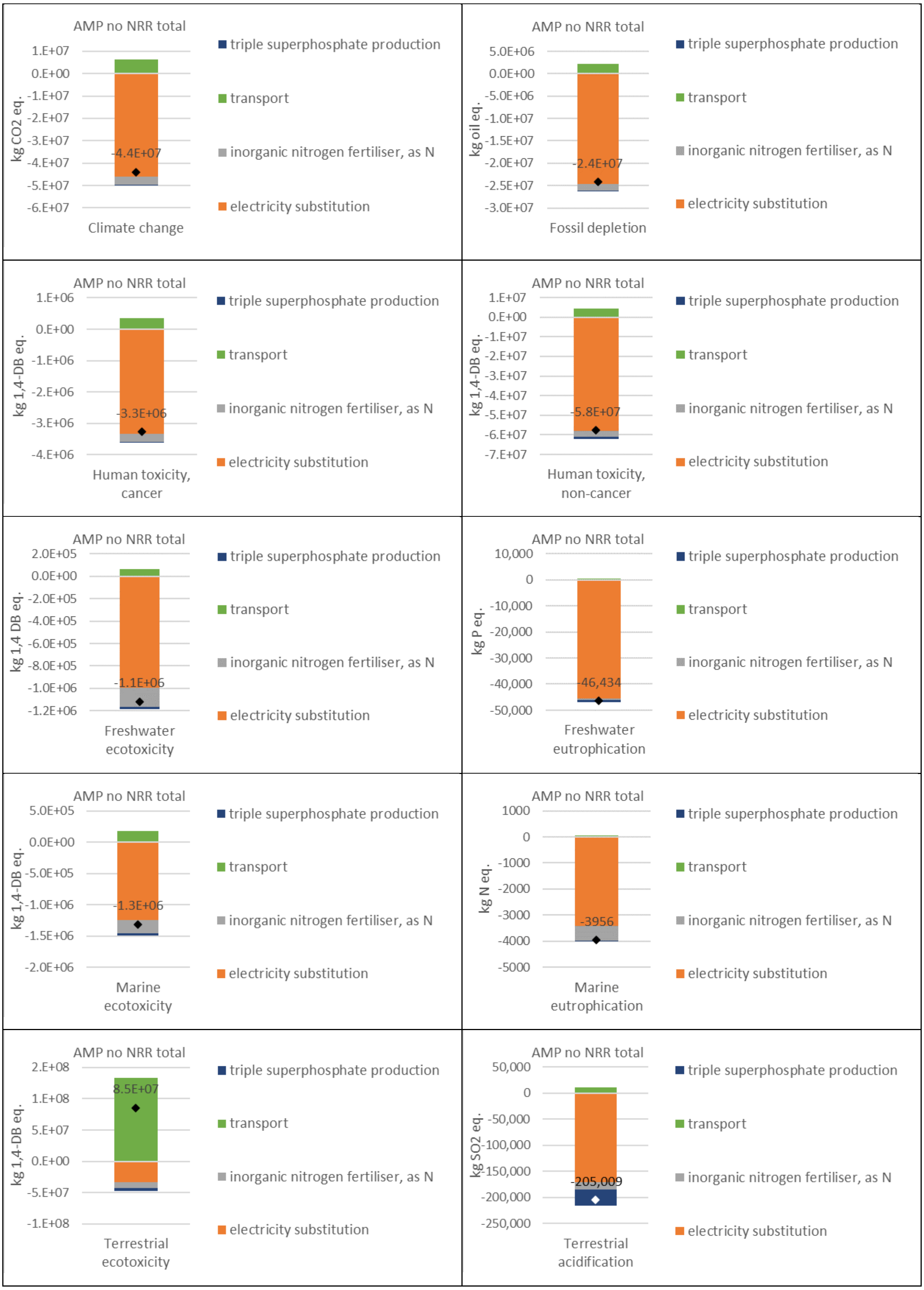


Fig. 2.10: AM-Power (AMP) without NRR total annual system impact

2.2.2.6 AM-Power (AMP) with NRR, total annual impact of the system

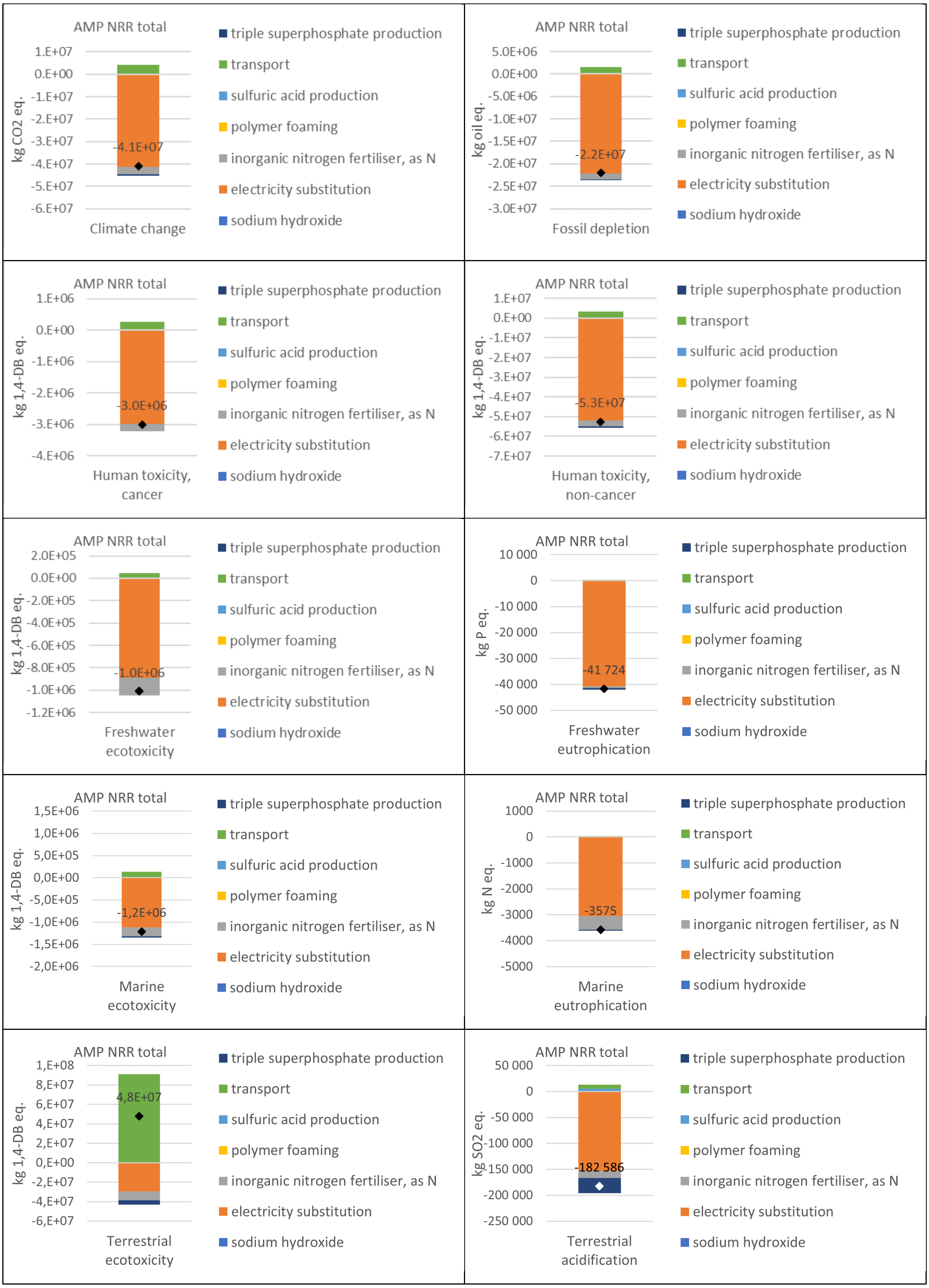


Fig. 2.11: AM-Power (AMP) with NRR total annual system impact

2.2.3 Interpretation

The AM Power facility has integrated NRR solutions for the above (goals and scope) elaborated economic factors. Through extracting nutrients and creating higher value products, closer and more attractive markets should be exploited. Savings of CO_2-eq are the highest of SYSTEMIC demonstration plants with over 41,000 t CO_2-eq/year and a comparatively small difference of only 9% between operating and not operating NRR systems, showing that the NRR system installed is very energy efficient, ranging in the top of SYSTEMIC plants. Fossil depletion savings amount to 22,000 t per year of oil equivalents, also an outstanding result. All other impact categories show savings in different orders.

The only negative impact is again on terrestrial ecotoxicity. The NRR system improves the negative effect significantly, from 85,477 t 1,4 DB-eq to 48,063 t 1,4 DB-eq, almost halving the initial impact. The equivalent of about 17,000 t*km of road transport are saved [8].

2.3 BENAS

2.3.1 Introduction

Fig. 2.12: BENAS plant

BENAS GmbH, a thermophilic anaerobic digestion plant in Ottersberg (40 km east of Bremen), Lower Saxony, Germany, in operation since 2006 with a total annual substrate processing capacity of 174,000 tonnes. Processing corn silage, plant residues and poultry litter.

2.3.2 Life Cycle Impact Assessment - LCIA

2.3.2.1 BENAS without NRR, Functional Unit m³ CH_4

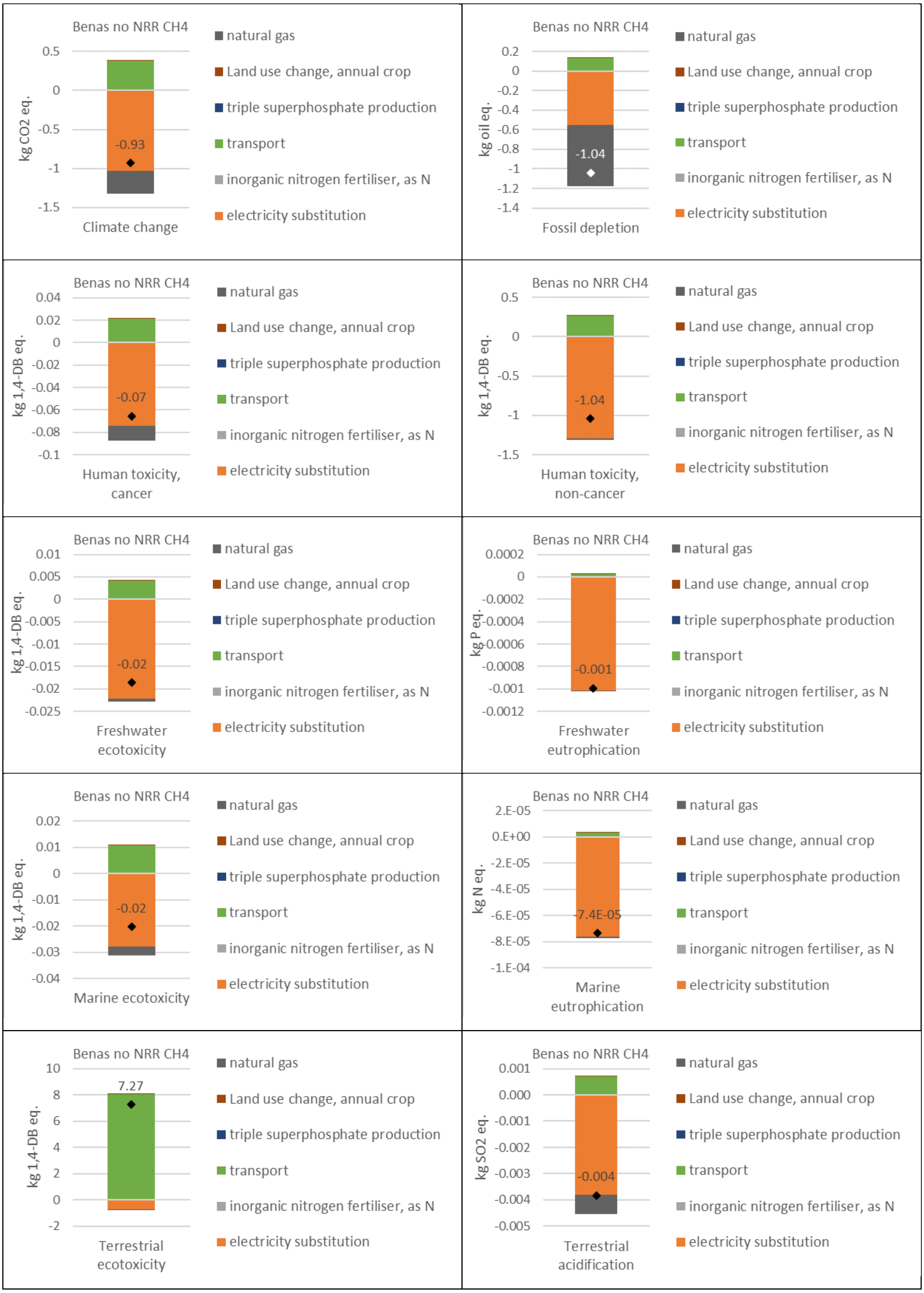


Fig. 2.13: LCIA – BENAS without NRR per m³ CH_4

2.3.2.2 BENAS with NRR, Functional Unit m³ CH_4

Fig. 2.14: LCIA – BENAS with NRR per m³ CH_4

2.3.2.3 BENAS without NRR, Functional Unit t of substrate

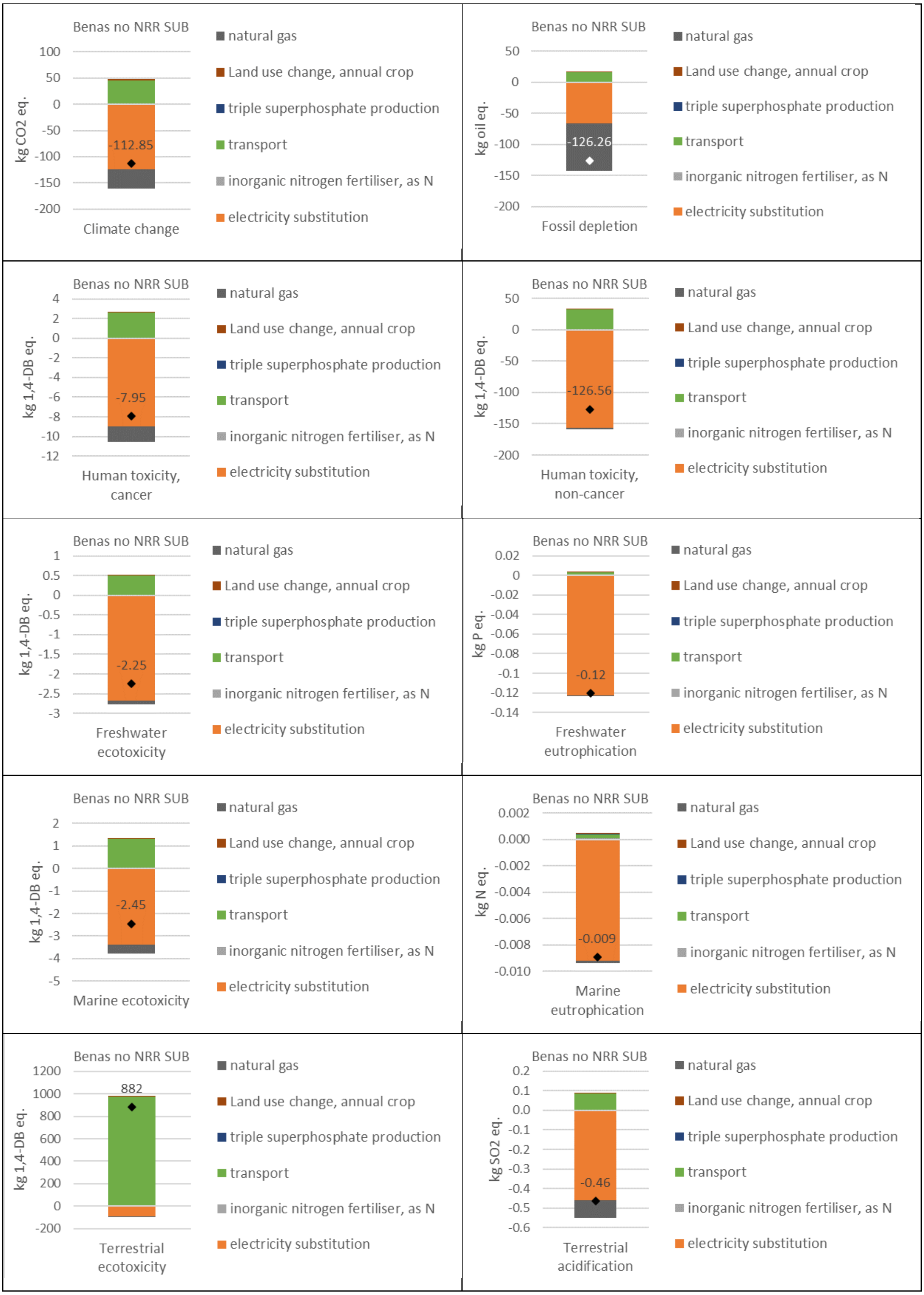


Fig. 2.15: LCIA - BENAS without NRR per t substrate

2.3.2.4 BENAS with NRR, Functional Unit t of Substrate

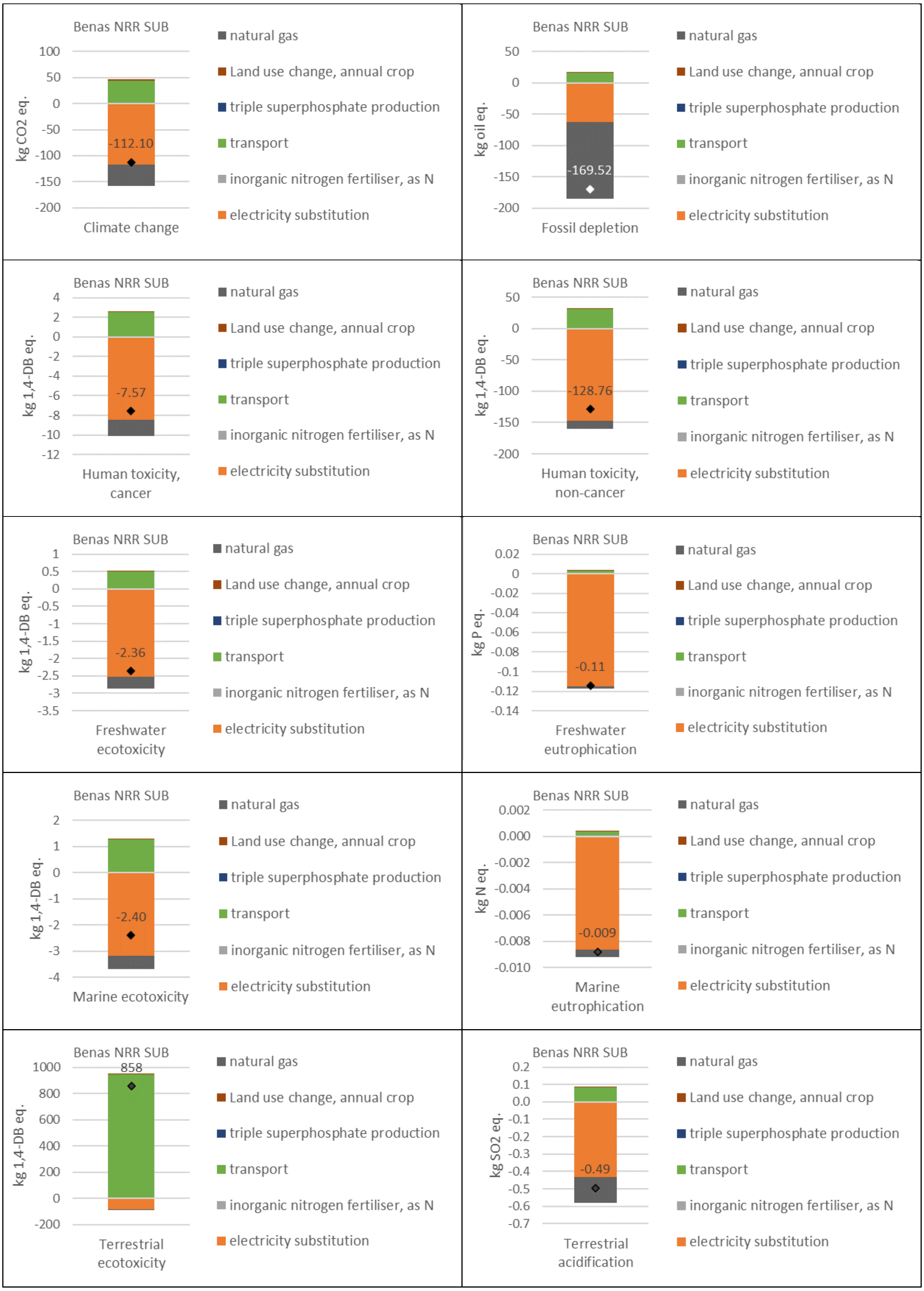


Fig. 2.16: LCIA - BENAS with NRR per t substrate

2.3.2.5 BENAS without NRR, total annual impact of the system

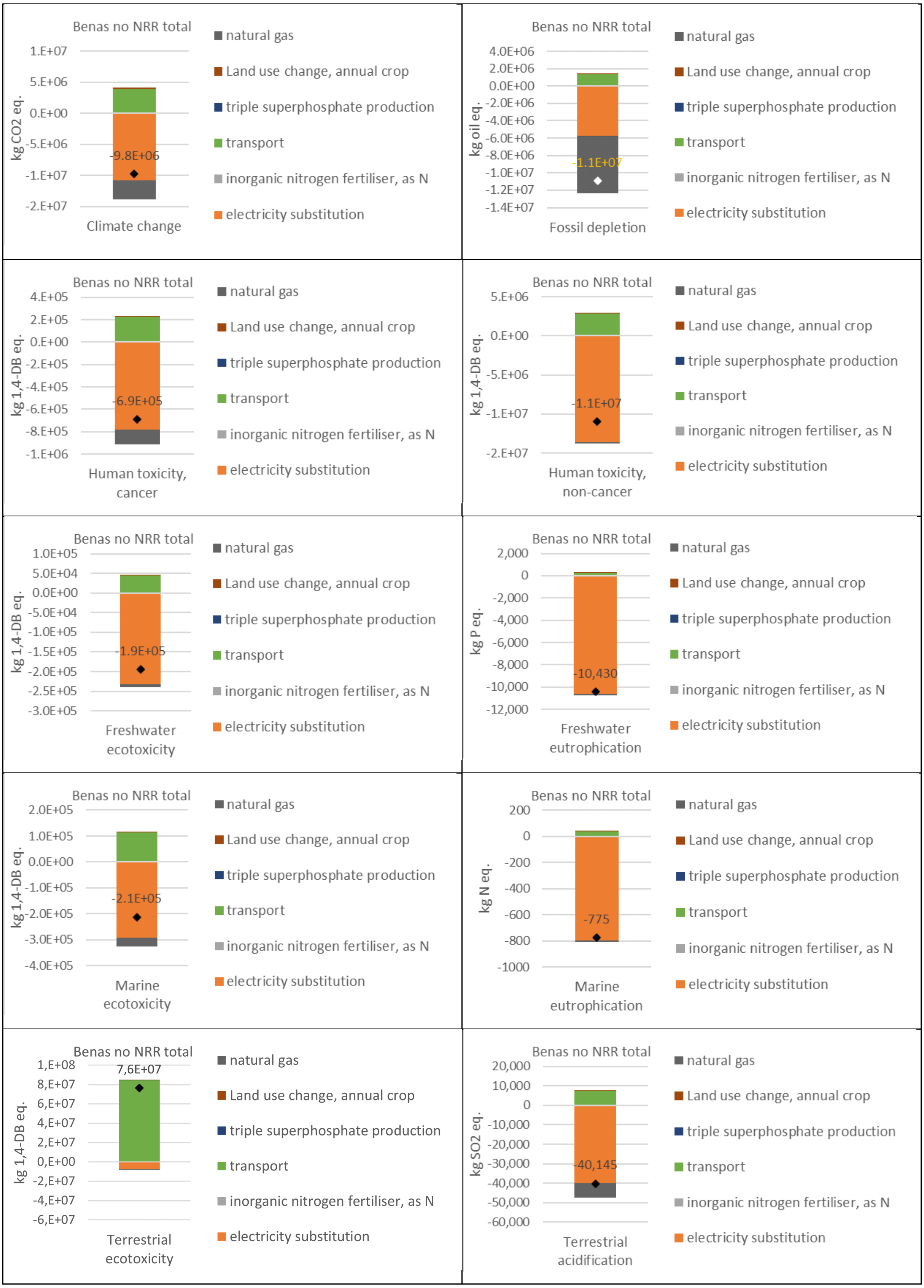


Fig. 2.17: LCIA - BENAS without NRR, annual system impact

2.3.2.6 BENAS with NRR, total annual impact of the system

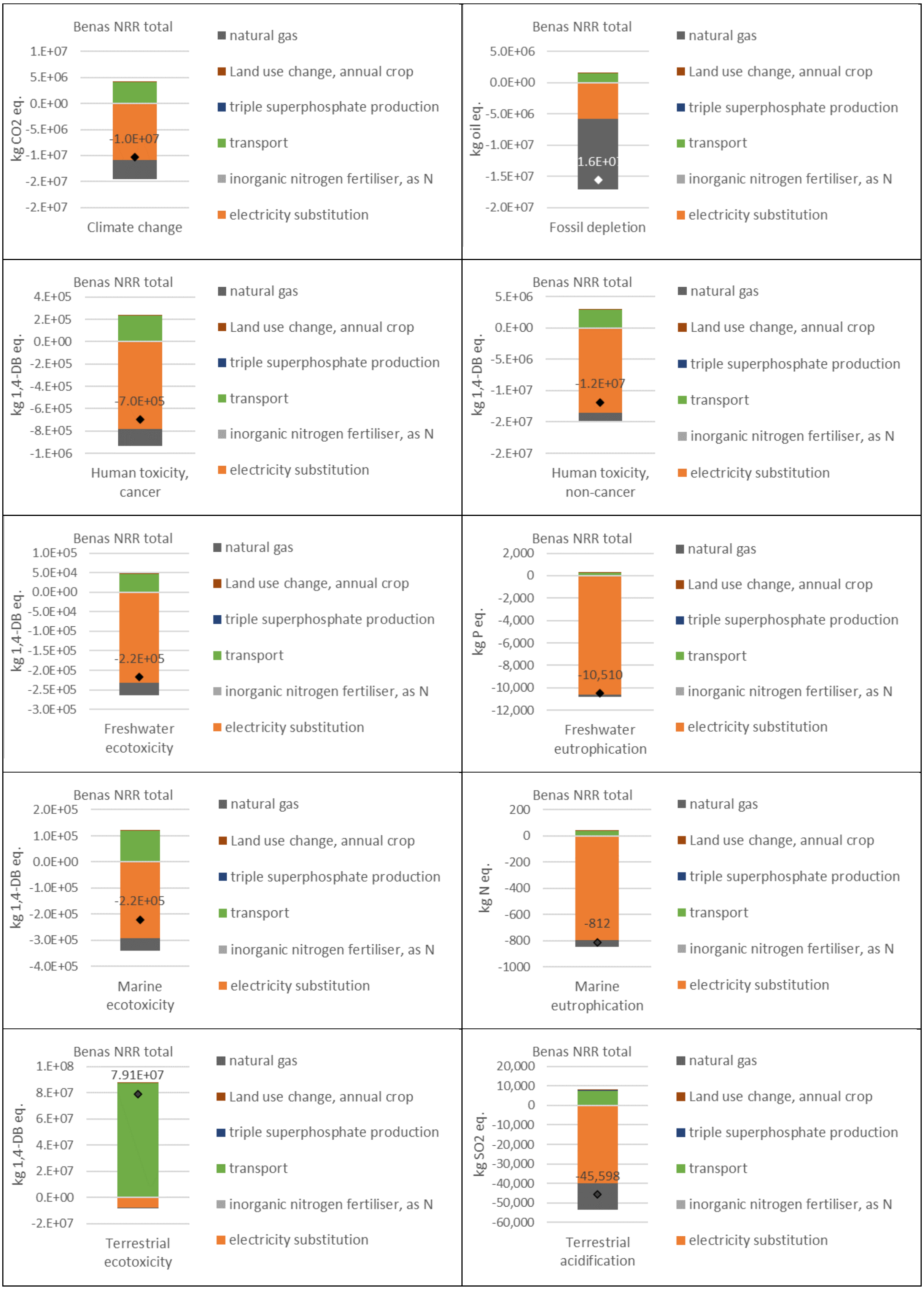


Fig. 2.18: LCIA - BENAS with NRR total annual system impact

2.3.3 Interpretation

BENAS is another unique case within this project due to being the only AD plant feeding energy crops into the process. This is represented in the LCIA through the lack of positive impact from nutrient substitution since all nutrients recovered are again used for energy crop production and cannot be calculated as replacement of conventional fertiliser for food production. Together with high transport loads and long distance the process suggests having a smaller positive environmental effect. However, the replacement of conventional electricity and natural gas provide a meaningful positive impact on environment in almost all categories, especially in fossil depletion and climate change. The biogas + NRR system saves about 10,000 t/y CO_2-eq, with and without the NRR system operational, providing evidence for an excellent energy efficiency of the system.

The installed NRR systems itself may not contribute to the positive environmental impact but facilitates nutrient management on the field and therefore may contribute to a higher yield of energy crops, which is not calculated within this paper. However, the installed NRR system surely ensures a professional nutrient management and facilitates the use of higher N-content substrates as well as the obedience of existing Nutrient directives.

The terrestrial ecotoxicity, again the only impact category with a negative result (79,121 t DB-eq) is almost unaffected by the NRR system. This is due to high transport distances between the cropland from where the substrates are harvested and where the fertilising products are used and the biogas plant.

2.4 Groot Zevert Vergisting (GZV)

2.4.1 Introduction

Fig. 2.19: GZV plant

Groot Zevert Vergisting B.V., a mesophilic anaerobic digester plant in Beltrum (35 km southwest of Enschede), Achterhoek Region, Province Gelderland, The Netherlands, in operation since 2004 with a total annual substrate treatment capacity of 135,000 tonnes. Processing pig manure and residues from agro-food industry.

2.4.2 Life Cycle Impact Assessment - LCIA

2.4.2.1 *Groot Zevert Vergisting (GZV) without NRR, Functional Unit m³ CH_4*

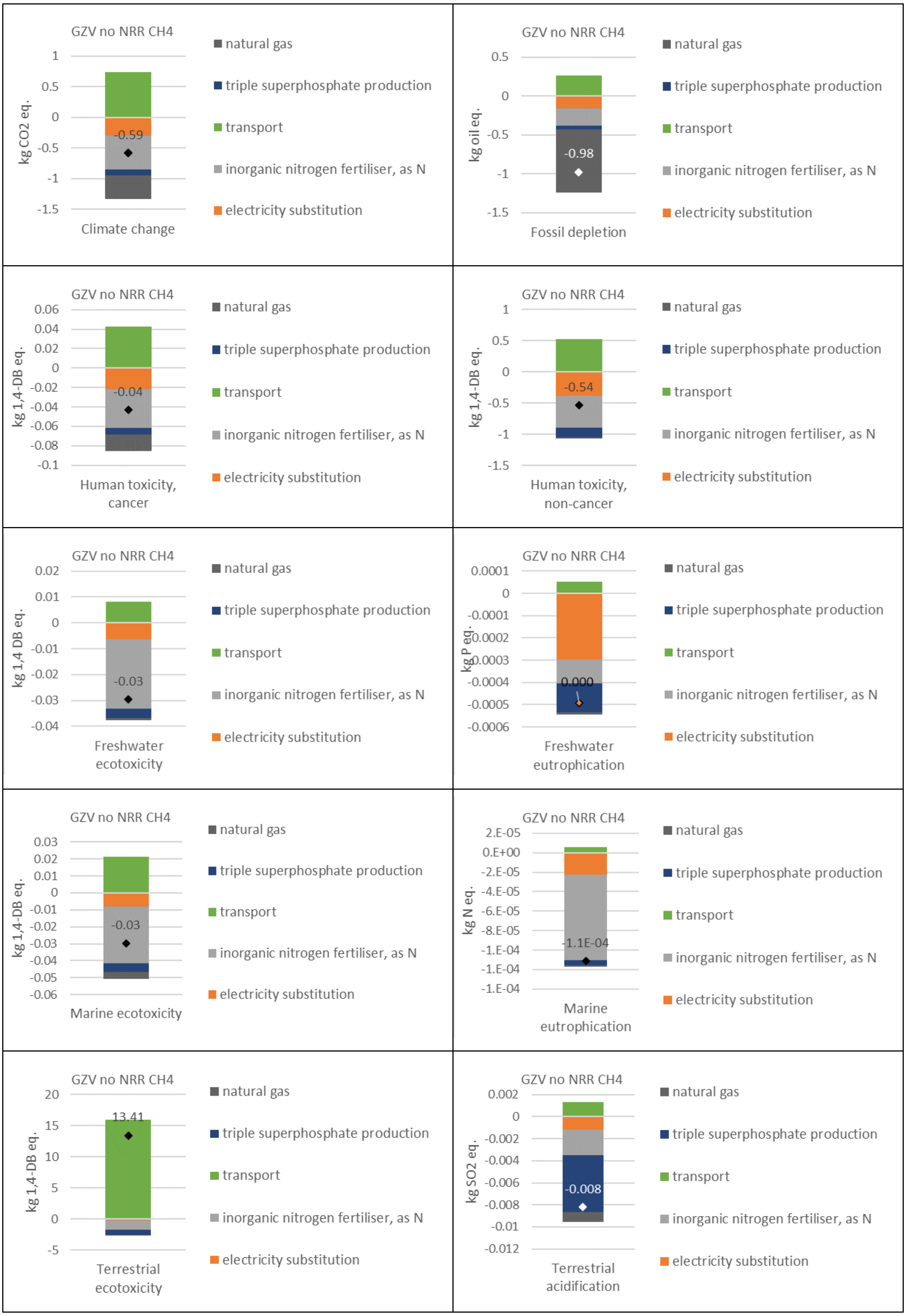


Fig. 2.20: LCIA – Groot Zevert Vergisting (GZV) without NRR per m³ CH_4

2.4.2.2 Groot Zevert Vergisting (GZV) with NRR, Functional Unit m³ of CH_4

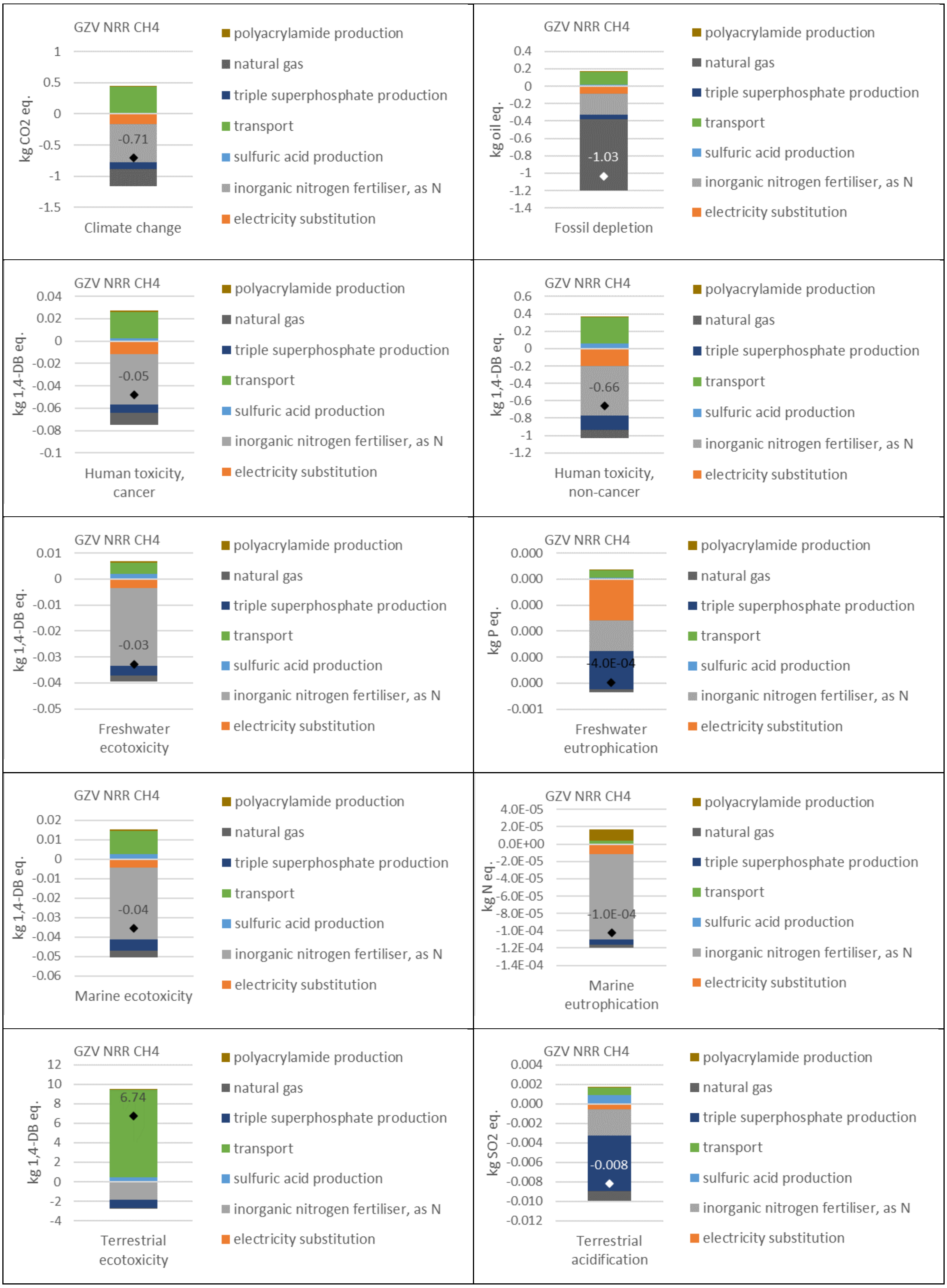


Fig. 2.23: LCIA – Groot Zevert Vergisting (GZV) with NRR per m³ of CH_4

2.4.2.3 Groot Zevert Vergisting (GZV) without NRR, Functional Unit t of substrate

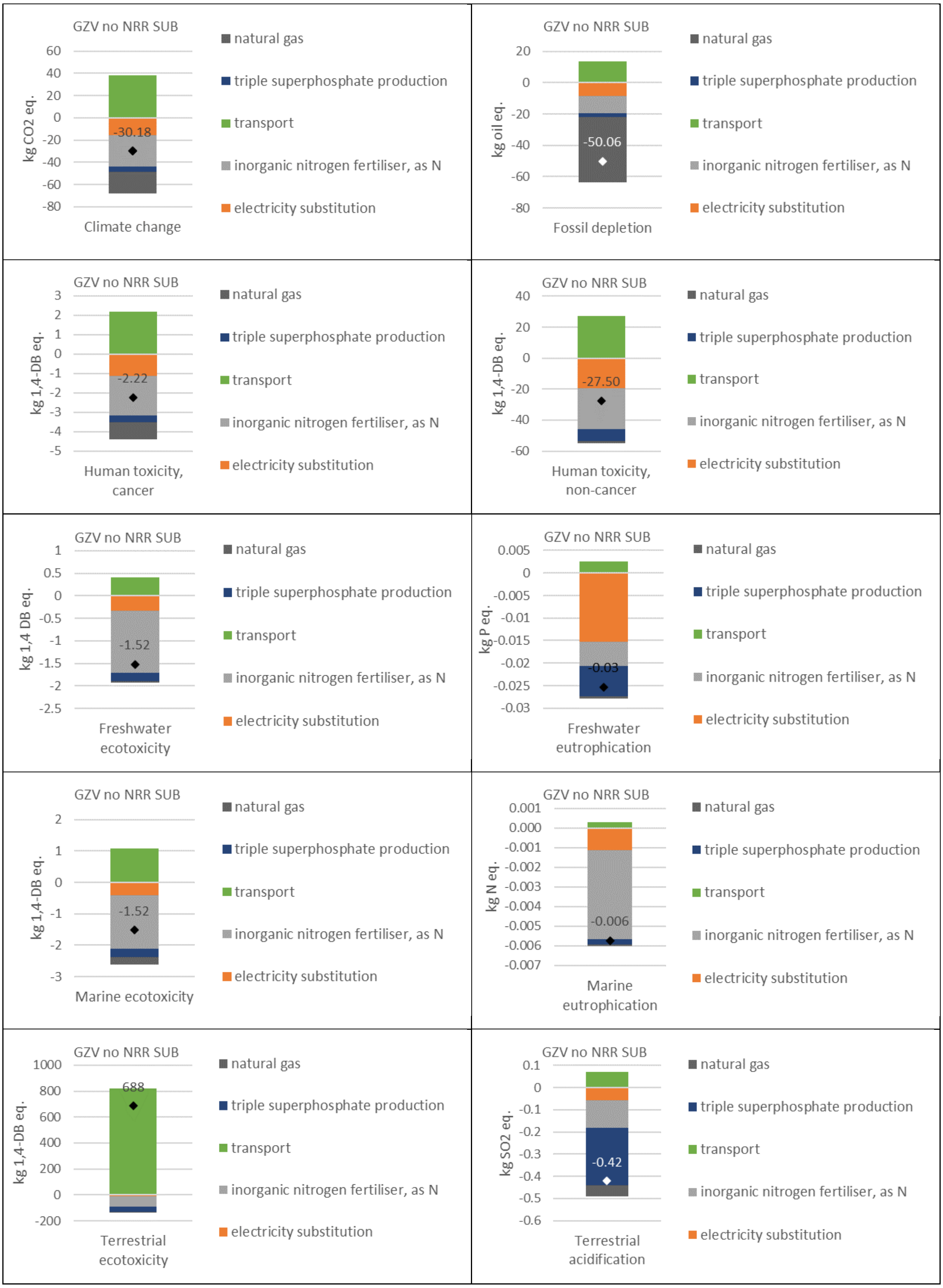


Fig. 2.23: LCIA – Groot Zevert Vergisting (GZV) without NRR per t of substrate

2.4.2.4 Groot Zevert Vergisting (GZV) with NRR, Functional Unit t of substrate

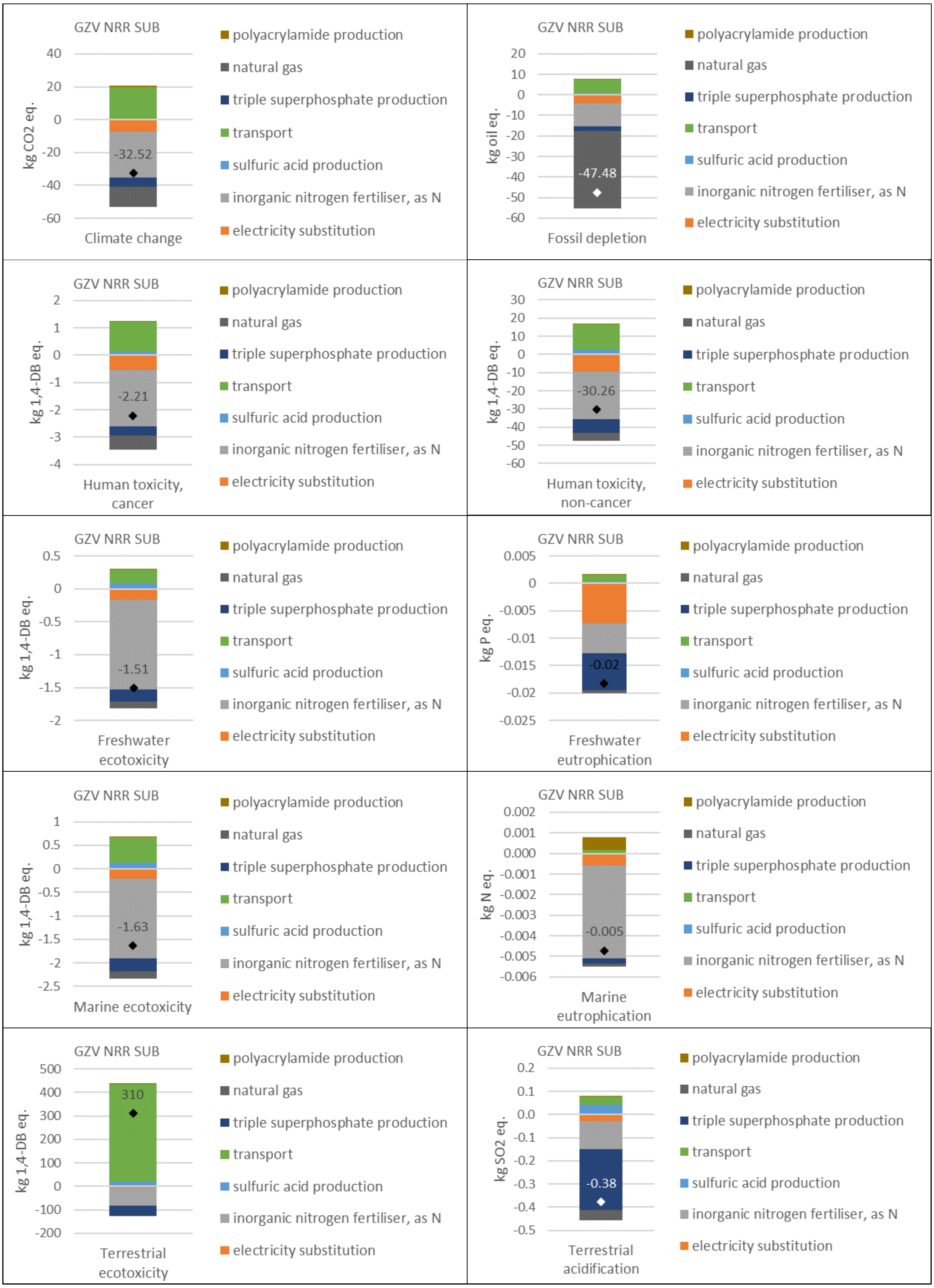


Fig. 2.24: LCIA – Groot Zevert Vergisting (GZV) with NRR per t of substrate

2.4.2.5 Groot Zevert Vergisting (GZV) without NRR, total annual impact of the system

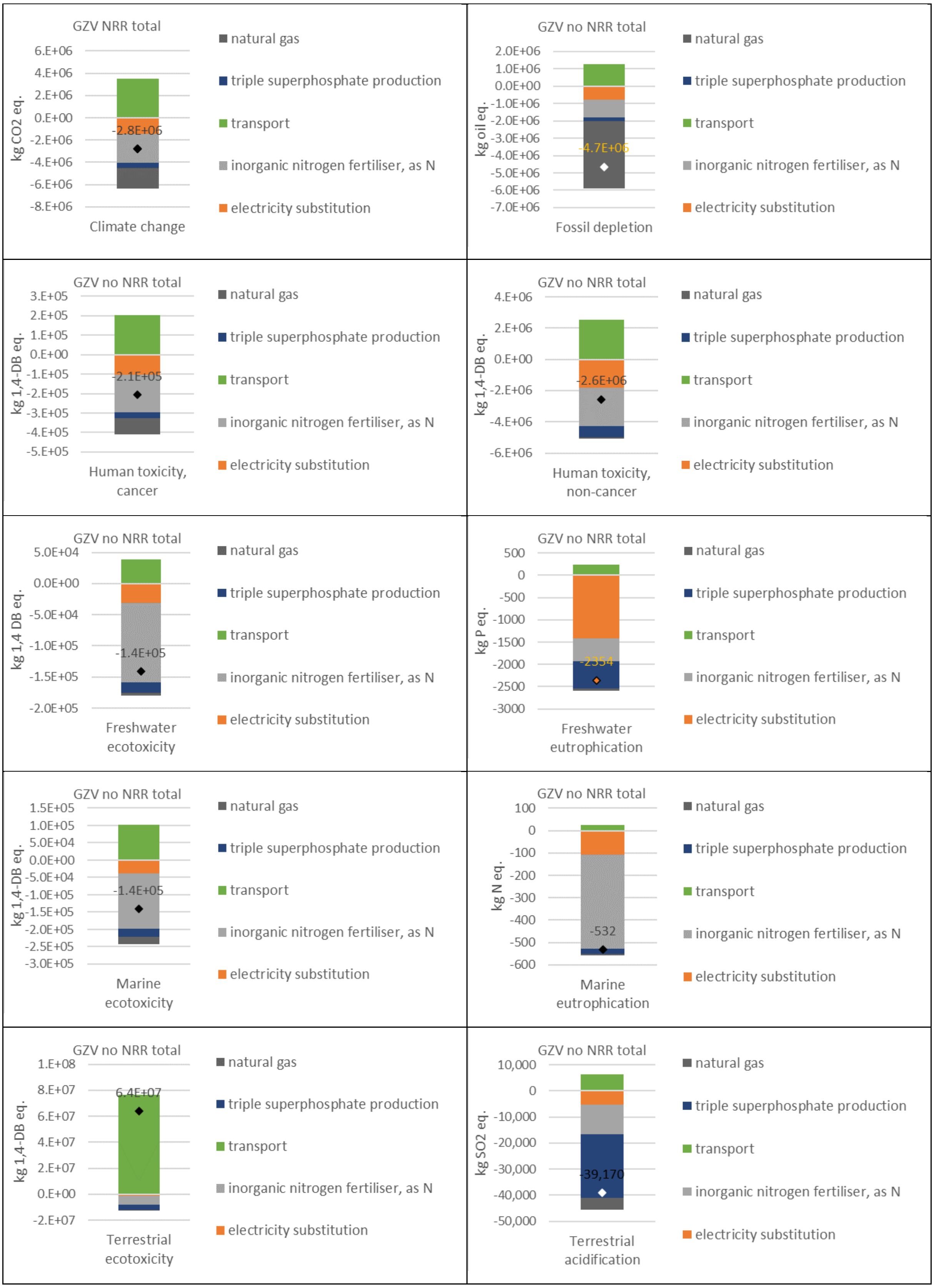


Fig. 2.24: LCIA - Groot Zevert Vergisting (GZV) without NRR, total annual system impact

2.4.2.6 Groot Zevert Vergisting (GZV) with NRR, total annual impact of the System

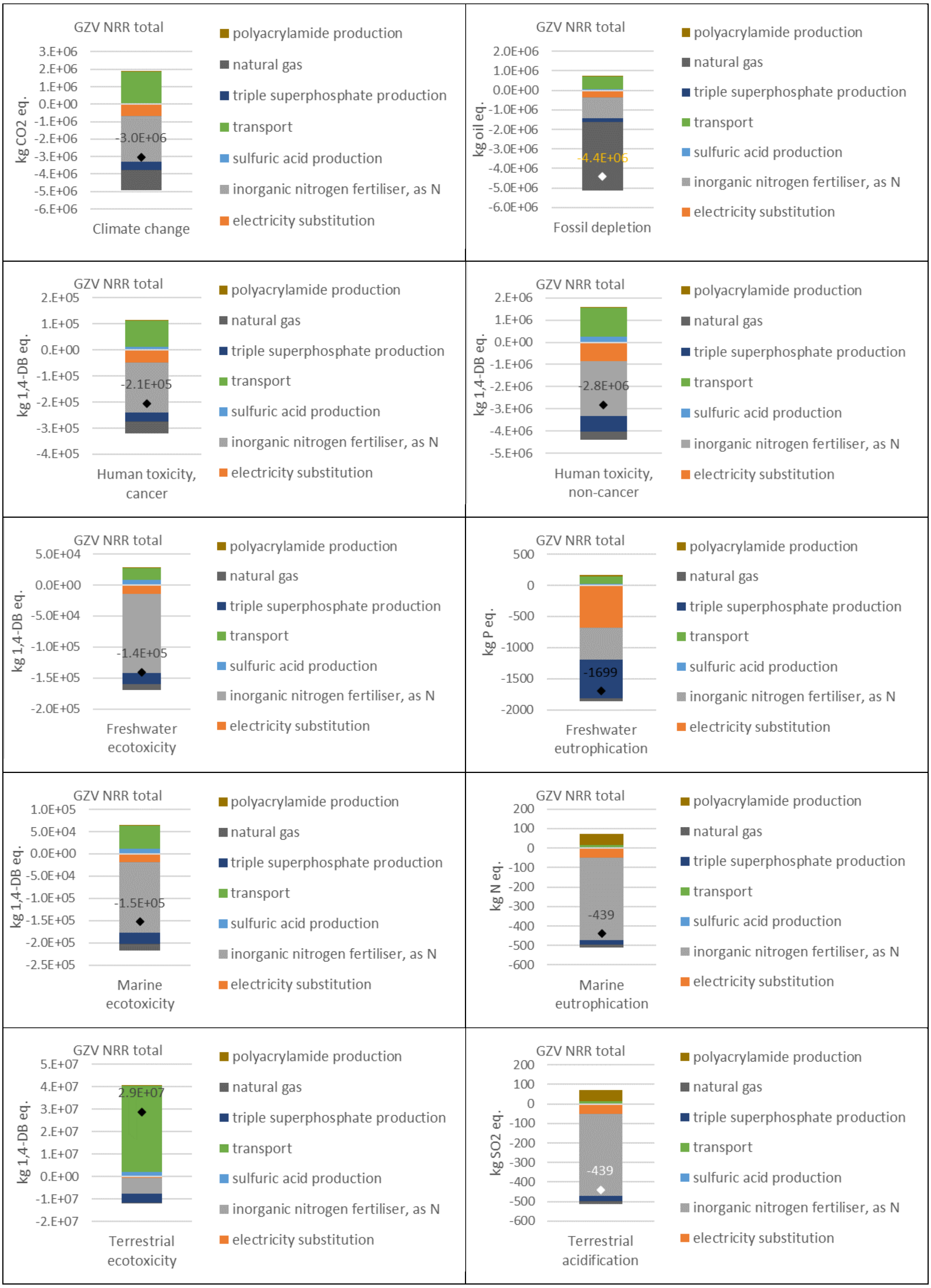


Fig. 2.25: LCIA - Groot Zevert Vergisting (GZV) with NRR, total annual system impact

2.4.3 Interpretation

In comparison to other demonstration plants GZV's NRR solutions GENIUS and RePeat stand out for having a visible positive impact on the electricity conversion and therefore higher CO_2-eq savings with the NRR systems operational in comparison to the basic biogas plant. The overall annual emission savings are over 3,000 t CO_2-eq with NRR and 2,800 t without.

Operations of the NRR system has a significant impact on terrestrial ecotoxicity, reducing the negative effect from 64,000 t DB-eq to 29,000 t DB-eq, less than half the impact of the original plant layout. This effect is largely due to reduced road transport distances and marginally supported by improved N replacement.

The latest GZV development, replacement of peat in potting soils and mushroom growing media will further improve the environmental benefit of NRR in comparison to the base case. In contrast to conventional P fertilisers, peat has a truly relevant climate impact.

2.5 Waterleau New Energy (WNE)

2.5.1 Introduction

Fig. 2.26: WNE plant

Waterleau B.V., a mesophilic anaerobic digestion plant in Ypres (80 km west of Ghent), West-Flanders, Belgium, in operation since 2012 with a total annual substrate treatment capacity of 120,000 tonnes. Processing manure and biowaste.

2.5.2 Life Cycle Impact Assessment - LCIA

2.5.2.1 Waterleau New Energy (WNE) without NRR, Functional Unit m³ CH_4

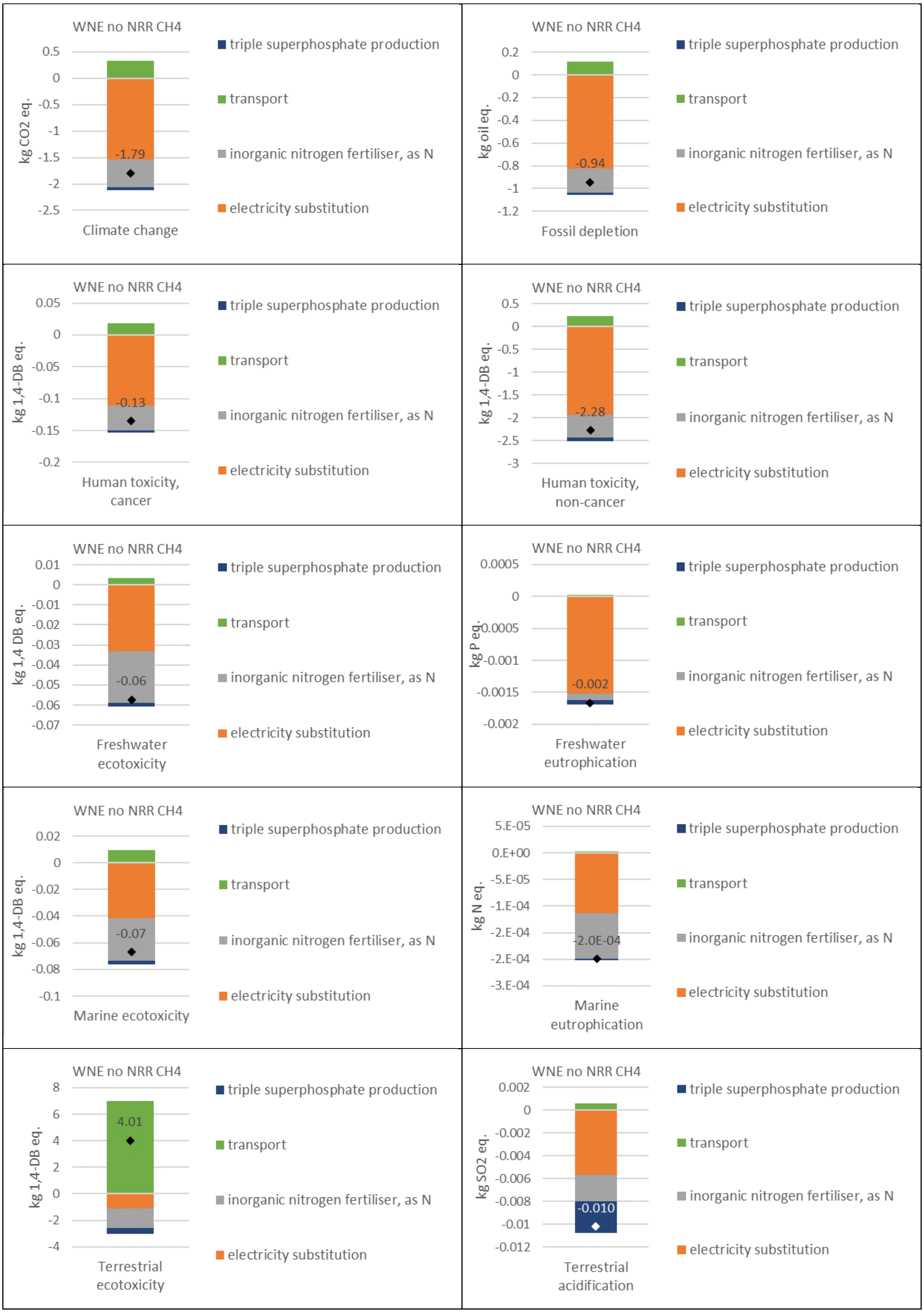


Fig. 2.27: LCIA – Waterleau New Energy (WNE) without NRR per m³ CH_4

2.5.2.2 Waterleau New Energy (WNE) with NRR, Functional Unit m³ CH_4

Fig. 2.28: LCIA – Waterleau New Energy (WNE) with NRR per m³ CH_4

2.5.2.3 Waterleau New Energy (WNE) without NRR, Functional Unit t of Substrate

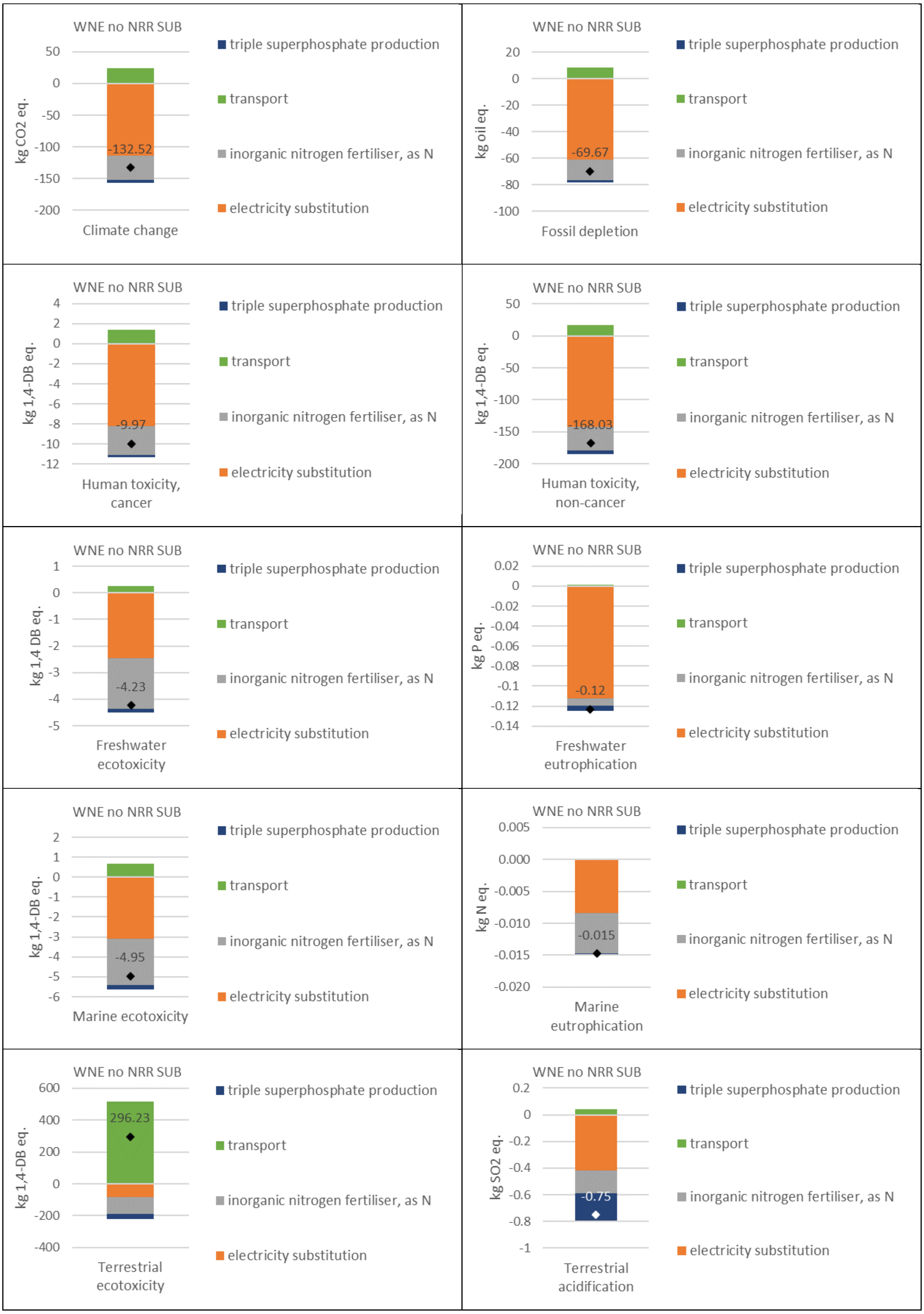


Fig. 2.29: LCIA – Waterleau New Energy (WNE) without NRR per t of substrate

2.5.2.4 WNE with NRR, Functional Unit t of Substrate

Fig. 2.30: LCIA – Waterleau New Energy (WNE) with NRR per t of substrate

2.5.2.5 Waterleau New Energy (WNE) without NRR, total annual impact of the system

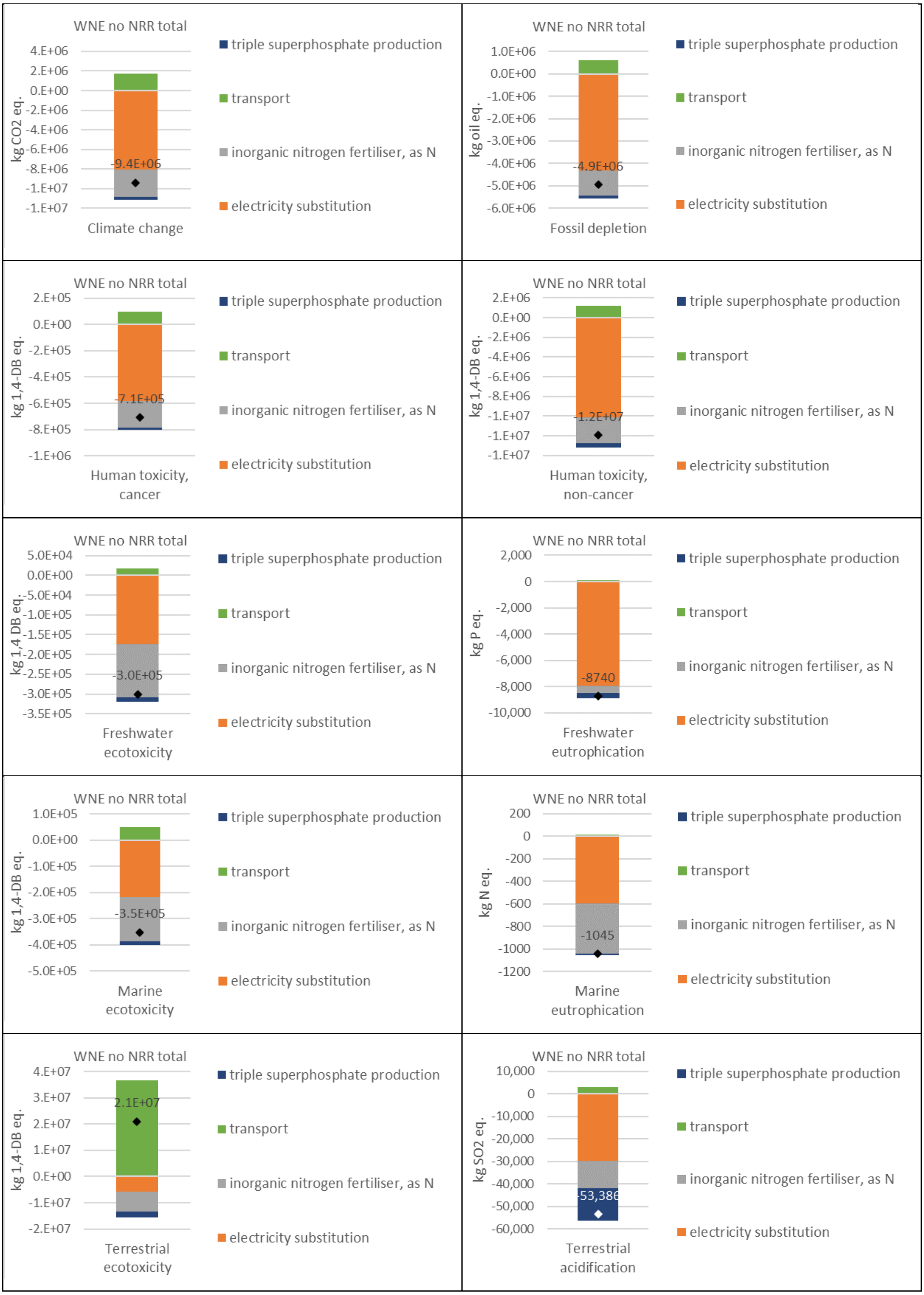


Fig. 2.31: LCIA – Waterleau New Energy (WNE) without NRR total annual system impact

2.5.2.6 Waterleau New Energy (WNE) with NRR, total annual impact of the system

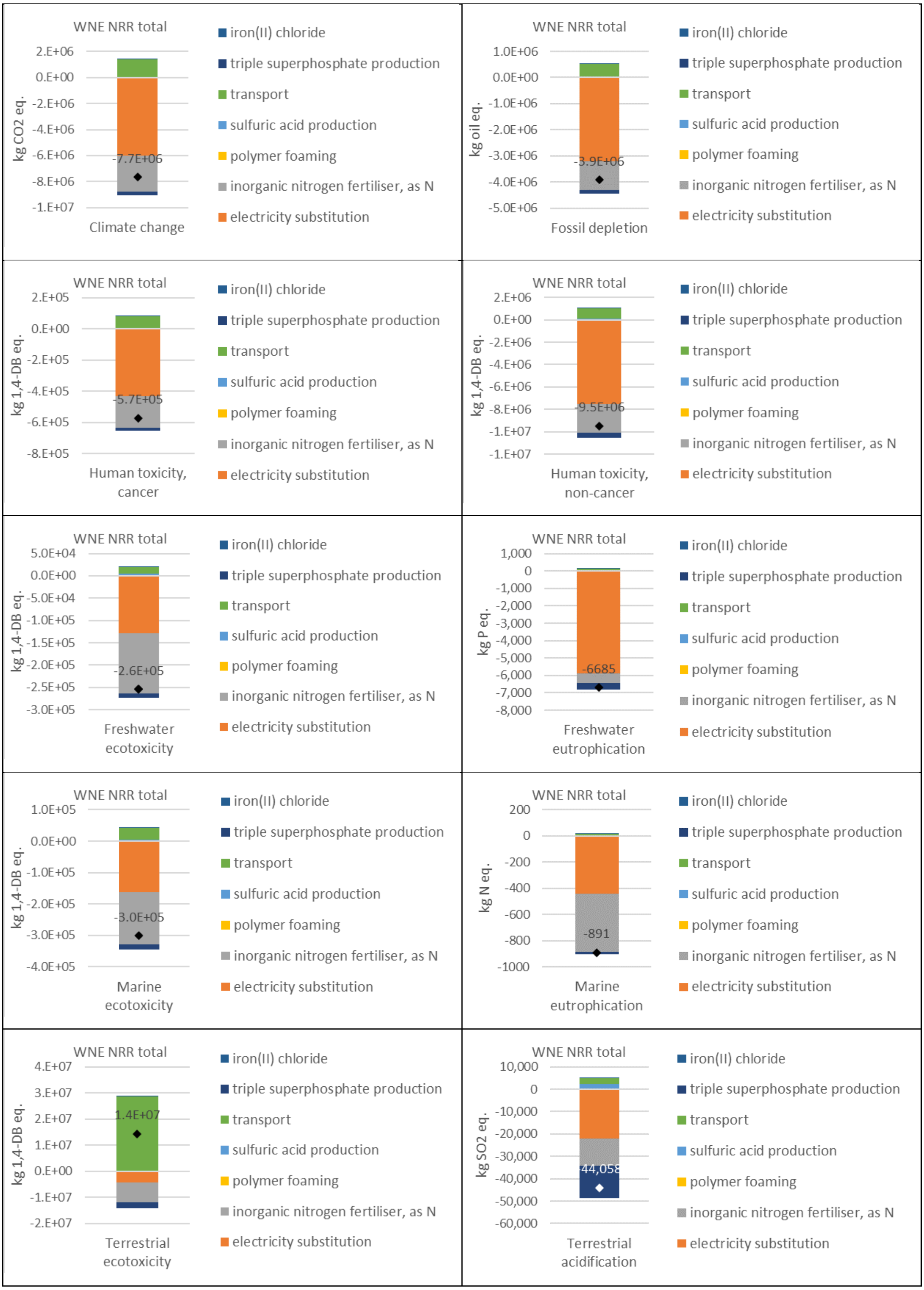


Fig. 2.32: LCIA – Wateleau New Energy (WNE) with NRR total system impact

2.5.3 Interpretation

Similar to the process of AMP, the reduction of electricity fed to grid reduces the overall positive climate impact of NRR systems. WNE forgoes about 19% of its GHG reduction potential by operating the NRR system. The CO_2-eq values are about 9,400 t/y without and 7,700 t/y with the NRR system operational.

A very positive impact of NRR is shown for terrestrial ecotoxicity, from 21,000 t 1,4 DB-eq without the NRR system to 14,500 t 1,4 DB-eq with the NRR system operational, both figures calculated as the total annual impact of the plant.

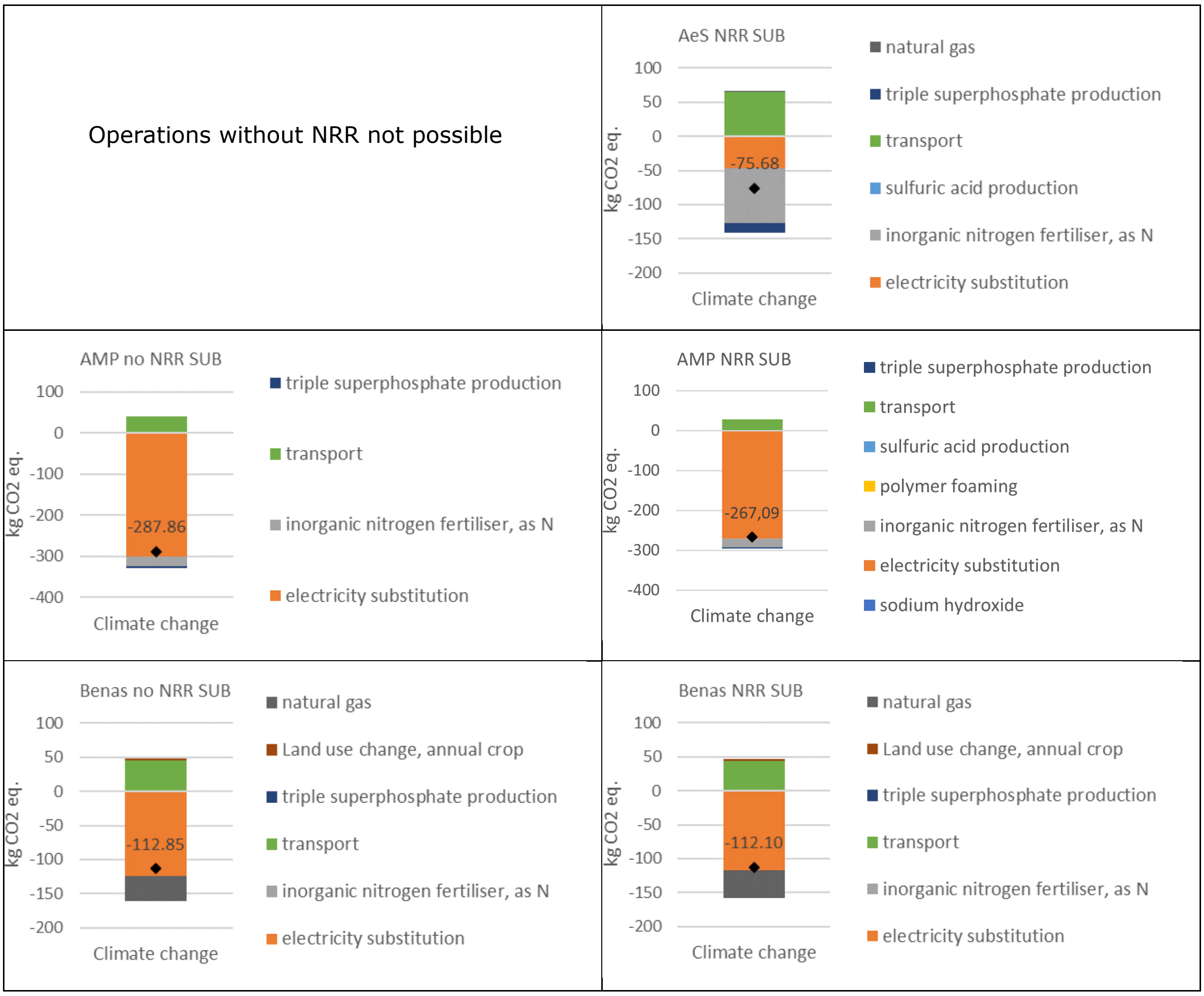
3. Discussion

The assessment of the environmental effects of all SYSTEMIC demonstration plants shows only positive effects for all selected impact categories except for terrestrial ecotoxicity. For this category, all plants have a negative impact on the environment, mainly due to transport of substrates and products.

Apart from assessing all impact categories for every plant individually, different impact categories are compared by ton of substrate for all demonstration plants. This comparison was selected due to the SYSTEMIC focus on substrate and nutrients, while in SYSTEMIC energy conversion is considered as a side effect.

In terms of impact categories, greenhouse gas emissions, (3.1), human toxicity (3.2), freshwater eutrophication (3.3), marine eutrophication (3.4) and terrestrial ecotoxicity (3.5) were selected to consider the most relevant, nutrient related categories alongside with the climate impacts.

3.1 Comparative effects by plant on climate change (greenhouse gas emissions) in kg $CO_{2\text{-eq}}$ per ton of substrate treated:



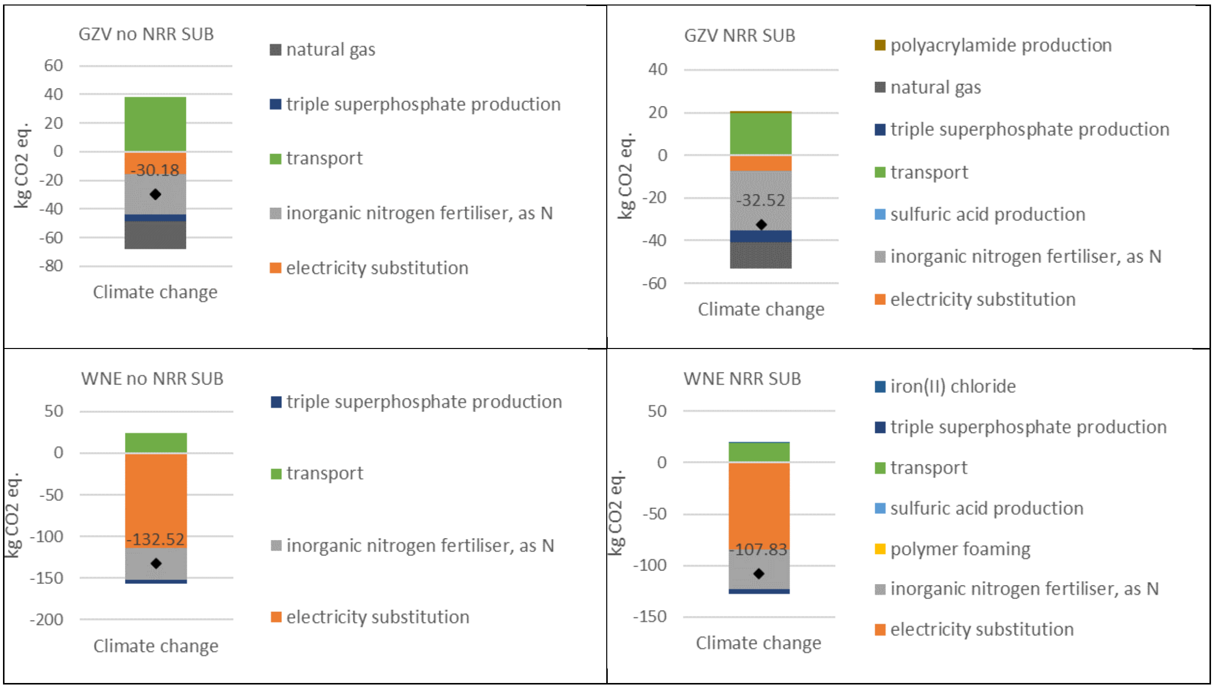


Fig. 3.1 Comparison of GHG emissions in kg CO_{2-eq} per ton of substrate treated by plant without (no) and with NRR.

Interpretation

All demonstration plants save greenhouse gas emissions expressed as kg CO_{2-eq}, between 30 and 287 kg/t substrate without NRR and between 33 and 267 kg/t substrate with NRR systems. The negative effect of NRR systems on GHG emissions is between 0,7% (BENAS) and 22% (Waterleau New Energy), providing evidence for a high energy efficiency of NRR systems. Remarkable is a positive effect of NRR systems on GHG emissions at Groot Zevert and an almost negligeable effect of NRR systems at BENAS – GHG emission savings without NRR are 30.18 kg/t substrate and 32.52 kg/t substrate with NRR at GZV as well as 112.84 kg/t substrate and 112.10 kg/t substrate with NRR system at BENAS, indicating a positive or no effect of NRR on GHG savings. At GZV this is due to higher compensation rates for N fertilisers and lower transport distances. At BENAS it may be due to the use of gypsum for ammonium sulphate production and the efficient internal energy recovery systems. Other systems forgo between 7% (AMPower) and 22% (Waterleau NE) of their GHG savings for the NRR system.

LCA results also show that the effect of NRR on transport related CO_2 emissions (green bars in the graphic) does not have the highest impact – electricity or fertiliser substitution typically has more impact.

3.2 Comparative effects by plant on human toxicity (non-cancer) in kg 1,4-DCB-Eq per ton of substrate treated

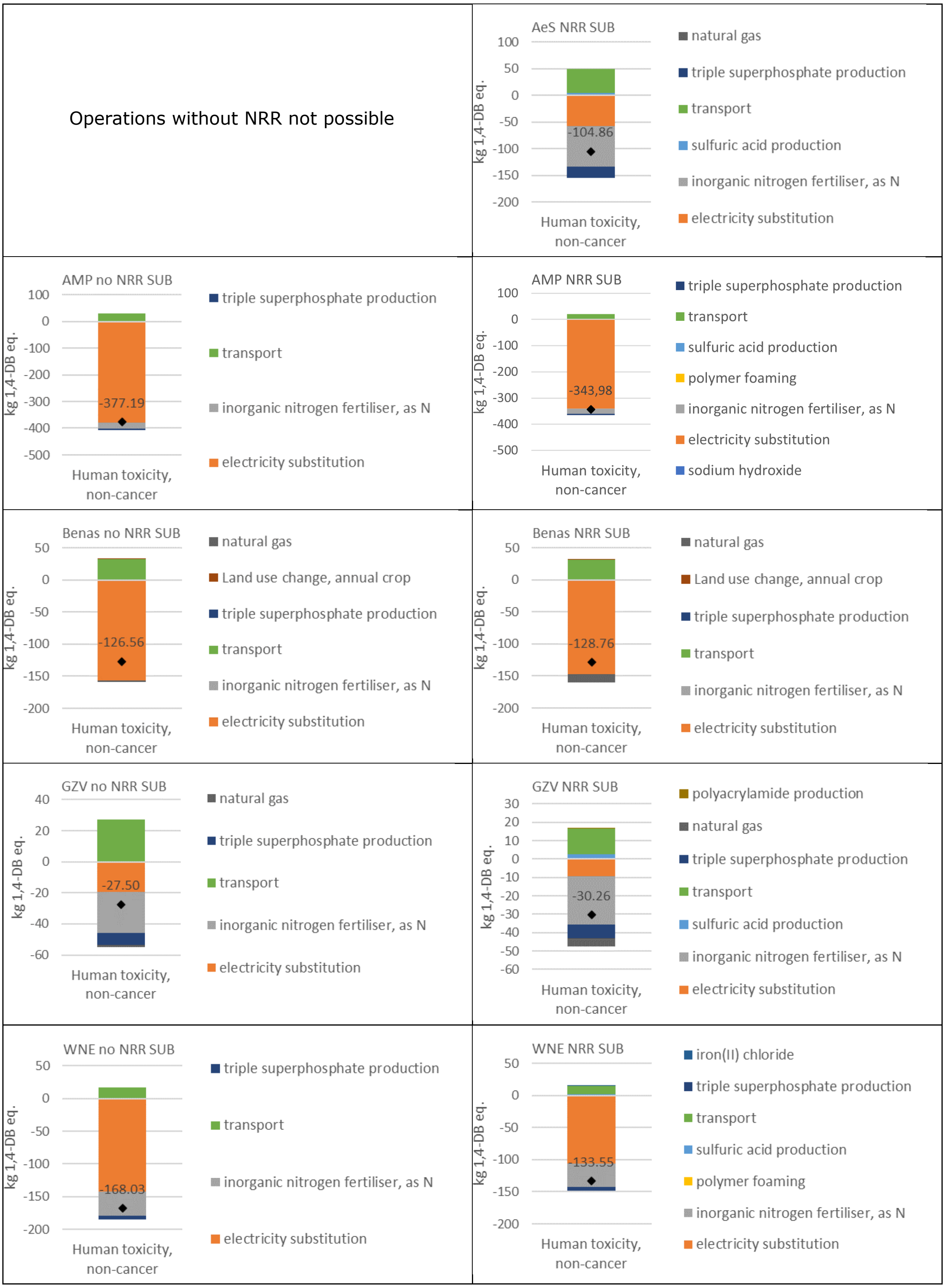


Fig. 3.2 Comparison of non-cancer human toxicity in kg 1,4-DB eq. per ton of substrate treated by plant without (no) and with NRR.

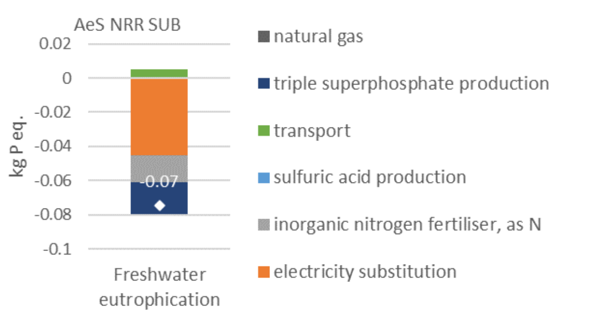
Interpretation

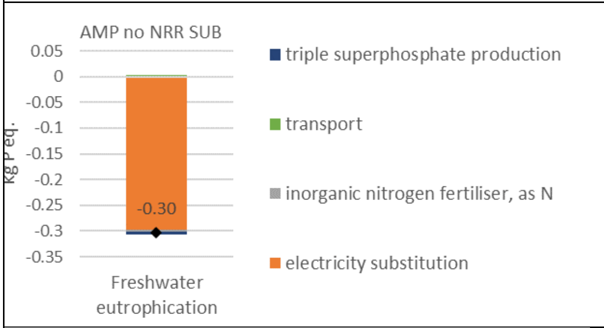
The effect of NRR on human toxicity is always positive. The impact is lower, and the corresponding values are negative.

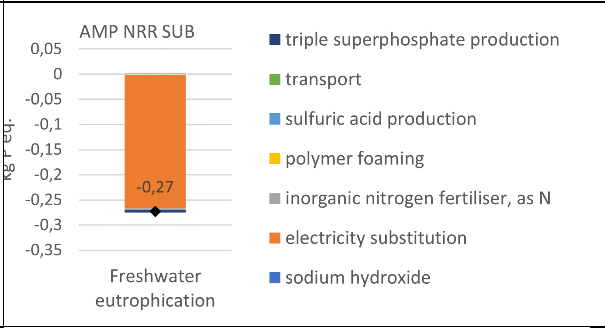
The reduction is 104 kg 1,4 DB-eq. at Acqua & Sole, 129 kg at BENAS (vs. 127 kg without NRR), 30 kg at GZV (vs 28 without NRR). In contrast, the human toxicity potential reduction of the two plants in Flanders is slightly lower with than without NRR, 344 kg (vs. 377) at AMPower and 134 kg (vs. 168 kg) at Waterleau NE. In both cases the foregone benefit for electricity production is higher than the extra burden of transport without the NRR system. Yet, all plants generate relevant human toxicity benefits per ton of substrate treated.

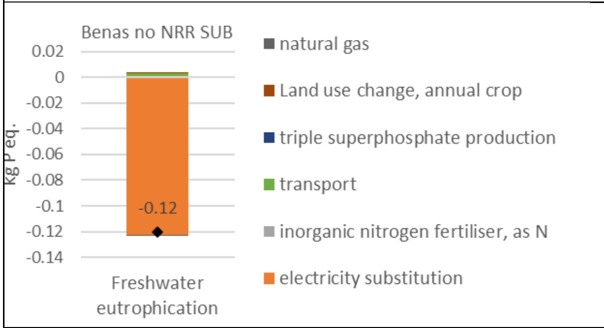
3.3 Comparative effects by plant on freshwater eutrophication in kg P per ton of substrate treated

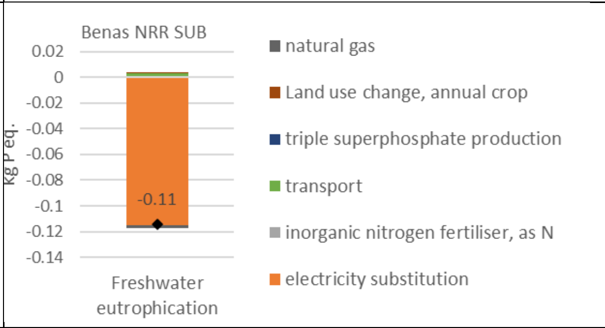
Operations without NRR not possible

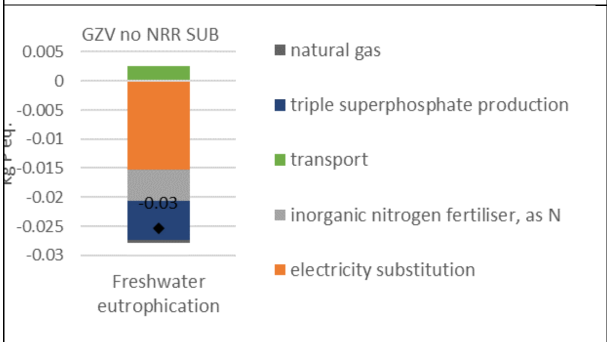


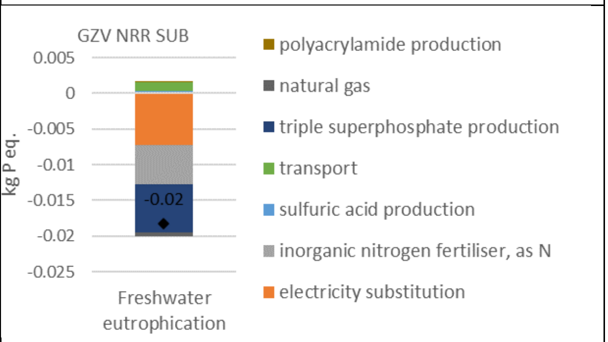












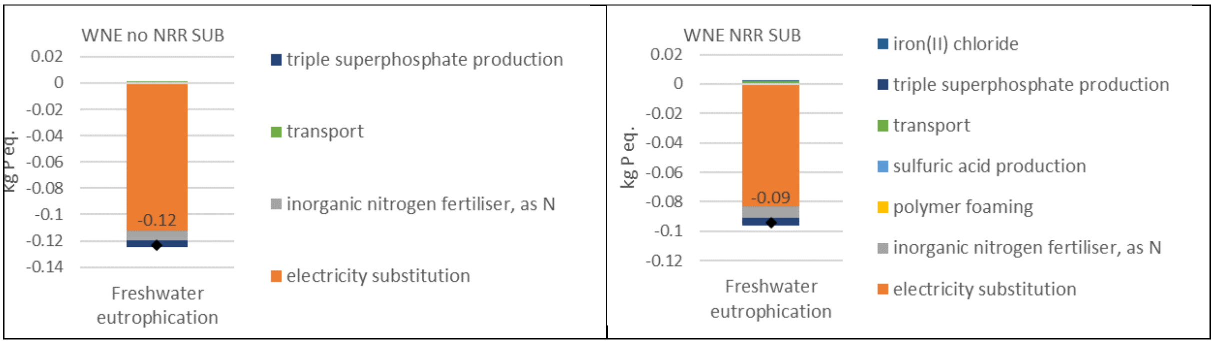
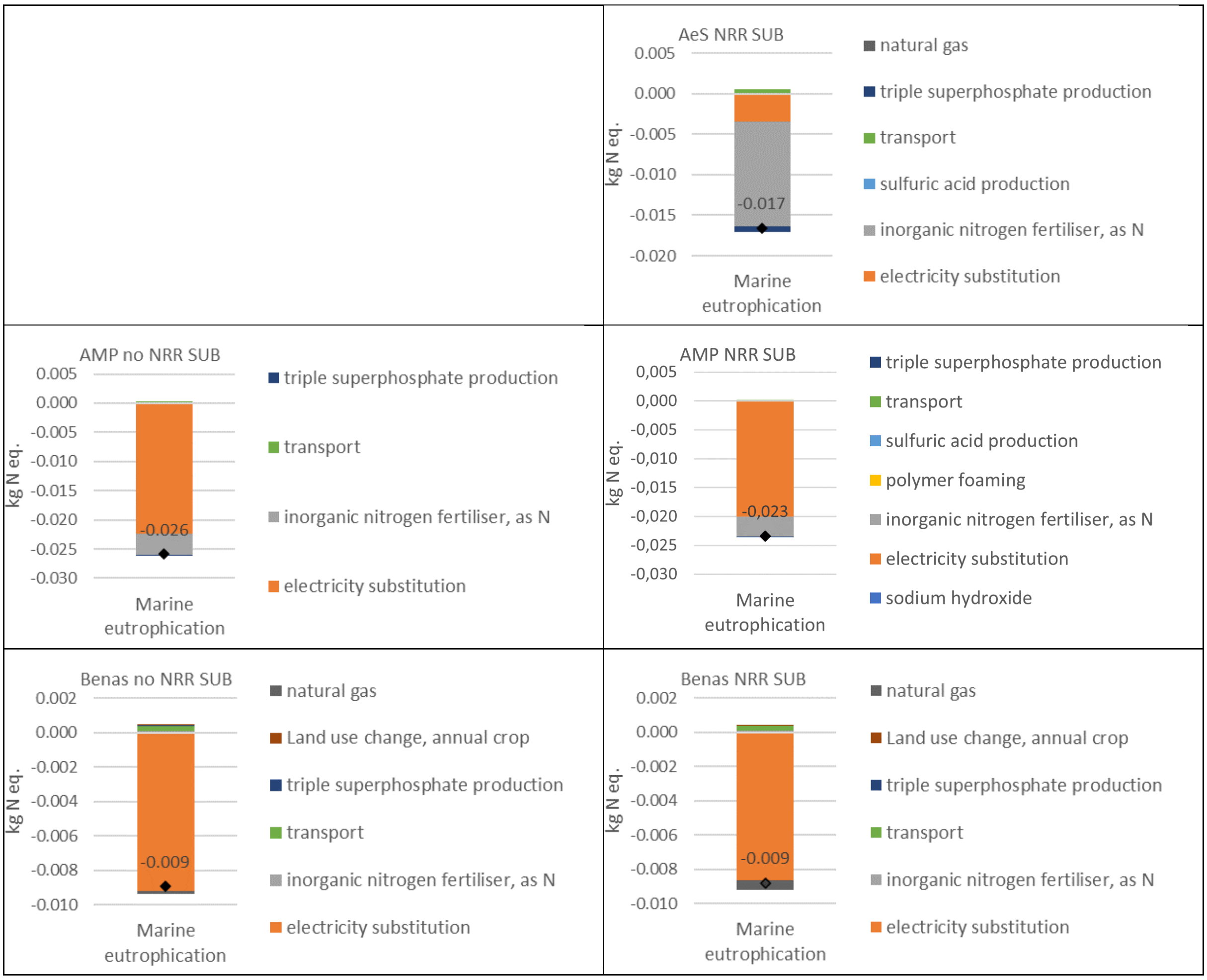


Fig. 3.3 Comparison of freshwater eutrophication in kg P per ton of substrate treated by plant without (no) and with NRR.

Interpretation

Freshwater eutrophication is lower than reference scenarios for all plants. Acqua & Sole save modest 0.07 kg P per ton of substrate, AMPower 0.27 kg P, BENAS 0.11 kg P, GZV 0.02 kg P and Waterleau NE 0.09 kg P. The effects of NRR on freshwater eutrophication are almost negligible. It should be noted that the P content in digestate is always below 10 kg/ton. Yet, all plants generate relevant freshwater eutrophication benefits in relation to the base case.

3.4 Comparative effects by plant on marine eutrophication in kg N per ton of substrate treated



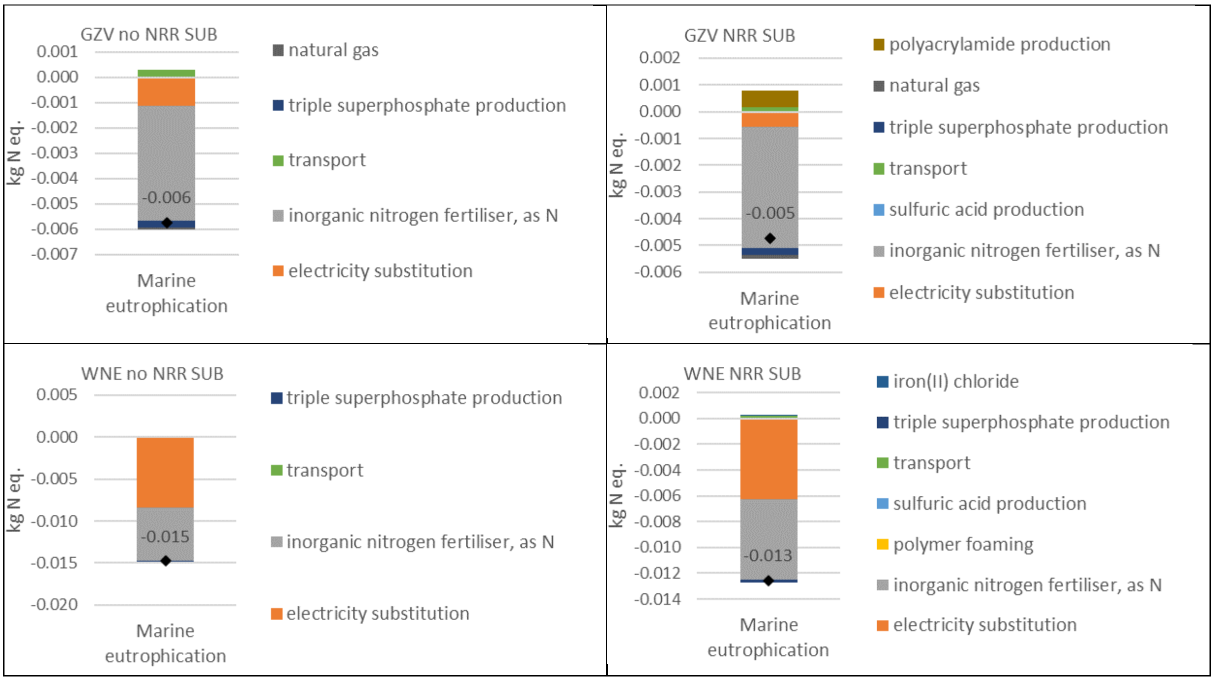


Fig. 3.4 Comparison of marine eutrophication in kg N per ton of substrate treated by GZV without (no) and with NRR.

Interpretation

Marine eutrophication is lower than reference scenarios for all plants. As for P, the systems save a few grams of N-derived marine eutrophication either due to substitution of electricity (AMP, BENAS, WNE) or of N-fertilisers (AeS, GZV and WNE). The effect of NRR close to negligible, but the tendency is beneficial for all cases, all with beneficial effects in the range of 5-15 g/ton of substrate, albeit with only a marginal difference between NRR systems operational or not.

3.5 Comparative effects by plant on terrestrial ecotoxicity in kg 1,4 DB eq. per ton of substrate treated

Fig. 3.5 Comparison of terrestrial ecotoxicity in kg 1,4 DB eq. per ton of substrate treated by plant without (no) and with NRR.

Interpretation

Terrestrial ecotoxicity, i.e. the effects of emissions from mainly transport related chemical substances (e.g. abrasion of brakes, tyres, combustion engine emissions) on terrestrial organisms and terrestrial plants is the only impact category with relevant negative effects in comparison to the reference case. As shown in Fig. 3.5, the main contributor to this impact category is road transport (all SYSTEMIC related transports are road transports). Two plants, Acqua & Sole and BENAS are affected by the long distance of substrate transport to the plant. Acqua & Sole uses digestates and recovered products in vicinity to the biogas plant while BENAS uses all products on cropland where the substrates are produced.

Also, terrestrial ecotoxicity makes the impact of NRR per ton of substrate most visible. Three plants show significant impacts of the NRR system while two plants show minimal or no difference. Groot Zevert Vergisting more than halves the terrestrial ecotoxicity impact from 688 kg DB-eq to 314 kg DB-eq. AMPower reduces the impact significantly from 559 kg DB-eq without to 314 kg DB-eq with NRR. Waterleau New Energy reduces the impact by one third from 296 kg DB-eq without to 203 kg 1,4 DB-eq with NRR. In contrast, BENAS shows only a small benefit by an impact of 858 kg DB-eq with and 882 kg without NRR, due to long transport distances between the biogas plants and the fields. Acqua & Sole has the highest impact of 1,006 kg 1,4 DB-eq per ton of substrate, mainly due to the long transport distance of substrate from all parts of Italy to the plant in Lombardy. In general, the impact of road transport by truck on terrestrial ecotoxicity is calculated at 2.20-2.40 t 1,4 DB-eq/km [8].

Yet, as the main impact in this category is due to transport it does not mean that biogas production and NRR are the main causes for road transport. Transport may simply be caused by livestock density and nutrient use limits in the region. It may thus be assigned to the inventory of the system without any causal relationship between the system and the impact. In Flanders and the Netherlands, the negative effects may be unavoidable while effects in Germany and Italy are mainly caused by the long distances between the substrate production and the biogas plant.

4. Conclusion

In the first part, conclusions are referred to the LCA related paragraphs in the SYSTEMIC Description of Action (DoA) to provide direct answers to the critical questions, statements and commitments of the LCA study :

LCA of the fertilisers and organic amendments will be made to evaluate the environmental sustainability of the eco-innovative system compared to the current common/regular approach, which will derive information of environmental positive and negative side-effects.	The present report provides detailed results on the environmental effects of the eco-innovative systems compared to the current approach, i.e., comparing the environmental impacts for 10 impact categories (KPIs). In 9 impact categories, NRR systems had a positive impact. In 1 impact category, terrestrial toxicity, the impact was significantly lower with NRR systems compared to operations of AD plants without NRR but overall negative, mainly due to road transport caused by procurement of substrate and supply of products. Yet, road transport was not entirely caused by AD plants and NRR systems, it frequently caused by livestock concentration at least in Flanders and the Netherlands.
Show-casing and demonstrating the economic, social and environmental sustainability of the eco-innovative business cases by means of a LCA assessment Derivation of sustainability indicators for the produced secondary products by means of a LCA assessment which includes possible positive and negative side-effects and risks, such as those associated with harmful substances	LCA provided robust evidence on environmental sustainability of the eco-innovative business cases by case-by-case and by comparative assessment of environmental effects in regard to 10 impact categories (KPIs) that were selected and assessed as indicators for the sustainability of the secondary products in a cradle-to-farm gate approach: climate change, fossil depletion, human toxicity (cancer & non-cancer), freshwater ecotoxicity and eutrophication, marine ecotoxicity and eutrophication and terrestrial ecotoxicity and acidification.
The objective of WP2 is to develop economic and environmental KPI's and to integrate these into business models. Information from the five demonstration plants (collected in WP1) is used to derive economic KPI's and environmental KPI's (LCA assessment) which are subsequently used as input for the business model. Environmental KPI's will be derived in order to compare the sustainability of recovered product with their synthetic counterparts. KPI's will be derived by LCA assessment including the impact of the processes at the AD plants (mass and energy balances, water and carbon footprint, GHG emissions, usage of chemicals, transport) as well as the impact of the utilisation of the products in the field (risks for eutrophication, spreading of contaminants, carbon sequestration) as well as their impact on climate change and resource depletion. Data from WP1 on mass and energy balances of the NRR processes and the environmental impact assessment of the products will be used as input for the LCA assessment.	The KPIs of an LCA are impact categories. The critical question was if operations of the NRR systems have a negative impact on the environment. To answer the question the energy and material inputs were assessed against selected impact categories and numeric values, standing for typical substances assigned to the distinct categories. Conventional (synthetic) fertilisers are compared by replacement. A negative value in the Life Cycle Impact Assessment (LCIA) stands for a positive environmental effect, a positive value stands for a negative effect. The impact of handling and using the products in agriculture have not been included in the LCIA due to high variability of use-related emissions. Up to 95% of ammonia N (NH_3) may be lost from organic fertilisers to the environment because of unprofessional handling and unfavourable (weather) conditions. As handling and use influence would distort the LCIA result, system boundaries were unanimously set as cradle-to-farm gate. The only negative impact value is shown for the assessment of terrestrial ecotoxicity to which mainly road transport is a relevant contributor. In all cases NRR systems gradually (BENAS) or

	substantially (Groot Zevert Vergisting, AMPower, and Waterleau New Energy) improve the impact. This is due to long-distance substrate supplies (Acqua & Sole, BENAS) and product supplies to more or less distant fields (BENAS). The eco-innovative systems assessed have a highly relevant positive effect on climate change for both, conversion of waste (energy crops at BENAS) to renewable energy and production of N-P-K fertilisers replacing Haber-Bosch and fossil derived conventional products. Environmental effects in other categories were entirely positive, albeit with comparatively low total impacts.

In Conclusion, all LCIAs proof the significant positive environmental impact of biogas plants with nutrient recovery and recycling. The replacement of fossil energy (electricity and natural gas) by biogas is a major contribution to lower greenhouse gas emissions and supply risks. Even for processes in need of long distance transport, the contribution to reducing global warming is impressive. The second function of a biogas plant, the management of organic wastes, shows its potential in the replacement of conventional nutrients that without treatment cannot be used at all (sewage sludge), can only be used with a limited scope or can be made available for larger markets in farer destinations.

Although the reduced positive impact of NRR systems on GHG in some plants, at a first glance, seems to be an argument against their implementation, their overall impact on the biogas plant must be taken into account. Where more energy is foregone for NRR, usually significantly higher positive impacts are demonstrated for terrestrial ecotoxicity. In all investigated cases, NRR technologies result in a higher competitiveness and flexibility, or even are the reason for the existence of a biogas plant. None of the nutrient management solutions shows a significant negative effect compared to the base case and none turned the overall result negative. Terrestrial ecotoxicity, mainly related to road transport, has a significant impact but in the majority of investigated demonstration cases (AM-Power, Groot Zevert Vergisting and Waterleau New Energy) is not caused by the biogas plant and its NRR system. In regions with high livestock density, the impact of road transport is due to concentrated livestock production and not caused by the biogas plant. Yet, terrestrial ecotoxicity at Acqua & Sole could be improved by sourcing substrates from wastewater treatment plants in the region. The NRR System of BENAS is highly effective but the impact on terrestrial ecotoxicity is affected by the distance between cropland under the company's management and the biogas plant.

Overall, NRR technologies contribute to the sustainability of the biogas sector. Yet, the magnitude of the positive impact depends on the individual case, on the type and use of fertilising products. The impact assessment of product use has equally shown positive results, with exceptionally low emissions of ammonium sulphate in contrast to untreated digestate and even in comparison to conventional mineral N fertilisers.

The environmental effects of eco-innovative systems as demonstrated in SYSTEMIC have still room for improvement, among others by replacement of fertilising materials with exceedingly high environmental impact, e.g., peat in growing media and by N higher recovery rates and production of more ammonium sulphate as an exceptionally low emission fertilising product, including during its use on cropland. The higher the share of mineral products in the recycled fertiliser mix, the lower the risk for nutrient losses during handling and use.

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SYSTEMIC

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