Trade-offs of National Circular Economy Agendas

Comparing the wins and losses across economy, society, and environment for the Circular Economy Programme of the Netherlands

by

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In partial fulfillment of the requirements for

the degree of Master of Science of Industrial Ecology

at Leiden University and the Delft University of Technology.

to be defended publicly on Monday August 29, 2022 at 09:30 AM.

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Summary

In recent years, there has been an emergence of the concept of “circular economy (CE)”, which promises to close the loop in terms of resource extraction and consumption in the prevailing economic paradigm. This promises environmental and socioeconomic benefits, but the risk exists where the benefits of the circular transition might be unevenly distributed, with potential trade-offs in the implementation of CE. The Netherlands has an agenda, the ”National Programme for Circular Economy (NPCE)” to achieve a full CE transition in the Netherlands by 2050. However, the agenda is at an early stage of implementation, the effects of the implementation of this policy are not well understood,

This research approaches the CE transition at a macro-level to allow for top-down examination of the macroeconomic effects of the NPCE on the Dutch economy and its constituent sectors. 3 state-of-the-art macroeconomic modelling approaches were found in existing literature: Multi-regional Input-Output Analysis (MRIOA), Computable General Equilibrium and Integrated Assessment Models. An evaluation of the 3 approaches on their overall strengths and weaknesses and their applications for CE modelling was then performed. MRIOA was found to be the most suitable for the modelling for CE scenarios, as it had three benefits over the other competing modelling approaches. Firstly, it was an established modelling approach for modelling the macroeconomic effects of CE. Secondly, it has a high level of data resolution, making it suitable for modelling trade-offs between environmental and socio-economic indicators. Lastly, the availability of publicly available datasets and modelling tools provides convenience in extending existing models and datasets for the purposes of our research.

After the selection of the most suitable macroeconomic modelling method, an approach for the modelling of national CE strategies with EE MRIOA was developed. This approach builds upon existing EEIOA methods for CE, more specifically Donati’s 2019 paper on modelling CE interventions with EEIOA. It lays out the method to create CE scenarios from complex CE projects that employ a combination of CE strategies using the software tool Pycirk and EXIOBASE v3.3 input-output dataset. The model was then applied to the case study of the Netherlands, taking reference from the list of projects in the latest Dutch CE implementation programme for 2021-2023. With the current state of Dutch CE implementation programme, national CE strategies were found to be at an exploratory or pilot stage and difficult to model with the developed approach. To address this, adaptations to the method were implemented to model early stage CE projects as interventions.

To evaluate trade-offs, this study provided a formal definition of wins and losses for each footprint category based on the desired direction of changes in footprint categories. The impacts of the CE scenarios were mapped across six footprint categories: Global Warming Potential, Total Energy Use, Material Extraction footprint, Blue Water Extraction, Value Added and Employment.

When the impacts were compared, for the construction sector, the biggest reduction of footprints are seen in the manufacturing sectors for construction components, whereas the biggest increase in footprints are seen in transport and freight sectors. The scale of wins in material extraction footprint is potentially -17.96%, double the size of losses in value added and employment. For the plastics sector, the biggest reduction of footprints are seen in the plastics manufacturing sectors. The scale of wins in energy use footprint is potentially -4.46%, greater than other footprint categories by around five times. Comparing across priority chains, the biggest potential wins were found in the construction priority chain, and the best interventions modelled, in decreasing order, being Modularity, Material Passports, and Producer Responsibility.

Overall, it was found that the trade-offs of the Dutch CE transition occur between wins in the environment dimensions, at the cost of losses in socioeconomic dimensions. For the case study, wins were observed in the global warming, material, and energy indicators, while losses were observed in the value added and employment indicators. Depending on the type of CE intervention, trade-offs can also be expected between economic sectors. In terms of economic sectors, transportation is the sector expected to gain the most from the transition to a circular economy, and manufacturing of construction components and plastics are sectors expected to lose.

This study recommends that to address the trade-offs as a result of the Dutch CE agenda, policymakers and industry actors should take action on 2 fronts: tackling the costs to society and economy, and enhance growing economic sectors from the CE transition. With the existence of trade-offs, the policymakers should be wary of potential rebound effects when pursuing the transition to the circular economy. A proactive stance is needed in monitoring and managing the transition of the economy as it progresses to prevent rebound effects.

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Abbreviations

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Abbreviation	Definition
CE	Circular Economy
CEAP	Circular Economy Action Plan (of the European Commission)
CGE	Computable General Equilibrium
EC	European Commission
EE	Environmentally Extended (Input-Output)
MR	Multi-regional (Input-Output)
NPCE	National Programme for Circular Economy (of the Netherlands)
IAM	Integrated Assessment Model
IO	Input-Output
IOA	Input-Output Analysis
SDG	Sustainable Development Goals (United Nations)

Tracks/Subagendas for Implementation Programme

Abbreviation	Track/Subagenda
Prevention	Prevention: more with less and reduced leakage (for Plastics)
RP	Greater supply and demand for renewable plastics (for Plastics)
BQ&ER	Better quality and better environmental returns (for Plastics)
Co-op VC	Strategic co-operation across value chain (For plastics)
MP	Materials Passport (for construction)
PR	Producer Responsibility (for construction)
Modularity	Modularity (for construction)
Circular SC	Circular supply chains, regulations, tendering and commissioning (for construction)

1

Introduction

1.1. Concept of Circular Economy

In recent years, there has been an emergence of the concept of “circular economy”, championed by organisations such as the Ellen MacArthur Foundation and the Platform of Advancing Circular Economy (PACE). In essence, the circular economy is a rethink of the prevailing economic model. The current economy operates on a linear model, which adopts a “take-make-dispose” philosophy (Ellen MacArthur Foundation, 2013). Raw materials are extracted from sources of natural resources in the environment, manufactured into products with a finite lifespan, sold and consumed, then disposed as waste once their useful lifespan has been reached.

The linear economy presents several issues which have become increasingly apparent. Firstly, the linear economy is unsustainable from a resource perspective. Raw materials used for the manufacturing of products is finite and is becoming increasingly scarce with current consumption patterns. Secondly, the generation of waste is in itself a major logistical dilemma. Significant effort and resources need to be invested to manage the flow of waste, which in the current linear economy paradigm, has no significant use and economic value. Thirdly, while waste in the linear economy embodies significant amount of material, the value of these embodied materials is not recognised, and this perpetuates the exploitation of limited natural resources over the resources embedded in waste (Planetark, n.d.).

The circular economy promises a solution to the problems of the linear economy. It starts by recognising the value of waste as a potential source of material, which can be exploited and extracted in a way similar to natural resources. This creates an alternative supply of materials, encouraging waste to flow back into the economy, closing resource loops and providing a means to manage waste besides disposal. This in turn satisfies some of the demand for material generated from production, reducing the pressures on scarce natural resources to provide the resources needed in the economy (Ellen MacArthur Foundation, 2013).

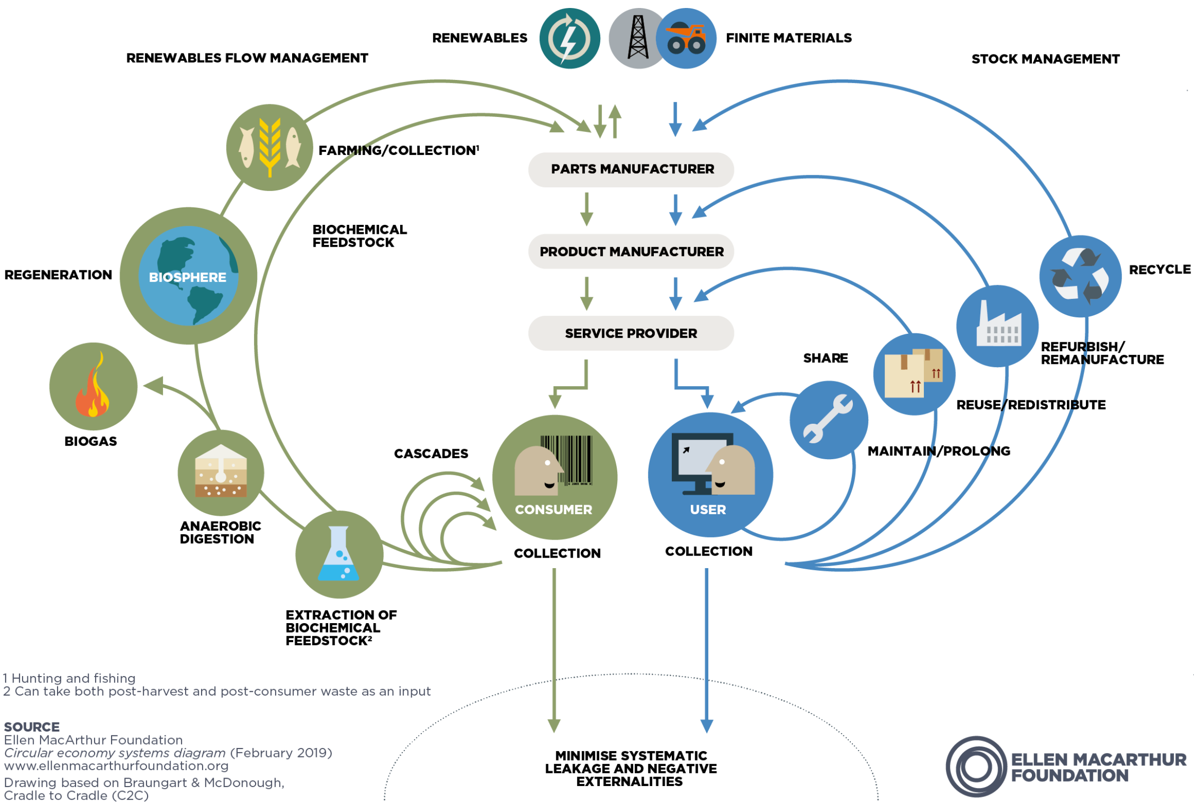

Figure 1.1: The butterfly diagram, showing the and material supply chains and linear economy. (Ellen MacArthur Foundation, 2013)

1.2. Perspectives on the Objectives of Circular Economy

Many regional, national and international bodies recognise the issues with the current linear economy and the purported benefits of circular economy, and this can be seen in the increasing interest by these bodies to move their economies towards Circular Economy. For example, the European Commission has adopted their new Circular Economy Action Plan (CEAP) in March 2020 (European Commission & Directorate-General for Communication, 2020).

1.2.1. European Union

From the European Union (EU) perspective, the European Green Deal was launched on December 2019, with the aim to address climate change and environmental degradation (European Commission, 2022b). As part of the Green Deal, the European Commission (EC) is adopting a circular economy through the new Circular Economy Action Plan (new CEAP), in an effort to develop a climate neutral, resource-efficient and competitive economy. By 2050, the EU wants to achieve climate neutrality (European Commission, 2020). To fulfil this ambition, the EU needs to accelerate the transition towards a regenerative growth model that gives back to the planet more than it takes and advance towards keeping its resource consumption within planetary boundaries. Ultimately, the EU has to urgently reduce its consumption footprint and double its circular material use rate in the coming decade (European Commission, 2020).

1.2.2. The Netherlands

The Netherlands is one of the frontrunners in circular economy. In 2016, The Dutch Government has formulated the ambition to achieve a fully circular economy by 2050, by launching the National Programme for a Circular Economy (NPCE) (Ministerie van Algemene Zaken, 2021; Planbureau voor de Leefomgeving, 2022; The Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, 2016). This is prior to the European Green Deal in 2019 and one year after the first CEAP released in 2015 (European Commission, 2022a).

The motivation of the Netherlands in pursuing a transition to circular economy stems from a commitment to address the triple planetary crises of climate, biodiversity and pollution, and well as resource independence from other countries through the extraction of secondary resources from existing products (Ministerie van Infrastructuur en Waterstaat, 2021).

1.3. Current State in Circular Economy in the Netherlands

In 2016, during the launch of the programme “A circular economy in the Netherlands by 2050”, The Dutch government has defined five transition agendas as part of the NPCE: Biomass and food, plastics, manufacturing industry, construction industry and consumer goods. Besides the long-term target of achieving a complete transition to a circular economy, the Dutch government has also set a short-term objective to achieve a 50% reduction in the use of primary raw materials (minerals, fossil and metals) by 2030 (The Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, 2016). In 2017, an agreement was drawn between the government and supporting partners to recognise the shared ambition between the signing parties to achieve a circular economy in the Netherlands and support each other on the process and implementation of the transition agendas (Ministerie van Algemene Zaken, 2017).

As of 2021, the Integral Circular Economy Report (ICER) was published. The report concluded that the Dutch government, together with other parties, have managed to create a basis and structure for achieving a circular economy in the Netherlands (over 400 parties have signed the National Agreement on the Circular Economy). However, the report also cautioned that several trends in resource use continue to increase (6 out of 7 overall national targets are not expected to be achieved). It also noted that the Dutch economy still functions rather linearly and there is not enough innovations that could radically affect the existing use patterns for material resources. The report suggests that to achieve more progress towards a circular economy, stronger governmental and policy action is needed, to drive socio-economic renewal of the existing economy and phasing out the linear production and consumption chains (Hanemaaijer et al., 2021).

In their latest update, the NPCE report (Ministerie van Algemene Zaken, 2021) focuses on three themes: Higher on the R ladder (explained in 1.4.2, Systemic change from a linear to a circular economy, and impact through a focus on raw materials flows. The Netherlands recognises that interest in the circular economy has grown in recent years, even at the regional level with EU Green Deal and the EU Circular Economy Action Plan. Therefore, to keep in step with regional CE developments, the report concluded that the Dutch government needs to adopt an enhanced policy focus. The government will need to scale up and speed up developments towards circular economy. Voluntary efforts are insufficient; the government needs to move towards binding measures with industry actors.

1.4. Key Concepts

When discussing the effects of the transition towards circular economy, there are some key definitions, which will be elaborated here.

1.4.1. Intervention and Strategy

Based on Donati et al. (2020), circularity interventions are ”actions or processes that preserve resources inside the economy”. Aguilar-Hernandez et al. (2018) summarises the general principles of circularity interventions: Minimising Waste disposal; optimising material loops; and promoting a restorative environment.

While in most academic literature interventions and strategies are used interchangeably, Donati et al. (2020) clearly differentiates between interventions and strategies. A CE strategy is a set of policy interventions and improvement options (CE interventions). CE interventions under a CE strategy umbrella try to achieve a common objective in the CE transition, but the approach to achieve said objective is different. For this paper, a distinction from Donati et al. (2020) will be used.

1.4.2. R-ladder

The Dutch government refers to an R-ladder when referring to circularity strategies. In their latest version, the R-ladder consists of 6 levels, going from R1 to R6. As a general rule, the smaller the number and the higher up the ladder the strategy is, the smaller the resource demand and the shorter the length of resource flows in the economy, reducing the size of the resource loop. Hence, circular strategies higher up the R-ladder are preferred for achieving a circular economy.

1.4.3. Circularity trade-offs

Barbier and Burgess (2019) discussed in their paper the systems approach to sustainability, which characterises sustainability as the ”maximisation of goals across environmental, economic and social systems”. They then referred to Barbier (1987), which defines the general objective of sustainable development as the ”maximisation of goals across environmental, social and economic systems using an adaptive process of trade-offs” between the three aforementioned systems. Attempting to maximise the goals for only one system does not neces-

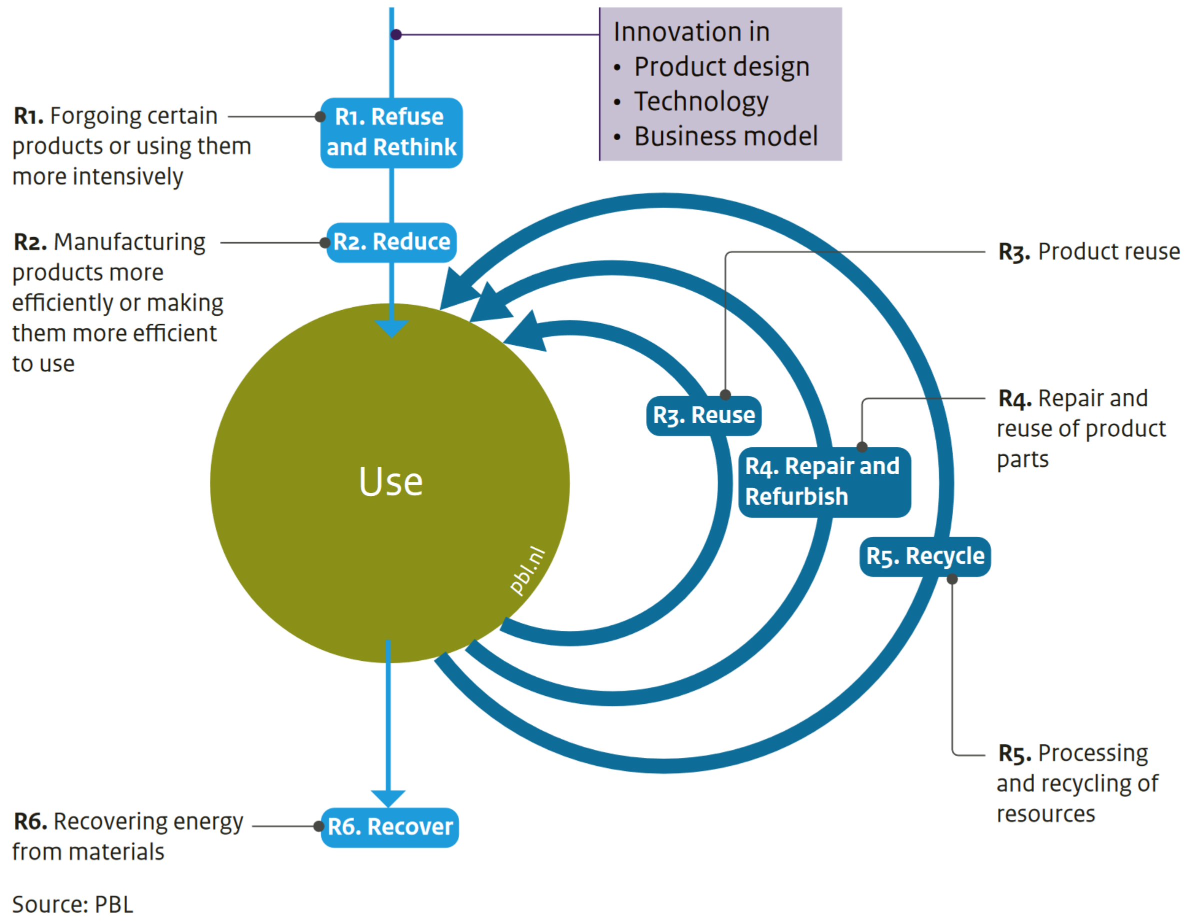

Figure 1.2: The R-ladder of circularity strategies (Rood & Kishna, 2019)

sarily produce a sustainable outcome, since potential impacts to the other systems can be ignored as a result. Trade-offs are thus necessary to manage the positive and negative effects that arise due to interactions between systems. In the Zhao et al. (2021) paper on the trade-offs between sustainable development goals (SDGs), trade-offs occur when one or multiple SDG targets are enhanced at the cost of impeding the progress toward other SDG targets. Therefore, for this research, the transition to CE aims to improve the three dimensions of environment, society and economy, and a trade-off occurs when there is improvement of some dimensions as a result of the transition to CE, at the cost of impacting the other dimensions. A example as suggested in Wijkman and Skånberg (2015) is the loss of jobs (social dimensions) in sectors such natural gas in a transition to renewable energy (environmental and economic dimensions).

1.5. Outline

For this thesis report, Chapter 1 provides an introduction of CE, the the current state and motivations behind the transition to CE for the Netherlands. It also defines some key terms and concepts used in the research. Chapter 2 goes introduces the problem behind the thesis, the research questions and research approach used for this thesis. Chapter 3 examines the macroeconomic modelling methods for CE, and compares the shortlisted modelling methods to select the most suitable modelling method. Chapter 4 proceeds to explain the modelling development and implementation process to model projects under the Dutch CE agenda in the selected modelling method. Chapter 5 analyses the results obtained by running the model, and Chapter 6 discusses the findings, research contributions, limitations and conclusions for the report.

2

Research Problem

2.1. Problem Introduction

2.1.1. Trade-offs in the Circular Economy

In the introduction, the current state of CE in the Netherlands points to serious policy interest, both at the regional EU level and the national level to pursue a CE transition.

From the motivations of the EU and the Netherlands, there are multiple reasons for working towards CE. While the main impetus to transition from a linear to a circular economy is generally framed from a resource standpoint, the transition also promises additional benefits in the environmental and socio-economic dimensions.

Extracting materials from waste alleviates the environmental harm caused by the exploitation of natural resources and lessens the pollution as a result of waste treatment and disposal. The circular economy is also projected to create jobs and stimulate economies by preserving values and redesigning financial instruments (Schröder, 2020). In their paper, McCarthy et al. (2018) claims that new jobs are created mainly in recycling, rental and repair services, remanufacturing, secondary material production, and the sharing economy, jobs are also shifted away from extractive sectors into more manufacturing and service-oriented sectors, resulting in the up-skilling of the workforce.

However, the transition is not without its costs as well, as economies, industries and supply chains need to adapt and integrate elements of circular economy, which can result in the obsolescence of much of the existing infrastructure and workforce supporting the linear economy.

Since there are both benefits and costs in the transition towards circular economy, it is in the interest of the Dutch government to understand these trade-offs as it continues to realise its ambition of achieving a fully circular economy.

2.1.2. Economy-wide Approach

Existing literature on the transition towards circular economy generally acknowledge the process of transition to be systemic, involving changes to supply chains of production that can span across multiple economic sectors and across geographical regions (Kirchherr et al., 2017). To study the systemic effects, research has approached the circular economy transition from multiple levels: micro, meso, macro (Ghisellini et al., 2016; Prieto-Sandoval et al., 2018).

For this study, CE transition is approached at the macro-level. A macroeconomic modelling approach allows a top-down examination of the overall structure of the economy. The top-down approach also shows how the circular economy transition affects the interactions between different economic sectors and its impacts. This provides insight on the overall effects of the CE transition at the national level, such that the Dutch government can better anticipate systemic issues and manage a smoother transition.

2.2. Research Gap

Even though the Dutch government is one of the first governments to release an agenda for the transition into a circular economy, there is still limited academic literature examining the circular economy transition.

Opportunities and projected savings for a circular economy transition were identified in an early paper by Bastein et al. (2013), with emphasis on metal, electrical and agro-food sectors. Other studies are industry or materials specific. Verrips et al. (2019) looked at plastics and the Dutch circular economy. K. van Leeuwen et al. (2018) examined wastewater in a CE as a source of energy and raw materials. Golsteijn and Valencia Martinez (2017) examined the opportunities in e-waste, Van Buren et al. (2016) on the role of the logistics sector. Lastly, Crielaard (2015) explored CE on the Dutch construction sector.

In terms of modelling the Dutch circular economy, the Dutch Ministry of Economic Affairs commissioned a study to perform footprint calculations using a Dutch National Accounts Consistent Database in 2017 (Walker et al., 2017). This resulted in a Single-country National Accounts Consistent (SNAC) multi-regional input-output (MRIO) table, based on the EXIOBASE database for the purposes of modelling the environmental footprint of NPCE. As of 2019, CBS Netherlands has produced a report that details the method to keep the SNAC MRIO table up-to-date by harmonising old data in the EXIOBASE with new national account numbers of the Netherlands (Walker et al., 2019). However, there is no existing literature actually quantifying the impacts of the circular economy at the whole-of-economy level for the Netherlands.

An initial exploration of the existing academic literature established that there are multiple models that academics have employed to perform economy-wide modelling of the circular economy (Aguilar-Hernandez et al., 2018; Böhringer & Rutherford, 2015; McCarthy et al., 2018). In particular, GCE and EEIOA models stand out as the preferred modelling methods to model transactions in complex multi-industry economies. There have also been established approaches in modelling circular economy interventions, typically by characterising these interventions as strategies which can then be introduced as changes into the economy-wide models (Aguilar-Hernandez et al., 2018; Blomsma & Brennan, 2017; Ghisellini et al., 2016). While measures of circular economy effects have been defined, circular economy research is mainly rooted on the idea of the analysis of benefits in terms of physical rather than monetary flows (Ghisellini et al., 2016), and most papers on circular economy tend to emphasise the economic and environmental effects over the social effects (Kirchherr et al., 2017; Padilla-Rivera et al., 2020). There have been limited studies trying to measure the impacts of the circular economy across all three dimensions of economy, environment and society. For sustainable development, it is important to ensure that progress in one of the dimensions is not offset by negative impacts in other dimensions. This study will provide a more holistic evaluation of the impacts of existing circular economy strategies, such that potential negative impacts of the transition towards circular economy can be addressed with the development of a more balanced circular economy implementation plan.

In the context of the Netherlands, academic research is limited in modelling the extent of effects of the Dutch circular economy agenda, especially regarding whole-of-economy trade-offs and impacts. Most literature tend to be industry and material specific, and focus on the opportunities associated with the transition of a particular sector towards circularity.

2.3. Problem Statement

The implementation Dutch CE agenda is still in an early stage. As evidenced from the research gap, there is little understanding of the multidimensional effects of the implementation of Dutch circular economy programme at the macroeconomic or national level. The lack of awareness of the national-level trade-offs creates a blind-spot for important stakeholders such as the government and industry. This can lead to sufficient action to address potential negative systemic effects that arise out of the transition towards circular economy. Hence the problem statement:

> The implementation of the Dutch National Programme for Circular Economy is national and systemic. It is expected to produce both benefits and costs across the dimensions of environment, society and economy. However, these trade-offs are not well understood.

Since the NPCE is a national-level agenda, this research will place emphasis on developing a methodology for modelling national-level circular economy agendas using an macroeconomic model, and measuring the effects across all three areas of environment, society and economy. This methodology will then be applied to the case study of the Netherlands, which will give the resultant trade-offs between the three areas that will result from the implementation of the Dutch NPCE.

2.3.1. Main Research Question

What are the potential trade-offs in environmental and socio-economic impacts of the Dutch National Programme for Circular Economy (NPCE)?

2.3.2. Sub-questions

1. What are the current state-of-the-art methods for modelling the trade-offs of the circular economy?
2. What are the macroeconomic models most suitable for the assessment of circular economy trade-offs?
3. What are the approaches to create a circular economy scenario out of a set of national circular economy strategies for modelling?
4. What are the effects of the Netherlands' circular economy strategies?

2.4. Research Approach

For this thesis, an approach to model the macroeconomic effects of circular economy is first developed, before application onto the case study of the Dutch NPCE. The purpose of the approach is to represent various circular economy strategies at an macroeconomic scale, in the form of changes to the economic structure. Once the approach is selected, modelling and macroeconomic analysis can take place to determine the trade-offs of the Dutch circular economy agenda. The overall research approach is represented in figure 2.1.

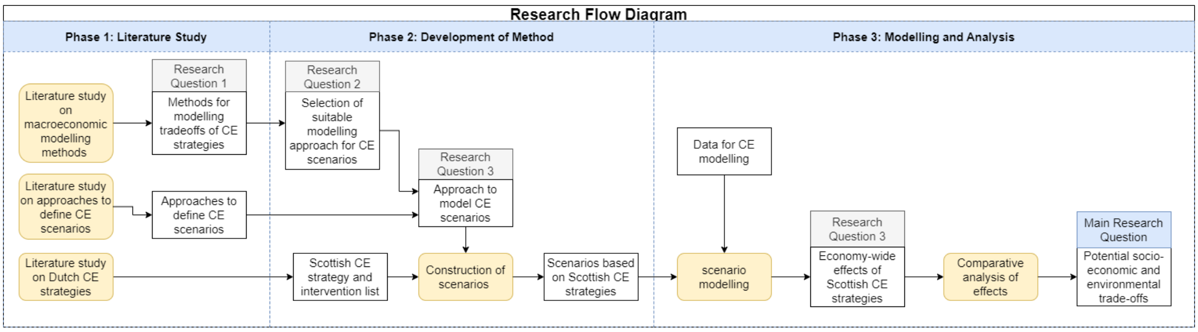

Figure 2.1: The research flow diagram, representing the 3 phases of research for this study.

2.4.1. Literature Review

Before this approach can be constructed, a review of the different methods of classification of circular economy strategies will be conducted, both to classify individual circular economy interventions into distinct strategies for modelling, and to understand effects of these strategies on the three dimensions of economy, society, and environment.

Next, before modelling the macroeconomic impacts of CE strategies, it is important to understand the state-of-the-art modelling tools to perform macroeconomic analysis of the impacts and trade-offs of the CE strategies. A review of existing macroeconomic models and their existing applications to CE research will be conducted. This will provide the current state-of-the-art approaches to modelling the circular economy, which will answer sub-question 1.

With the shortlisted macroeconomic models, the strengths and weaknesses of the models will be compared. This will determine the most suitable model to analyse CE strategies and their impacts and trade-offs. The selection of the most suitable model will answer sub-question 2.

Lastly, following the identification of a suitable modelling method, the macroeconomic effects of these strategies need to be codified. A review of existing characterisation methods will provide the way to convert qualitative policy interventions described in literature into quantitative changes to the macroeconomic structure of the Dutch economy. The literature study will also yield indicators that are able to represent the effects of the circular economy strategies across the three dimensions.

2.4.2. Development of Model

With an approach to characterisation of CE strategies and a macroeconomic method for modelling the CE selected, the next step will be to combine these separate elements into a cohesive way to model circular economy strategies. The method of combining will be the creation of scenarios: a set of modelling assumptions and choices to represent the implementation of a singular or a combination of circular economy strategies in an economy. Literature review will be performed on the approaches to formulate circular economy scenarios for the selected modelling approach. The approach to formulating circular economy scenarios will answer sub-question 3.

Parallel to the literature review on scenario modelling, a review on policy papers, government papers and relevant academic literature will be conducted to gather a complete picture of the current state of the CE transition in the Netherlands. This will provide details on existing CE strategies adopted by the Dutch government to achieve its CE goal, and their likely effects on the economic structure. This review will provide the justification for the modelling choices and data supporting numerical data for modelling.

Once the modelling approach and the scenario formulation approach has been established, the approach is then applied to the selected case study of Dutch NPCE. The Dutch circular economy agenda will be characterised into distinct strategies that can be modelled using the selected modelling approach.

Data collection of macroeconomic datasets will also occur at this stage. These datasets form the baseline data for analysis but might require further processing such it represents the circular economy scenarios that will be modelled for this study. Using the scenario modelling approach, data in the economic datasets will be amended to capture the projected effect of Scottish circular economy strategies on the economic model.

2.4.3. Modelling and Analysis

Once the data (economic datasets and scenarios) necessary for analysis is prepared, the data analysis will be performed. Individual policy interventions will be modelled to obtain the macroeconomic effect when each policy intervention is applied. The results of the data analysis with determine the effects of the circular economy strategies across the environmental and socioeconomic dimensions. This will answer sub-question 4.

Comparative analysis of the effects will show the potential trade-offs between the 3 dimensions if the circular economy policy were to be implemented successfully, which will present the answer to the main research question.

3

Review and Selection of Circular Economy Macroeconomic Model

To understand the circular economy from an economy-wide perspective, researchers have developed a number of methods to model the circular economy transition. McCarthy et al. (2018) detail 2 general methods: accounting modelling and economy-wide quantitative models; and concludes that economy-wide quantitative models are more suitable for modelling the transition as it has the ability to capture larger and more complex inter-industry economic interactions.

There are a few variations of economy-wide quantitative models in academic literature. McCarthy et al. (2018) identify 2 forms: Computable General Equilibrium (CGE) and macroeconomic models. Similarly, in Wiebe et al. (2018), they distinguish between 3 different kinds of input-output (IO) tools: static demand-driven , dynamic econometric IO models and CGE models.

3.1. Computable General Equilibrium Models

3.1.1. General Introduction to CGE

A CGE model is a system of equations that describes an economy as a whole and the interactions among its parts. The model includes exogenous and endogenous variables and market-clearing constraints. The model finds an economy-wide equilibrium by simultaneously solving all of the equations in the model. At equilibrium, given some set of prices, the quantities of supply and demand are equal in every market. CGE models are *computable* models, that are able to quantify the effects of shocks introduced to an economy. Circular economy interventions can be introduced as the shocks for the modelling of the macroeconomic effects.

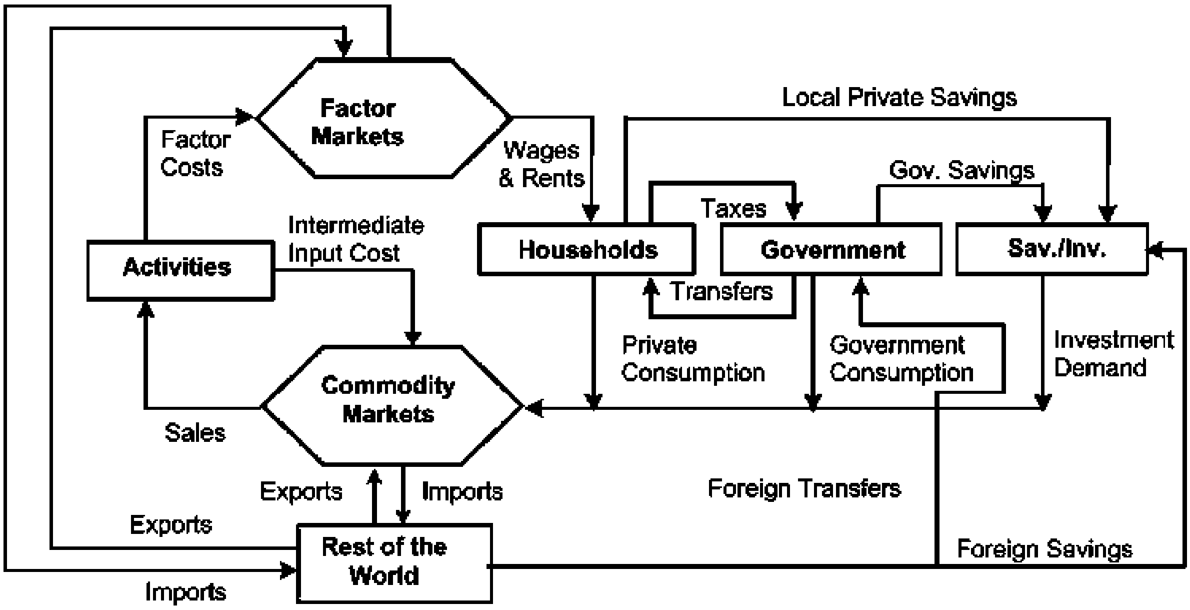

Figure 3.1: Structure of Payment Flows in the Standard CGE model. (Lofgren, 2004)

The equations of a CGE model are based on actual data for an economy with reference to a particular base year. The production function for each industry is based on firms' technology in the economy – inputs and production levels – in that base year. Since a CGE model utilises real economic data, the values obtained once a new equilibrium is reached after the modelling of a change in the structure of the economy gives an anticipated value of the impact on the economy. This allows the modeller to quantify the values associated with the outcomes of various "what-if" scenarios (Burfisher, 2021).

The CGE model takes on some assumptions: firms are assumed to maximise profits, with both product and factor markets typically assumed to perfectly competitive. Profit maximisation dictates that firms will minimise costs, with factor demands generally responsive to factor prices. Household consumption is assumed to be utility-maximising, responding to differences in price across goods and services. Finally, to match demands and supplies in the economy, prices will adjust in goods/services and factor markets accordingly (Partridge & Rickman, 1998).

There are both static and dynamic models for CGE. A static CGE model provides comparison between the initial and final states of equilibrium of the economy when policy or technological change is implemented as a shock to the economic system. Static models can identify the who are the overall losers and winners from economic shocks, but does not show costs and benefits associated with the transition as it progresses from the initial to final states. Dynamic models allow for the modelling of the behaviour of the economy throughout the transition process between initial to the final equilibrium. However, complete dynamic CGE models become very complex and regional and sectoral details are compromised (Babatunde et al., 2017).

3.1.2. Application of CGE for CE

CGE as a modelling approach is already used by the Scottish Government in their economic analysis (The Office of the Chief Economic Adviser, 2015). Through the calculation of the initial and final equilibrium systems, it can be used derive computationally the impacts of CE policies or shocks to an economy. CGE models are suitable for the modelling of circular economy transition as they are able to account for the inter-dependencies between different sectors of the economy and reveal the wider, sometimes indirect, effects of shocks to the economy (The Office of the Chief Economic Adviser, 2015).

There have been a number of CGE models developed to analyse environmental policies and the circular economy, namely:

MAGNET

The Modular Applied GeNeral Equilibrium Tool (MAGNET) is a recursive dynamic, multiregional, multi-commodity CGE model, covering the entire global economy. MAGNET was developed on top of The standard Global Trade Analysis Project (GTAP) model. MAGNET, however, improves upon the base GTAP model by offering more flexibility in model aggregation (definition of regions and sectors) and more options for changing a model's structure through modular design and the addition of various extensions, which allows the general GTAP model structure to be tailored to the research question at hand (Bartelings et al., 2021).

UCL ENGAGE

UCL ENGAGE model is a standard multi-sectoral, multi-region, dynamic computable general equilibrium model. UCL ENGAGE-materials disaggregates GTAP material extraction sectors used in the base ENGAGE model, such that resource efficiency and circular economy scenarios can be analysed with greater detail with respect to materials and minerals (Winning et al., 2017).

EXIOMOD

The EXIOMOD model was developed by TNO in the Netherlands. It uses the EXIOBASE dataset to create a global environmentally- orientated CGE model. It was developed to answer resource efficiency questions primarily for the EU (Bulavskaya et al., 2016).

Ellen MacArthur Foundation

Böhringer and Rutherford (2015) developed a static multi-regional CGE model for the Ellen MacArthur foundation. It was developed for the modelling circular economy, to analyse the effects of technological shifts and governmental policy as a result of a circular economy transition.

3.2. Input-Output Models

3.2.1. General Introduction to IO Models

Miller and Blair (2009) defines an IO model as "in its most basic form, a system of linear equations, each one of which describes the distribution of an industry's product throughout the economy".

Products (rows) \ Products (columns)	Products				Final uses			Total
	Agriculture, forestry, etc.	Ores and minerals; etc.	...	Services	Final consumption	Gross capital formation	Exports	
Agriculture, forestry, etc. Ores and minerals; etc. ... Services	Intermediate consumption by product				Final uses by product and by category			Total use by product
Imports	Intermediate consumption of imported products				Final use of imported products			
Value added	Value added by component							Value added
Total	Total supply				Total final uses by category			

Empty cells by definition

Figure 3.2: A simplified representation of a product-by-product IO table. (United Nations, 2018)

From E. S. van Leeuwen et al. (2005), input–output analysis has been an established method in quantitative economic research. Input–output models are built on the fundamental assumption that any output will have a corresponding input. Inputs can be in the form of raw materials and services that are produced or provided by other industries but can also be in the form of labour from households or certain amenities provided by the government. The output consists of the products and services produced or provided by that sector. An input–output table is constructed with double-entry bookkeeping: the totals of the columns equal the totals of the rows. Input–output tables have been constructed with different scopes and resolutions. IO models exist for the global economic system, national economic systems, and regional economic systems. System-wide effects of an exogenous shock in an economic system can be analysed with IO analysis. This is done by tracing the direct and indirect effects of that initial exogenous shock into an economic system across all economic sectors.

IO models can be scaled beyond a single national economy. Regional IO tables have been developed to capture international trade and supply chains. Using regional input-output tables, multi-regional input-output (MRIO) models can then be used to examine the interdependencies and linkages between industries, households, and the government, both in and between countries.

The input–output framework can also be extended to account for the associated effect of interindustry activity, such as on environment and pollution, energy consumption or people and social institutions.(Miller & Blair, 2009).The inclusion of environmental extensions allows provides the emissions intensity per unit of economic activity. From Kitzes (2013), EEIO is generally used for the modelling of two aspects:

- To calculate the hidden, upstream, indirect or *embodied* impacts associated with a downstream consumption activity, otherwise known as the *footprint* of the consumption activity; or
- To calculate the embodied value-added or impact in goods and services traded between regions.

3.2.2. Application of IOA for CE

The transition to a circular economy consists of economy-wide changes; this can affect a large variety of economic sectors. Therefore, it is useful to not only account for the effects on the industries directly affected but also those linked to these industries, whether upstream and downstream the supply chain, or within and between regions. Multiregional input−output analysis (MRIOA) allows us to assess these economy-wide changes and allows the modeller to track the transformation of products at each stage along the supply chain and thus capturing material flows across industry sectors and between intermediate and final goods producers and consumers (Wiebe et al., 2019).

IOA is one of the most widely employed modelling approach for the assessment of circular economy (Donati et al., 2020). However, in their review of EEIOA based studies on circularity intervention, Aguilar-Hernandez et al. (2018) note that most studies revolve around waste IO analysis or a hybrid economic-physical model to represent circularity interactions in supply chains. Most studies also tend to focus on a single region or sector.

3.3. Integrated Assessment Models

Besides economy-wide quantitative models, other complimentary modelling approaches have also been adopted to study the transition to circular economy. One important approach is the use of Integrated Assessment Models (IAMs) (Hare et al., 2018).

IAMs are models that combine knowledge from different domains into a single assessment, such as energy models, technology models, economic models and climate models. Since the concept of circular economy is complex and combines multiple disciplines, with impacts expected social, economic and environmental dimensions, each discipline and dimension has a set of established assessment tools and methods. IAMs provide a method to combine different yet complementary modelling methods, each designed to capture different sustainability discipline and dimensions. The integration and application of multiple modelling methods into a single assessment model will allow for more robust evaluation of the transition to circular economy, since the most appropriate modelling method will be applied for each discipline and dimension (Oliveira et al., 2021).

3.4. Comparison of Modeling Methods

A summary of the 3 different modelling methods studied in this literature review is laid out in table 3.1. Considering the strengths and weaknesses of each of the methods, MRIOA and CGE are preferred since they are established macroeconomic modelling methods already used for the study of the effects of CE on the economy. However, the lack of dynamic economic modelling is preferred over the high aggregation of the CGE as the modelling of CE strategies and interventions can be very product and industry specific so a greater resolution in product and industry categories will allow for more accuracy in the creation of sector-specific CE scenarios. Another factor that largely influenced the selection of the modelling method is the availability of open-source tools and data. For MRIOA, the datasets such as World IO Database, EXIOBASE and OECD - Inter Country IO database are accessible to download (Stadler, 2014) and tools for modelling CE in IOA such as Pycirk are available for the public to use. Based on these factors, MRIOA was chosen as the modelling method for this study.

	Multi Regional IOA	**CGE**	**IAM**
Strengths	Calculating embodied impacts of trade along supply chains within and between regions	Dynamic CGE allows for dynamic accounting of the macroeconomic system, modelling of the behaviour of the economy as it transitions from the initial to the final equilibrium	Depending on the assessment methods combined, allows the combination of multiple dimensions of the circular economy, or allows the integration of top-down and bottom-up modelling approaches to the economic system.
Weaknesses	Static snapshot of the economy and does not allow for dynamic accounting of the changes to an economy after a shock. The linear approach of IOA also does not allow modelling of non-linear effects.	High aggregation or computational requirements especially for large dynamic models	Complexity in integrating models from different disciplines.
Data availability	EXIOBASE database and pycirk software publicly available	Commercial and in-house tools not publicly available	-

Table 3.1: Comparison between macroeconomic modelling methods for CE

3.5. Macroeconomic Impacts and trade-offs of CE

To understand the extent of effects caused by circular economy transitions, there must also be a method to quantify and measure these effects. The extent of this research is limited – circular economy research is mainly rooted on the idea of the analysis of benefits in terms of physical rather than monetary flows (Ghisellini et al., 2016), and most papers on circular economy tend to emphasise the economic and environmental effects and less the social effects (Kirchherr et al., 2017; Padilla-Rivera et al., 2020).

The shape of the effects is also not well-studied. Vanhuyse et al. (2021) warns of the risk that the benefits of the circular transition might be unevenly distributed, and that social, environmental, and techno-economic aspects have to be carefully evaluated alongside each other to avoid rebound effects and displacing issues elsewhere.

Looking at metrics, many studies are concerned with measuring the extent of transition towards circular economy (Corona et al., 2019; Moraga et al., 2019; Poponi et al., 2022), not quantifying the effects. In their study, Aguilar-Hernandez et al. (2021) chose Gross Domestic Product (GDP), Job creation and CO2 emissions for representing the effects of circular economy at a macroeconomic level. These three indicators, while limited, will form the base for studying the macroeconomic effects of circular economy. In their study, Bjelle et al. (2020) estimate biodiversity loss based on land use changes.

With EEIOA, satellite accounts, additional datasets that that connect the IO model to other aspects of the economy beyond monetary transactions. Satellite accounts for the environmental and social impacts can be connected with the base macroeconomic model to model the effects of economic activity across the supply chain on the other systems of environment and society.

4

Modelling Development and Implementation

Before trade-offs between impact dimensions can be determined, the impacts of CE interventions have to be first calculated. As established in Chapter 3, Input-Output tables with environmental extensions serves as the most practical choice for the modelling of the impacts of the circular economy. The theory and process for modelling using environmentally extended input-output analysis is explained below.

For this chapter, the EEIOA foundations of the model is first described, showing the theory behind the calculation of embodied impacts as a result of the final demands generated by an economy, and how circular economy scenarios are produced from the modification of an existing set IO tables. Secondly, the approach to modelling of CE strategies in MRIO tables is explained using the visual aid of blueprinting to provide a guide for making changes to the IO tables. Thirdly, an introduction to the modelling software tool and the dataset is provided.

The model is then implemented on the case study of the Dutch NPCE. The latest developments and projects for the Dutch CE agenda, summarised in the ”Updated Circular Economy Implementation Programme 2021-2023” report, is converted into CE interventions for modelling in MRIO tables. Modelling scenarios for the calculations of impacts and trade-offs are then derived from the interventions.

4.1. Environmentally Extended Input-Output Analysis (EEIOA)

4.1.1. Impact Calculation using EEIOA

EEIOA is based on the early works of Wassily Leontief (Leontief, 1970; Miller & Blair, 2009). Donati et al. (2020) provides a summary of the most important equations used for the impact calculations for EEIOA. The a demand-driven IO model, the embodied emissions or footprint associated with a set of final demands of an economy can be determined with the following equation:

$$EF = diag(f)(I - A)y \tag{4.1}$$

In the above equation, EF is the column vector of the embodied emissions associated with each production sector. The equation takes input parameters $diag(f)$, which stands for diagonal matrix for f, the column vector of environmental intensities (environmental pressure per unit of economic output); I, the identity matrix; A, a matrix of technical coefficients (whose entry ij is the volume of inputs from sector i that are required to generate one unit of output of sector j); and y is the column vector representing the set of final demand of products produced by each sector.

The matrix of technical coefficient is given by the following equation:

$$A = Z\, diag\ (x)^{-1} \tag{4.2}$$

where Z is the matrix of inter-industry transactions and x is the column vector of the total outputs delivered by each sector.

The total output vector x is also calculated by:

$$x = Zi + Yi \tag{4.3}$$

Z, as earlier, is the matrix of inter-industry transactions and Y is a matrix whose columns represent the final demand of different consumption categories (e.g., households, government, investment), i is a vector column of ones and when multiplied with a matrix gives the row sum (i.e. Zi and Yi).The row sum of the final demand matrix also gives the stimulus vector y used in the earlier equation (4.1), calculated as $y = Yi$.

For some impact dimensions (e.g., global warming) there are direct emissions caused by final consumption activities. When such direct emissions are present, direct emissions are added to embodied emissions of final demand to obtain total emissions.

$$EF_{total} = EF'\, i + f_y y \tag{4.4}$$

Prime ($'$) denotes the transpose of a vector, hence $EF'i$ is the column sum of the embodied emissions caused by final demand. f_y is a scalar for the intensity of the emissions caused per monetary unit of final demand (i.e., emissions caused by households per unit of final demand) while y is a scalar of total final demand obtained by the column sum of the final demand vector. $y = y'\, i$

4.1.2. Scenario Modelling in EEIOA

To model the environmental or socio-economic impact resulting from a CE strategy or intervention, we require a *baseline scenario* and a *counterfactual scenario* to be defined. The *baseline scenario* represents the reference EEIO system, whereas the *counterfactual scenario* represents the EEIO system whereby the changes to the changes brought about by the CE strategy or intervention have been implemented. To create the scenarios, interventions are represented as sets of changes that affect the production and consumption systems. These changes are then modelled into the EEIO system. Donati et al. (2020) classifies changes to the EEIO systems as either primary and ancillary changes. A primary change is the expected direct change to the economic system as a result of the implementation of the CE intervention, while ancillary change are predicted changes to the economic system due to the knock-on effects of the CE intervention affecting other connected or related sectors of to economy to the sector experiencing the primary change. Both types of changes manifest as changes to matrices in the IO system,

Donati et al. (2020) formally define the impact of the CE strategy or intervention as:

$$\Delta EF = EF^{*} - EF \tag{4.5}$$

where EF is the impact of the baseline scenario, and EF^{*} is the impact in the counterfactual scenario.

Since trade-offs are compared across different impact dimensions, the impacts are presented in a variety of units. Likewise, for each sector in the economy, the size of the changes can vary by orders of magnitude depending on the size of the impacts in the baseline scenario for that particular sector. Therefore, a normalisation was performed, and the changes in impact presented as a percentage change from the baseline impact:

$$\Delta EF(\%) = \frac{\Delta EF}{EF} \times 100\% \tag{4.6}$$

The counterfactual scenario (henceforth denoted by objects marked with $*$) adjusts elements in the matrix objects (f,A,Y) that form the baseline EEIO system. Values within the matrices are adjusted to reflect the changes to the economic system as a result of the CE strategy or intervention, while all other objects are unmodified. The impact of the counterfactual scenario can be calculated based on 4.1 by updating the objects in the equation that have been affected by the CE intervention:

$$EF^{*} = diag(f)(I - A^{*})^{-1}y^{*} + f_y^{*}y^{*} \tag{4.7}$$

The counterfactual EEIO system is expected to become unbalanced (total inputs does not match total outputs) when the adjustments are made to the technical coefficient matrix A. However for purposes of calculating the impacts before and after implementation of CE strategies and interventions, the EEIO system is not re-balanced, since dynamic effects of the changes to A are not considered.

The adjustment to a particular entry ij of an arbitrary M matrix object from the baseline to the counterfactual scenario, can be modelled as making an change to that entry to simulate a growth or reduction:

$$M_{ij}^{*} = M_{ij}\left(1 - k_a\right) \quad (4.8)$$

The change coefficient (k_a) is the magnitude whereby a value in the EEIO system is adjusted.

To model a substitution relation between adjustments in different elements in a particular matrix object:

$$M_{ij}^{*} = M_{ij} + \alpha\left(M_{mn}^{*} - M_{mn}\right) \quad (4.9)$$

where mn are the coordinate location of the original change in the M matrix and ij are the coordinate location of the substitution in the M matrix). α represents substitution weighting factor that allows the model to account for price and physical/material differences between products, materials or services.

4.2. Modelling CE Strategies in Input Output Tables

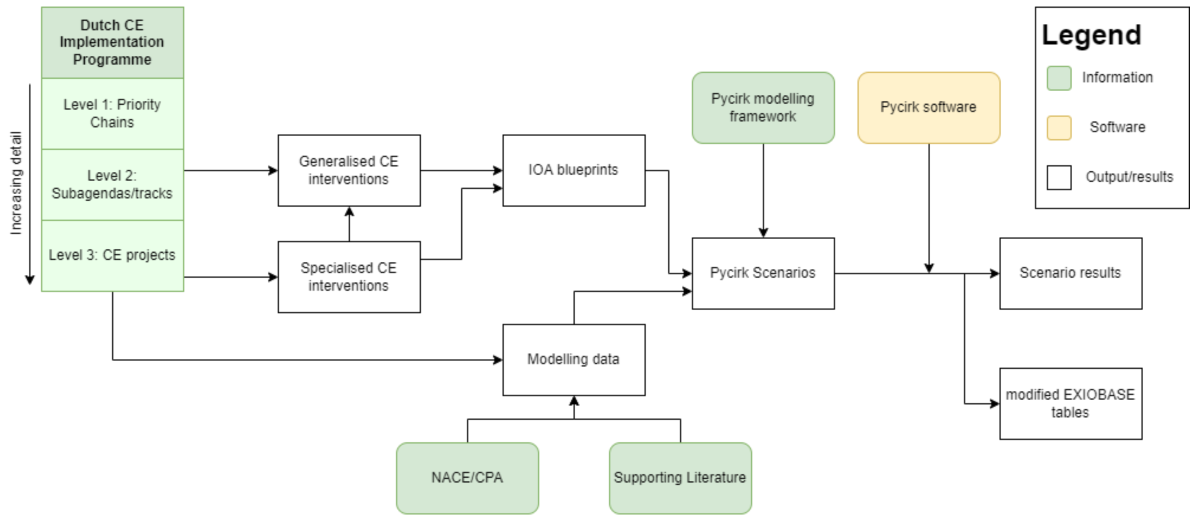

Figure 4.1: The modelling approach contextualised to the current state of the Dutch CE transition as presented in the Dutch CE Implementation Programme and macroeconomic tool used in this study.

Recall the distinction made between CE strategy and CE intervention defined in chapter 1.4.1. As explained in the previous section 4.1, to model a change to the economy as a result of CE, the manner and extent in which individual CE interventions affect economic flows and the environmental and social aspects of the economy are captured as modifications to input-output table and extensions. CE interventions instead of CE strategies are modelled since interventions have different approaches in the way that they achieve CE strategy objectives (e.g. different product sectors affected, reduction vs substitution of products). CE strategies are not directly modelled, but serve as a guideline template indicating the type of economic changes that can be made to a IO dataset.

With the selection of the macroeconomic tool, scenario modelling method, as well as the literature review on the Dutch CE agenda, the three are combined to form a CE scenario modelling approach that is specific in the context of the Dutch CE. The overall flow of the modelling approach used in this study is presented in figure 4.1.

4.2.1. Blueprinting CE Interventions

To visualise how Dutch CE interventions affect the structure of input output tables, the approach in Donati et al. (2020) is adopted, where *blueprints* are created for each CE intervention. *Blueprints* (an example shown in Figure 4.2) are simplified visual representations of the IO structure, that indicate where and how changes are applied in the EEIO system in order to simulate a CE intervention.

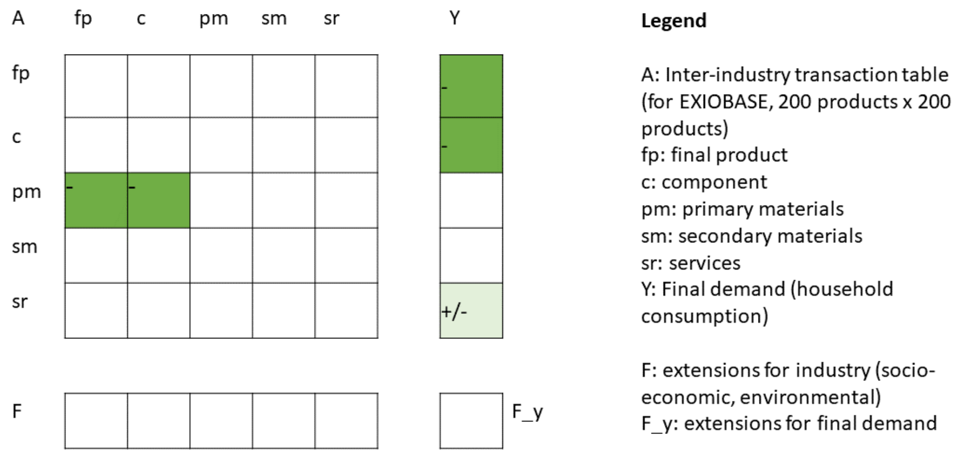

Figure 4.2: An example of a blueprint for modelling a CE intervention representing the Plastics subagenda "Prevention: more with less and reduced leakage" under the Dutch NPCE (adapted from Donati et al. (2020))

The blueprints show the technical coefficient matrix A, final demand Y, and the environmental extensions tables F and F_y respectively, as these are the matrices that will be modified to model the scenarios of CE interventions for EEIOA. In order to facilitate the identification of elements in across these tables where changes will be made, we subdivide the product categories into groups of similar economic and technical properties, referred to as *coordinate groups*:

- Final products (fp): fully manufactured consumer or capital goods that are not typically a component
- Components (c): a manufactured or semi-manufactured product that may be used as an

element in production or as subcomponent of final products

- Primary raw materials (pm): virgin material resulting from extraction or the refinement of extracted materials
- Secondary raw materials (sm): recycled materials obtained from pre- and post-consumer phase
- Services (sr): activities aiding the supply and maintenance of goods and value, including transportation

Symbols are used to indicate the direction of the intervention's changes to the values in the co-ordinate group. Decrease are indicated with a (−), increase with $(+)$, and cases where a substitution between two product categories under the same co-ordinate group may apply are indicated with $(*)$.

While interventions require individualised blueprints to represent their specific effects on the structure of the IO tables, their effects can be generalised at a strategy level, which can used to guide the selection of the appropriate coordinate groups for the creation of blueprints for CE interventions.

The blueprinting approach adopts the 4 strategies as laid out in Aguilar-Hernandez et al. (2018). However, the Dutch government adopts 6 level strategy as given in Rood and Kishna (2019). For cross-comparability, concordance was made between Aguilar-Hernandez's 4 strategy and Rood and Kishna's 6 strategy classifications.

Table 4.1 details the concordance mapping and general effects of Aguilar-Hernandez's 4 CE strategies to the IO table.

R-ladder CE strategy	Equivalent from Aguilar-Hernandez et al. (2018)	Description	Effect on IO Tables
R6 Recover	Residual waste management (RWM)	Related to post-consumption activities where the materials are disposed outside the economy	Increase in demand in waste management & recycling service categories.
R5 Recycle	Closing supply chains (CSC)	The re-integration of materials at different levels of the supply chain after being used, via for instance product reuse, component re-use, refurbishing, and recycling	Simultaneous change across different product categories, with decrease to inter-industry transactions for primary material categories and increase in inter-industry transactions for secondary material categories and waste treatment & recycling service categories.
R3 Reuse, R4 Repair and Refurbish	Product lifetime extension (PLE)	Associated with slowing down the resource use as a consequence of extending lifetime of products, via for instance design for longevity and improved maintenance	Decreased final demand for the final product categories and increase in inter-industry transactions in final product and material categories.
R2 Reduce	Resource efficiency (RE)	Processes or mechanisms which optimise resource flows by using less resources per unit produced	Decrease in inter-industry transactions between primary material product categories and reduction in environmental extensions for final product categories.

Table 4.1: Circularity Intervention categories and explanation, adapted from Aguilar-Hernandez et al. (2018)
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4.3. Pycirk Python Package

The *Pycirk* python package was developed by Donati (2021) for the creation and analysis of CE scenarios. The *Pycirk* package allows for the modelling of Circular Economy policy and technological interventions in EEIOA.

To create a counterfactual scenario within Pycirk, the user has to prepare an input file specifying the specific positions where changes are applied to the IO system, the absolute or percentage change to the original value, and whether substitution is applied, where the changes to one cell of the IO system is distributed to other cells. The desired output and results are also specified within the input file, and the user is required to specify the result assessment parameters the software will calculate.

4.4. EXIOBASE dataset

For the modelling of CE baseline and counterfactual scenario, we rely on the dataset from EXIOBASE V3.3 for the year 2011.

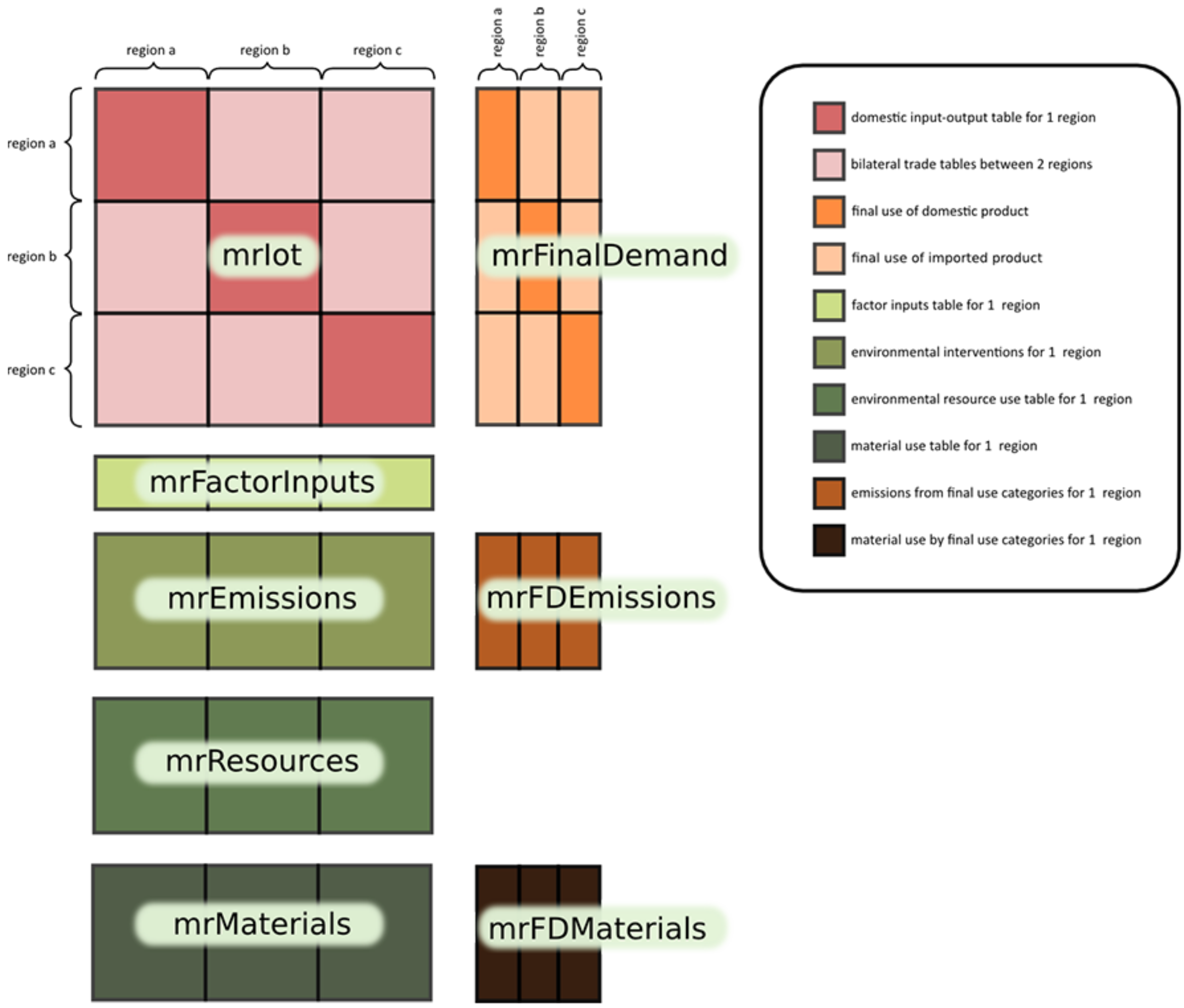

Figure 4.3: Structure of the EXIOBASE multi-regional IO system of tables, including tables for satellite accounts for environmental, social and material extensions. (EXIOBASE Consortium, 2015)

EXIOBASE provides environmentally extended multi-regional input-output (EE MRIO) tables ranging from 1995 to 2011 for 44 countries (28 EU member plus 16 major economies) and five rest of the world region (Stadler et al., 2021). EXIOBASE 3 builds the EE MRIO tables by using rectangular supply-use tables (SUT) in a 163 industry by 200 products classification as the main building blocks. EXIOBASE then extends the MRIO system through the provision of satellite accounts, in the areas of emissions, Water, material, land and employment accounts. (Stadler et al., 2018). The overall structure of the EXIOBASE EE MRIO system is shown in

Figure 4.3.

The EXIOBASE dataset is suitable but not ideal for our use case, since it predates the adoption of the Dutch NPCE by 5 years (NPCE was adopted in 2016). The resolution of 200 products provides sufficient resolution for the modelling of the economic sectors covered in the NPCE. The satellite accounts provide sufficient extension to the MRIO across environmental and social impact categories. Most importantly, the dataset contains the Netherlands as a distinct region in the IO tables, which allows us to model changes to the Dutch economy as a result of CE strategies and interventions.

4.5. The Netherlands Case Study

As first laid out in the *A Circular Economy in the Netherlands by 2050* programme (The Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, 2016), the government drew up “transition agendas” in which the five following value chains and sectors make up the *priority chains*: biomass and food, plastics, manufacturing, construction, and consumer goods. These value chains cover sectors that are important for the Dutch economy, where there is major environmental pressure, where there is already substantial social impetus for the transition to a circular economy, and that are in line with the European Commission’s priorities (The Ministry of Infrastructure and Water Management, 2019).

In the publication *Updated Circular Economy Implementation Programme 2021-2023* (of Infrastructure and Water Management, 2021), the Dutch government and the various signatories to the Raw Materials Agreement in each of the five priority chains detailed projects that they have embarked on to realise the NPCE. Since this document is the latest publication covering the Dutch transition agendas, it is assumed that the Implementation Programme represents the current state-of-affairs for the NPCE. The implementation programme also provides examples of existing CE projects in the Netherlands under each of the priority chains. These projects found in the Implementation Programme are assumed to be representative of the overall direction and progress of the priority chains in the transition agenda. A review was thus conducted on this Implementation Programme to gain an overview of the current state of the Dutch NPCE. and organise the existing circular economy projects in preparation for modelling with Pycirk.

Overall, there is no standardised way in which the different priority chains of the CE are organised in the Implementation Programme. Some of the priority chains have a clearly defined organisation for the different types of projects that fall under their umbrella. For these priority chains, they contain sub-agendas or tracks, which organise the projects under the priority chains into themes centred around common guiding principles or courses of action. Other priority chains have a loose set of projects that cannot be easily organised into common themes or circular economy strategies. Furthermore, the are cross cutting themes that do not belong in any single priority chain.

However, in general, a majority of projects in each CE priority chain have a defined product(deliverable of the CE project) and effect(expected outcomes or effects of the CE project). To enable the modelling of the NPCE as CE strategies, the product and effects of all projects in each priority chain were tabulated to give an overview of each priority chain. Using the overview tables, two additional properties were assigned to all projects based on their product and effect information: 1) the sub-agenda/track of the project, if available; 2) the industry or sector that is affected by the project.

Using the additional property of 1) sub-agenda/track, CE strategies that best match each of the CE projects are assigned. Using the 2) affected industry or sector, the projects can be matched to the closest relevant industry present in the EXIOBASE dataset. The decisions for the tabulation and organisation of each of the Priority Chains are explained in greater detail below.

Biomass and food

For the priority chain of *biomass and food*, six tracks were clearly defined in the transition agenda: 1) enlarging the supply of sustainably produced biomass; 2) getting the optimum value out of biomass and residual flows to create circular, bio-based products; 3) circular and regenerative use of soil and nutrients; 4) reduction of food waste; 5) the protein transition to more vegetable protein; 6) 'feeding and greening megacities' as the Dutch business model. Under this priority track, the projects are not matched with a single track each, but projects can be matched to multiple tracks. Therefore, the projects under *biomass and food* can represent more than one CE strategy.

The industries that are affected by *biomass and food* priority chain are numerous. In general, most agricultural and food industries are affected, that includes food crops, forestry dairy and lifestock industries, but also associated industries such as agricultural waste processing and wastewater treatment industries.

Plastics

For the priority chain of *plastics*, four courses of action are clearly identified in the transition agenda, which represent the sub-agendas for this priority chain: 1) prevention: more with less and reduced leakage; 2) greater supply and demand for renewable plastics; 3) better quality and better environmental returns; 4) strategic cooperation, across the value chain. Under this priority track, the projects are also not matched with a sub-agenda each, but also possibly multiple tracks.

The plastics transition agenda targets a small number of industries, mainly the production of raw plastic and the manufacturing of plastic into plastic products.

Manufacturing

For the priority chain of *manufacturing*, there are a total of 7 CE tracks identified by the transition agenda. However, under the 7 tracks, the specific industries in which the tracks are applicable to are not explicitly described. Presumably, due to the breadth of the manufacturing priority chain, only a few examples of projects under the tracks were provided in detail. Due to the difficulty in retrieving a complete snapshot of all CE projects that fall under the manufacturing priority chain, and lack of generalised information regarding the range of manufacturing industries that are affected by each of the tracks, CE strategies represented by the 7 manufacturing CE tracks are assumed to apply for all possible manufacturing industries that are represented in EXIOBASE.

Construction

For the priority chain of *construction*, the transition agenda describes 4 main thrusts, which represent tracks for the priority chain: 1) Market Developments; 2) Quantifications; 3) Policy, legislation and regulations; 4) Knowledge and awareness Under this priority chain, the 4 tracks present 2 issues. Firstly, the projects described in the priority agenda are not sorted into the tracks - the projects are described by the transition agenda to ”assist the work in one or more of those main thrusts”. The projects need to be manually sorted into the 4 tracks. Secondly, as compared to the previous priority tracks, the 4 tracks for construction as covered in the transition agenda do not directly represent circular economy strategies. Hence a separate set of sub-agendas/tracks for the construction manufacturing agenda is developed manually to represent the circular economy strategies.

Consumer goods

For the priority chain of *consumer goods*, no sub-agendas were provided in the transition agenda. Instead, the transition agenda lists *icon projects*, which are defined as the actions taken by the consumer goods industry and academia that complement policy efforts by the government. Similar to *construction*, the icon projects need to be manually classified into sub-agendas that represent circular economy strategies that are adopted under the priority chain.

For this priority chain, consumer goods also cover a large range of industries. The icon projects target product-specific supply chains which are spread across the manufacturing and services sector. The circular economy strategies are assumed to be generalised across the industry containing the target products.

In summary, the CE priority chains and their sub-agendas is represented in table 4.2.

Priority Areas	Sub-agendas/Tracks	Projects
Biomass and Food	Enlarging the supply of sustainably produced biomass	A uniform framework for the assessment of sustainability of biomass
	Getting the optimum value out of biomass and residual flows to create circular biobased products	Action plan for wood and woodlands
	Circular and regenerative use of soil and nutrients	Seaweed for Food and Animal Feed Programme
	Reduction of food waste	Bio-asphalt from wood
	The protein transition to more vegetable protein	Bioizon shred research programme
	'Feeding and greening megacities' as the Dutch business model	Circular Land Management
		Exploring possible applications of wood and wood waste
		Biobased routes for circular greenhouse farming
		National Agricultural Soils programme
		Regenarative Agriculture
		Land-based dairy farming
		Get more value in various ways from animal manure in the Achterhoek region
		Implementing the National Agenda 'Tackling Food Waste Together'
		National Action Plan for Fruit and Vegetables (NAGF)
		Development of the insect sector
		Developing energy and resources factory
Plastics	Prevention: more with less and reduced leakage	Plastic Pact
	Greater supply and demand for renewable plastics	Microplastics
	Better quality and better environmental returns	Chemical Recycling

Priority Areas	Sub-agendas/Tracks	Projects
	Strategic cooperation, within the value chain	Biobased plastics
		More and better sorting and mechanical recycling
		Application of recycled plastic material in new products and packaging
		International scaling up of plastic strategy
Manufacturing	Circular design in manufacturing industry	
	Security of supply of critical raw materials	Pilot for the security of delivery of critical materials for energy supply
	Uniform principles and calculation methods for product groups	Pilots for a National System for Environmental Performance of Products
	Materials efficiency	Urban Mining of Flat Screens
	Recycling Technology	Zinc reclamation
	Circular Business Models	Heat as a Service
	Circular procurement/IT category management	Circular procurement/IT category management
Construction	Market Development	Development of Materials Passport
	Quantification	Circular Cities
	Policy, legislation and regulations	Circularity In Building Regulations
	Knowledge and awareness	Brainport Smart District (BSD) Helmond
		Chain-wide agreements: circular concrete as a case study
		Chain-wide agreements, case study of producer responsibility for façade construction
		National government (RVB and RWS) as rolemodels in circular tendering and management
		Water boards and sustainable commissioning

Priority Areas	Sub-agendas/Tracks	Projects
		Project: Land, Roads and Hydraulic Engineering (GWW)
Consumer Goods	No sub-agendas, sorted by individual projects (icon projects)	The Dutch Circular Textile Valley icon project The National Circular Plastics Test Centre (NTCP) icon project The Mattresses icon project Household Appliances as a Service icon project The Sharing Economy icon project Circular Craft Centres E-commerce Consumer Approach to the Circular Economy From Waste to Resource: quality and quantity of constituent streams and reduction of residual household and business waste

Table 4.2: CE priority chains and their respective sub-agendas and tracks

4.6. Framework Adaptations for Case Study

While reviewing the Implementation Programme and performing blueprinting for the CE interventions contained inside, a number of issues were identified that necessitated adjustments to the generalised modelling approach to suit the structure of the implementation programme.

Firstly, categorisation of into a single aggregated product category in EXIOBASE is challenging because CE projects presented in the Implementation Programme tend to target either very specific materials or products. These materials and products only form a sub-portion of a product category in the EXIOBASE table. For example, the project *Seaweed for Food and Animal Feed Programme* targets the seaweed industry, which forms only a part of the aggregated product category *Marine Aquaculture*. This product category also includes fish farming and cultivation of other marine organisms as pets or for food. Another project *Microplastics* targets the cosmetics, detergents, clothing and textiles, paint, maintenance and vehicle tyre sectors, a for total of 6 distinct product categories. Therefore, process of matching is not straightforward. Much thought needs to be put into how suitable product categories in the EXIOBASE table are selected to represent the CE strategies, to ensure that the projects are accurately represented in modelling. It could also be possible that mapping the projects to sectors is not possible due to the level of aggregation used in EXIOBASE.

Secondly, some of the projects in the Implementation Programme adopt multiple CE strategies to achieve the transition agenda. For example, the chain-wide agreement *circular concrete* under the construction priority chain applies the strategies of RE and CSC. The modelling of individual projects as interventions in Pycirk will require the combination of the modelling blueprints of a number of general interventions.

To address the first two modelling problems arising from the complexity of modelling of the individual projects in the Implementation Programme as interventions and the difficultly in the selection of product categories in EXIOBASE in which to apply the CE intervention blueprints, the modelling of the Implementation Programme is approached at the subagenda/track level. Each subagenda will be assigned a CE strategy that best matches the objective of the subagenda, and product categories for each subagenda will depend on existing projects that are classified under the subagenda.

Thirdly, many projects described in the projects are exploratory or pilot studies, with the objective of gathering more knowledge, developing quantification tools or identifying areas of collaboration, without the direct intention of actively driving the CE transition. The exploratory, early-stage nature of these projects raise uncertainties about the ability of these projects make quantifiable changes to the economy and also whether the CE interventions adopted in these projects can be generalised into significant, long-term shocks to the economy for the creation of modelling scenarios for EEIOA. For example, exploratory and pilot projects form a significant portion of the projects under the construction priority area, that they form two out of four of the subagendas (*Quantification* and *Knowledge and Awareness* as identified by the Implementation Programme. Moreover, these projects typically lack concrete targets that can be used for creation of scenarios for EEIOA modelling.

To address the early-stage nature of the projects in the Implementation Programme, an exploratory approach to modelling is used. Instead of modelling existing targets, three levels of scenarios will be constructed for each of the CE interventions to model different extents of the implementation of circular economy interventions.

- Low (10% adoption)
- Medium (50% adoption)
- High (100% adoption)

Fourthly, there are products which apply across priority chains. Bioplastics for example, are included in the transition agenda for biomass and food, as well plastics priority chains. This creates potential issues with double-counting of the effects of the CE intervention as the same product is attributed to 2 priority chains.

Lastly, even as the projects in the Implementation Programme are a selection of existing CE projects adopted in the Netherlands, the are a total of 22 subagendas in the implementation

Programme. A subset of the priority areas in the Implementation Programme will be modelled as a case-study to keep the scope of the research manageable. The *plastics* and *construction* priority areas were chosen a case-studies due to the clarity of the product sectors that are targeted for the modelling of the CE intervention scenarios, and the fact that there are no overlap of products across these 2 priority chains to mitigate double-counting.

4.7. Blueprints for Selected Case Studies

4.7.1. Plastics

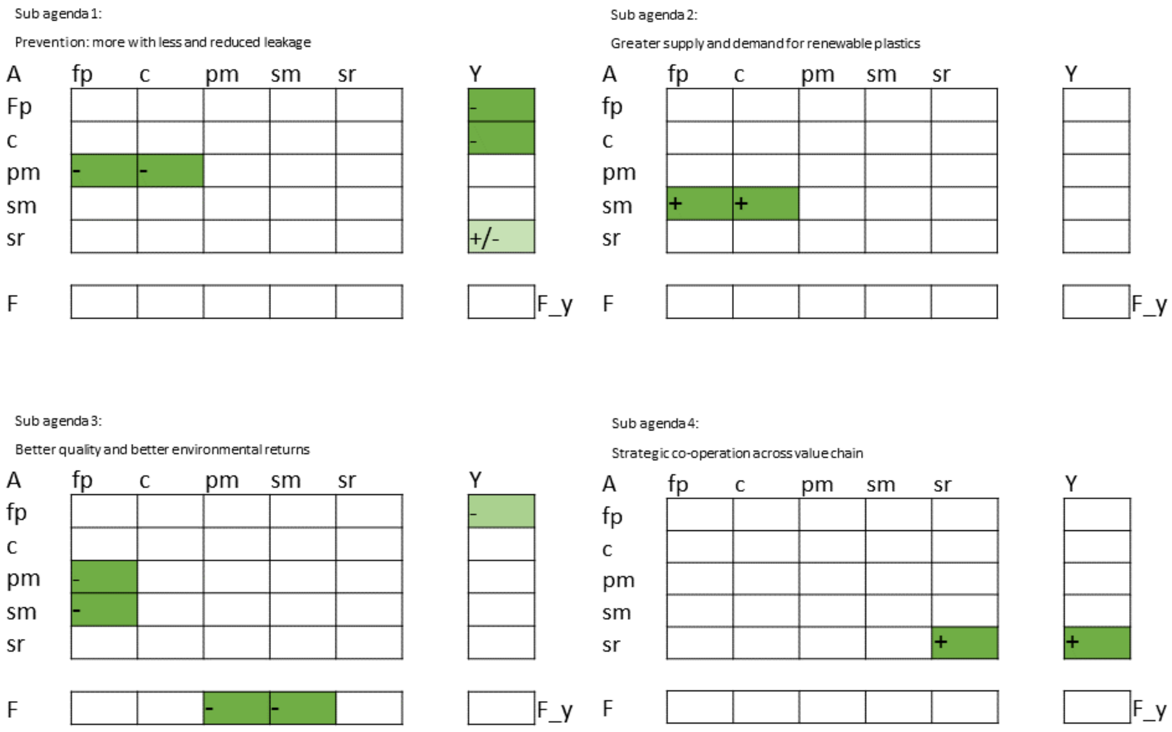

Figure 4.4: Blueprints developed for modelling for the plastics priority chain, covering their four subagendas.

For subagenda 1, Prevention: more with less and reduced leakage (Prevention), the aspect of ”more with less” is modelled by decreasing overall plastic consumption (final product and components plastic), and assuming a change in production methods of plastics to use less material, decreased primary plastic demand across final product/component sectors. Reduced leakage is modelled as an increase in demand for recycling services, but also decrease in demand for the incineration of plastics.

For subagenda 2, Greater supply and demand for renewable plastics (RP) was modelled by increasing use of secondary plastics for production of components and final products

For subagenda 3, Better quality and better environmental returns (BQ&ER), the reduction in microplastics is modelled in the form of design improvements, decreasing demand of plastic (primary and secondary) for the production of final products. The emissions intensity of primary and secondary plastics were decreased, due to 1) production of bioplastics (primary), with the assumption that bio-plastics produce less emissions; and 2) chemical recycling for production of secondary plastics is less emissions intensive vs traditional mechanical recycling processes.

For subagenda 4, Strategic co-operation across value chain (Co-op VC) was modelled as increased demand for plastic recycling services for households and customer facing services.

4.7.2. Construction

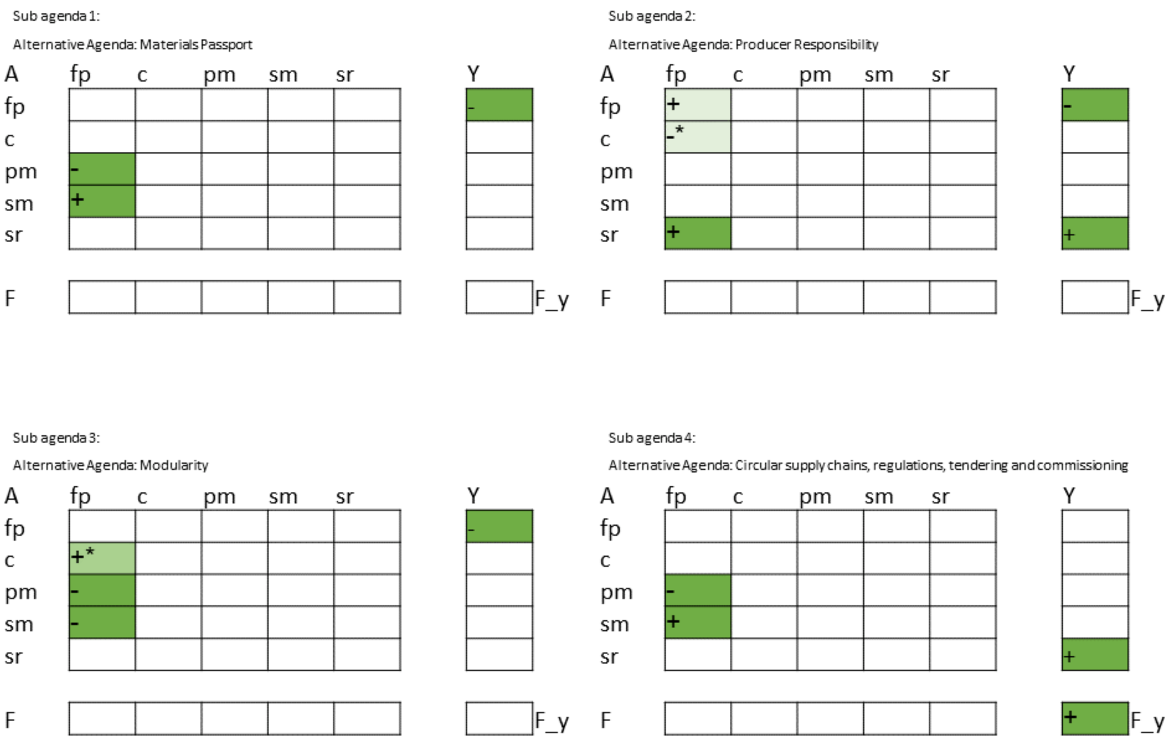

Figure 4.5: Blueprints developed for modelling for the plastics priority chain,covering four alternative subagendas created to replace existing tracks given in the construction priority chain.

As raised in the section 4.5, since the subagendas given in the implementation programme do not directly represent CE strategies, the projects detailed in the implementation programme under the construction priority chain were re-sorted into alternative subagendas that better represented their CE strategies. A total of 4 alternative subagendas were created.

For subagenda 1, Materials Passport (MP) is expected to increase lifespans for buildings and increase circular building practices. These are modelled as decreased demand for building final products for consumers and substitution of primary materials for secondary materials for construction for industry respectively.

For subagenda 2, Producer Responsibility (RP) is modelled as less demand for new building facades, together with more demand for façade takeback/collection services on the side of the consumer, and less demand for final products and components and more demand for transportation services on the side of the industry since facades need to be transported between users.

For subagenda 3, Modularity is modelled as a decrease in final demand since less new buildings are needed to fulfil demand from consumers. More components are needed to refurbish buildings. Less material use was modelled to represent the avoidance of construction and demolition of temporary structures.

For subagenda 4, Circular supply chains, regulations, tendering and commissioning (Circular SC), groups together general projects that promote circular construction practices, which is assumed to represent increased reuse of materials, higher quality recycling, increased use of greener and more circular materials in construction. Reuse of materials is modelled as a substitution of primary materials for secondary materials for the construction of final buildings and building parts, higher quality recycling was modelled as an increased final demand for recycling of construction waste. Circular construction practices was assumed to also result in greener buildings, which increased environmental performance for buildings (assuming during use phase).

5

Results

5.1. Interpretation of impacts and trade-offs

In this chapter, prior to analysing the trade-offs, the impacts of the CE interventions were examined in the form of footprints across one environmental dimension of Global Warming Potential (GWP100 (kg CO2 eq.)), one energy dimension of energy usage (total energy use (TJ)), two material dimensions across material extraction footprint, blue water extraction (Material Extraction (kt), Blue water (mm3)), one economic dimension (value added (M.EUR)), and one social dimension (Employment (1000 persons)). The footprints of the CE interventions are presented in the percentage change from the baseline footprint, This is to facilitate the comparison of the impacts across the different measurement units of footprint indicators and the different sizes of baseline footprints across different product sectors.

To determine trade-offs, the desired direction of change for each impact category is considered; for each scenario, a desirable change or 'win' is achieved when the change in the impact dimension occurs in the desired direction, and an undesirable change or 'lose' occurs when the change is in the opposite direction. The desired direction for each footprint category is represented in table 5.1.

When discussing trade-offs, wins and losses will be used to refer to desired and undesired changes in footprints; while positive and negative will be used to refer to the direction of the change in footprint.

Trade-offs occur when an intervention achieves a mix of wins and losses, i.e. the achievement of positive change in one impact dimension comes at the cost of negative changes in other dimensions. Beyond finding the existence of trade-offs, the extent of the trade-offs can be evaluated based on comparing the relative percentage change across impact dimensions.

	Direction of	
Footprint Category	**Desirable change**	**Undesirable change**
Global Warming Potential	-ve	+ve
Energy Usage	-ve	+ve
Material Extraction	-ve	+ve
Water Extraction	-ve	+ve
Value Added	+ve	-ve
Employment	+ve	-ve

Table 5.1: Wins and losses: impact categories and their respective directions for desirable and undesirable change in impact

5.2. Comparison of overall changes to impact between all interventions

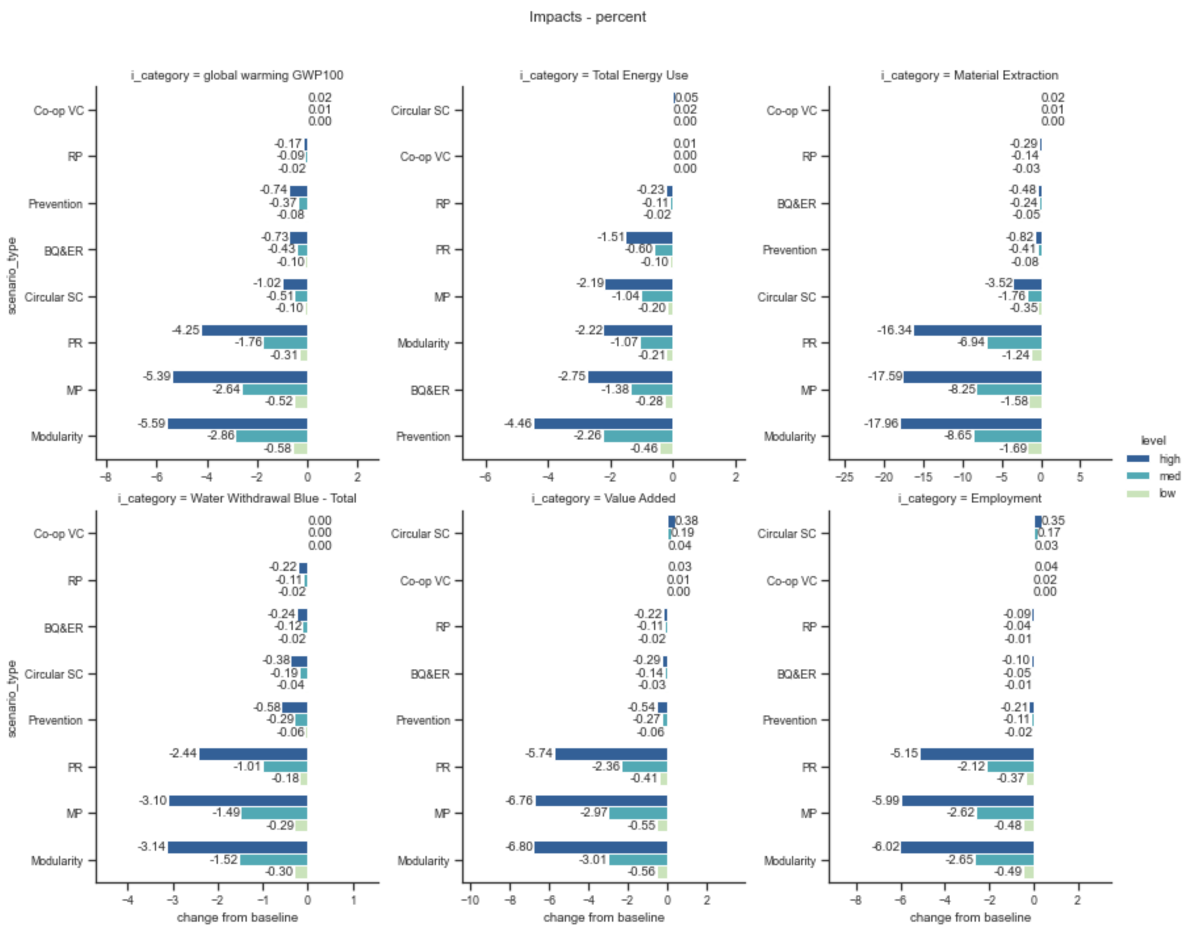

Figure 5.1: The percentage changes to footprint for the 6 impact categories of this study compared across the 8 interventions from the plastics and construction priority chain.

From figure 5.1, the footprints of the implementation of all 8 CE interventions are compared. The implementation of the CE interventions result in an overall decrease of the footprints across all impact dimensions, with the exception of the intervention *co-operation across the value chain* from the plastics priority chain. As the level of implementation of each CE intervention progresses from high to low, the size of the percentage change increases (the change becomes more positive or more negative).

Also from figure 5.1, the size of positive changes to the impact categories range from 0.00% to 0.38% across all impact categories, while the size of the negative changes range from -0.00% to -17.96%. The intervention *Modularity* generally produces the biggest reductions in footprints across all impact categories, followed by *Materials Passport* and *Producer Responsibility*. On the other hand, interventions *Co-operation across the value chain* and *circular supply chains* account for all instances of increases in impacts in all impact dimensions.

It is interesting to note that the intervention *circular supply chains* is the only intervention modelled in this study where the changes in impact occur in both directions. It produced positive impact in the 3 of the 6 footprint categories (Total Energy Use, Value Added, Employment), while having negative impacts in the other 3 footprint categories.

The interventions that produced the biggest reductions in footprint (*modularity, MP, PR*) target the construction sector. This suggests that the interventions for the construction priority chain, tend to be more successful in reducing the overall footprint of the Dutch economy as compared to the CE interventions for plastics. However, for the footprint category Total Energy Use, the intervention *Prevention* and *Better Quality and environmental returns* show the biggest reductions from baseline. This means that the plastic priority chain consumes a larger proportion of total energy use as compared to construction. This suggests that each product category or sector of the Dutch economy has a different footprint profile compared to each other.

In general, the implementation of the interventions tend to achieve wins in the impact categories of Global Warming Potential, Energy Usage, Raw Material Footprint and Blue Water Extraction, where a reduction of the impact footprint is seen as desirable. In contrast, losses were incurred for impact categories of Value Added and Employment, where reduction is undesirable. Overall, to achieve wins to the environmental dimension, a trade-off in the form of losses in the social and economic dimensions is the consequence.

5.3. Comparison of overall changes to impact between interventions in priority chains

To determine the relative effectiveness of each of the CE interventions within the 2 case studies, the percentage change in the total footprint of the Dutch economy is compared across the CE interventions.

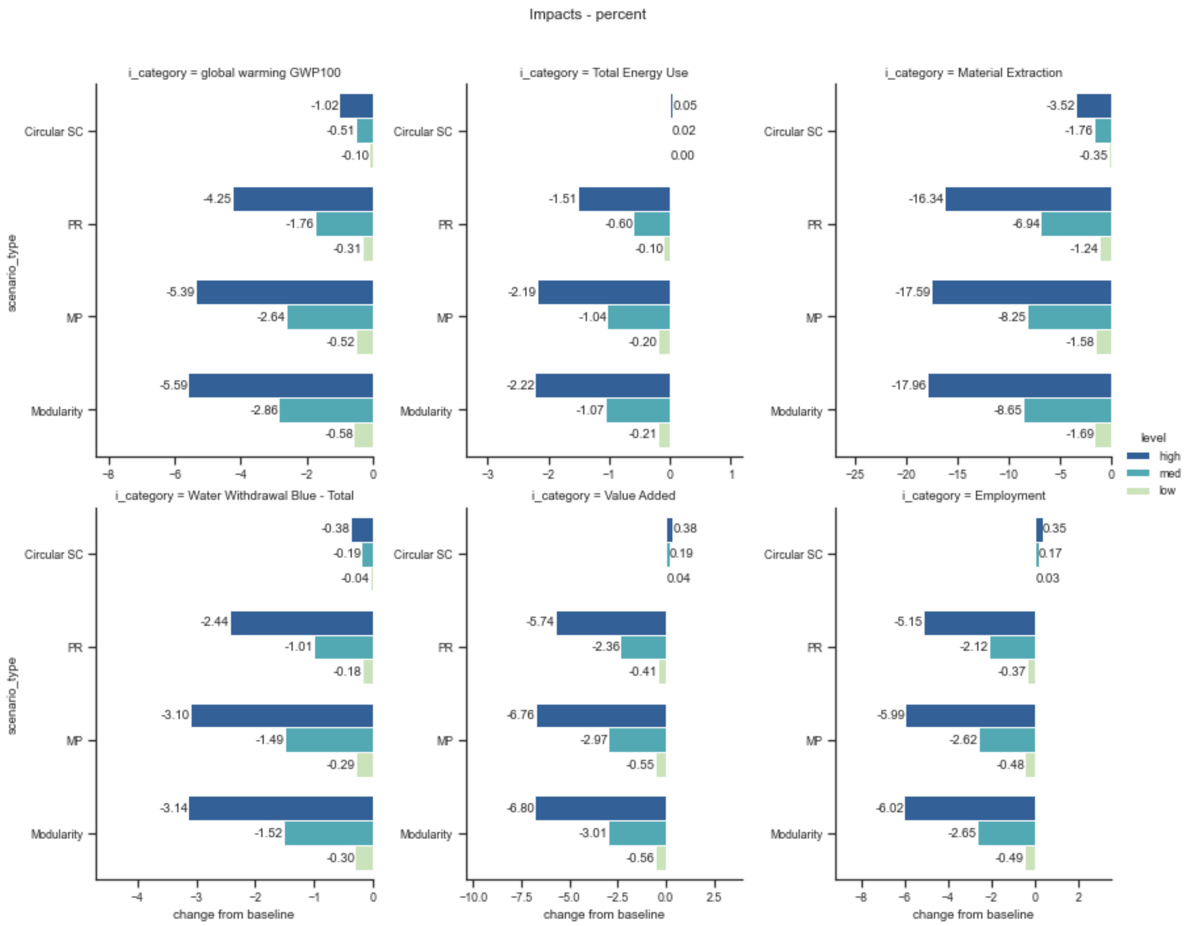

Figure 5.2: The percentage changes to impact for the 6 footprint categories of this study compared across the 4 interventions from the construction priority chain.

5.3.1. Construction

From figure 5.2, in the construction case study, the interventions that produce the biggest negative change in footprint is *Modularity,* followed by *Material Passport, Producer Responsibility* and finally *Circular Supply Chains,* with the size of the reduction ranging from -0.04 to -17.96%. The intervention that produces the biggest positive change is *Circular Supply Chains,* with the size of the increase ranging from 0.00 to 0.38%. The impact category that has the greatest reduction is raw material extraction (-0.35% to -17.96%), followed by value-added (-0.41% to -6.80%) and employment (-0.37% to -6.02%).

Modularity and Material Passport achieve similar levels of percentage change across all 6 footprint categories, and to a lesser extent *Producer Responsibility*, where the difference is less than 1% for all footprint categories and levels of implementation. *Circular Supply Chains* achieves a significantly smaller percentage change across all footprint categories as compared to the other 3 interventions.

In terms of trade-offs, the interventions in the construction priority chain tend to follow the overall trend of improvement of footprints in environmental dimensions the detriment of economic and social dimensions. Since the economic dimension (value added) and social dimension (employment) form the 2nd and 3rd greatest footprint reductions, it can be suggested that the achievement of environmental wins comes at the significant cost of economic and social losses.

However, *Circular Supply chains* is a unique intervention where there is desirable change in all footprints except for energy use, albeit the scale of the wins are smaller than the wins and losses of the other construction interventions. This trade-off can be attributed to the increased use of services, particularly transportation. Despite the growth in the transportation services sector as a result of this intervention, the increase in environmental and material footprint from transportation is possibly offset by the reductions in footprint from less demand for final products, resulting in the smaller scale of the impact changes for this intervention.

5.3.2. Plastics

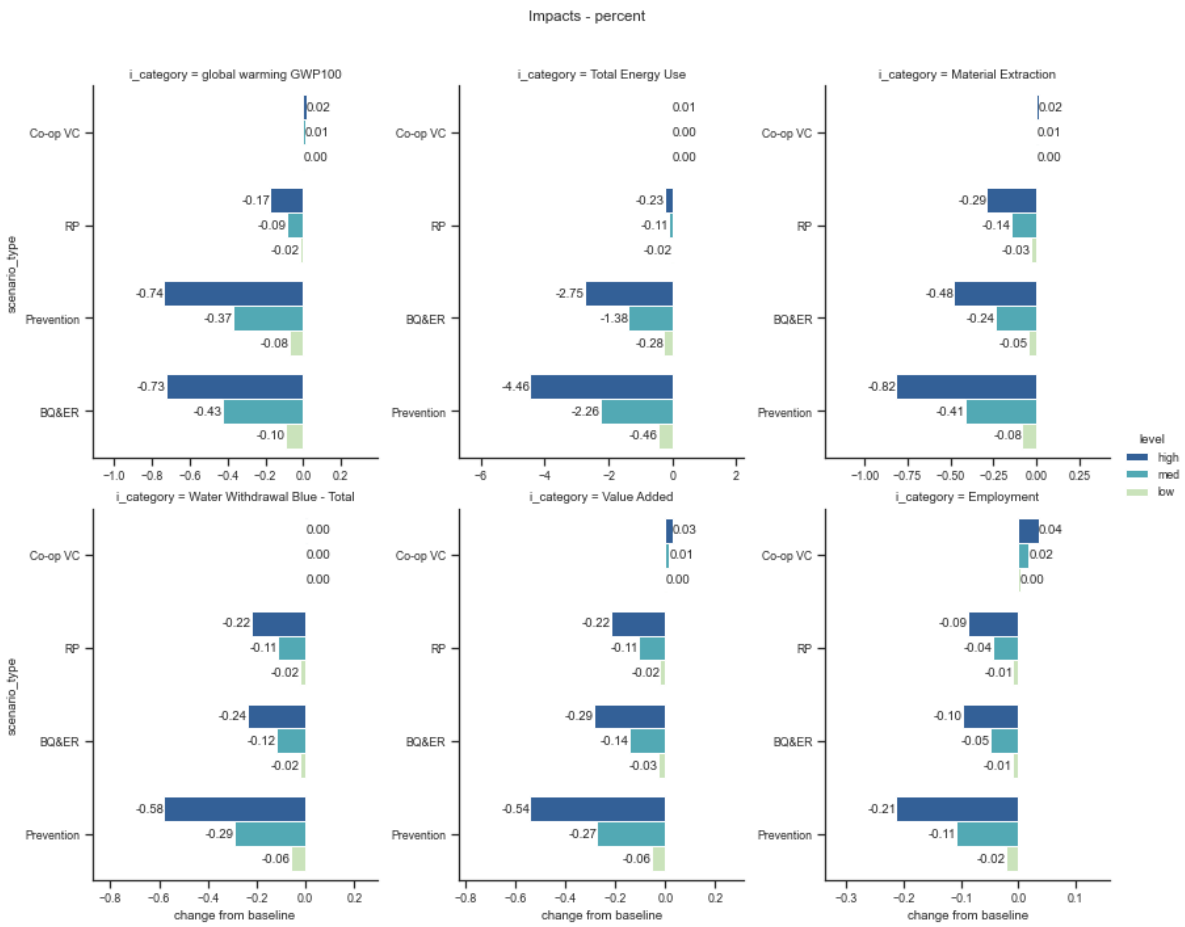

Figure 5.3: The percentage changes to impact for the 6 impact categories of this study compared across the 8 interventions from the plastics priority chain.

From figure 5.3, in the plastics case study, the intervention that produces the biggest negative change is *Prevention,* followed by *Better Quality and Environmental Returns, Renewable Plastics.* The range of the size of the negative change is from -0.01% to -4.46%. The intervention *Co-operation across the plastics value chain* produces only positive changes to all footprint dimensions, with the size of the positive change ranging from 0.00% to 0.04%.

The interventions in the plastics category is the most effective at reducing the footprint of Total Energy Use, where reductions of up to -4.46% are produced. The interventions are less effective in reducing the other footprint categories, with percentage changes from -0.82% to +0.04%. From this we can conclude that there is major dependence on energy use in plastics production.

In terms of trade-offs, the interventions in the construction priority chain tend to follow the overall trend of improvement of footprints in environmental dimensions the detriment of economic and social dimensions. However, *Co-operation across the plastics value chain*, is an exception that results in increased footprints generally across all footprint categories, in this case the trade-off is the improvement of value added and employment impacts at the cost of global warming potential, total energy use, blue water extraction and raw material extraction footprints.

5.4. Comparison of overall percentage change across footprint categories and implementation level for each intervention

To determine how footprint categories are affected within each intervention, the percentage change of the 6 footprint categories are plotted against each other for each scenario.

5.4.1. Construction

From figure 5.4, across all construction scenarios, material extraction is the dominant footprint category with the biggest reduction. The ranking of the rest of the footprint categories is not consistent across the individual scenarios. The size of the percentage change in footprint for material extraction is also significantly bigger than that of the other footprint categories, typically about 2 to 3 times bigger.

Across the intervention types, there are cases where the ranking of the footprint categories is not internally consistent. Impact categories move up and down in the rankings of which impact category has the biggest positive/negative change, as the level of implementation increases from low to high. For *material passports,* at lower levels of implementation of the CE intervention, the reduction of global warming potential is more significant that the reduction in employment. For *modularity*, the reverse is true.

5.4.2. Plastics

From figure 5.5, across all plastics scenarios, employment is the footprint category with the least reduction, while the ranking of the other impact categories is not consistent across the individual scenarios.

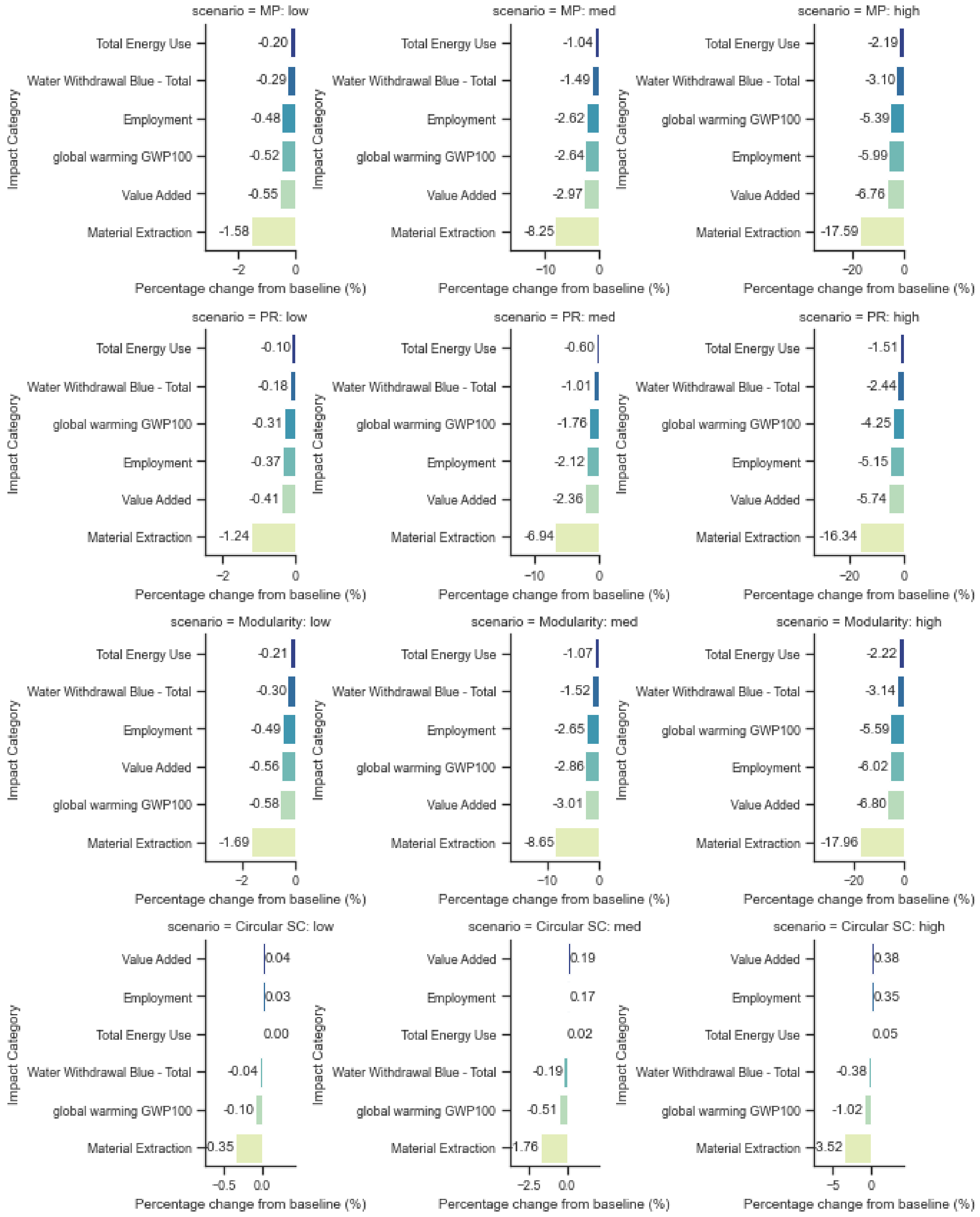

Figure 5.4: Comparison and ranking of percentage change of impacts across impact categories for each construction intervention.

For the interventions *Prevention* and *Better quality and environmental returns*, the negative decrease in total energy use is the dominant change from baseline, with -4.46% reduction and -2.75% reduction at high levels of implementation respectively. These numbers are more than double the percentage decrease for the rest of the impact categories, which range from -0.10%

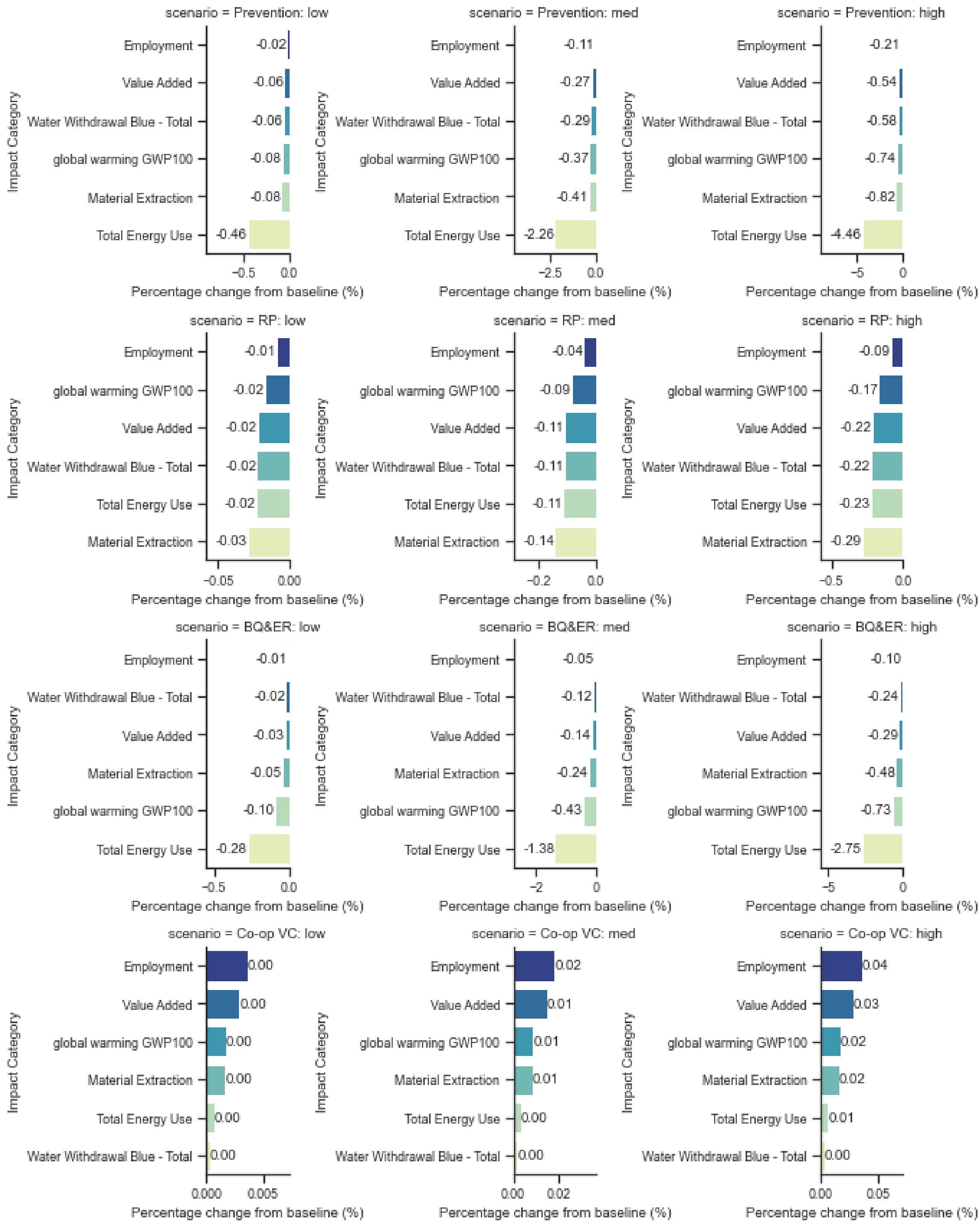

Figure 5.5: Comparison and ranking of percentage change of impacts across impact categories for each plastics intervention.

to -0.82% reduction at high implementation.

For the interventions *renewable plastics and co-operation across the value chain*, all footprint categories experience a small but similar extent of change, with the size of change ranging up to 0.3%.For Co-op VC, the change is smaller than 0.05% even at high implementation.

5.5. Comparison of percentage changes to impact at product level

To examine the economic effects at the sector level, the percentage change of footprints from baseline were calculated for each of the 200 sectors and ranked. The top 5 winners and losers (if applicable) were plotted against one another to determine the most significant trade-offs between sectors. Interestingly, the size of the changes and rankings of the product categories is consistent across all footprint categories. Therefore, the dominant footprint category as identified in the previous section would be used first as basis for comparison. Subsequently, only footprint categories with additional interesting findings will be discussed.

5.5.1. Construction

From figure 5.6, when examining the product-specific footprints for construction, the biggest reduction of footprints are shown in the manufacturing industry for construction components such as cement, lime and plaster (C_CMNT), Bricks, tiles and construction products (C_BRIK), other non-metallic mineral products (C_ONMM), re-processing of ash into clinker(C_ASHW), extraction industry of construction raw materials such as for sand and clay (C_SDCL), and the service industry of construction work (C_CONS). At high implementation, the size of the percentage reduction ranges from (-11.87% to -83.89%). Interestingly, for the intervention, *Circular Supply chains,* the rubber and plastics products category (C_RUBP) is also significantly affected, with a percentage reduction of -8.72% at high implementation.

The greatest increase in footprints are found in the *Circular Supply chains*, where re-processing of ash into clinker(C_ASHW), two transportation sectors – railway (C_TRAI) and other land transport (C_LND). Interestingly, there is a slight increase in footprints to secondary copper (C_COPW) and lubricants (C_LUBR) product categories, which are not directly connected to the construction sector.

For the intervention *material passport,* there is a reduction of positive percentage changes for re-processing of ash into clinker (C_ASHW). Percentage change started off at 2.57% for low implementation, reduces to 1.87% for medium implementation before reducing to an insignificant level at high implementation. It is the only product sector that demonstrates this trend.

The trade-off for the construction priority chain results in wins for the construction industry (construction work, manufacturing of construction, raw material extraction of construction materials) and losses in the transportation industry in environmental, resource, water and energy footprints, but the opposite for employment and value-added.

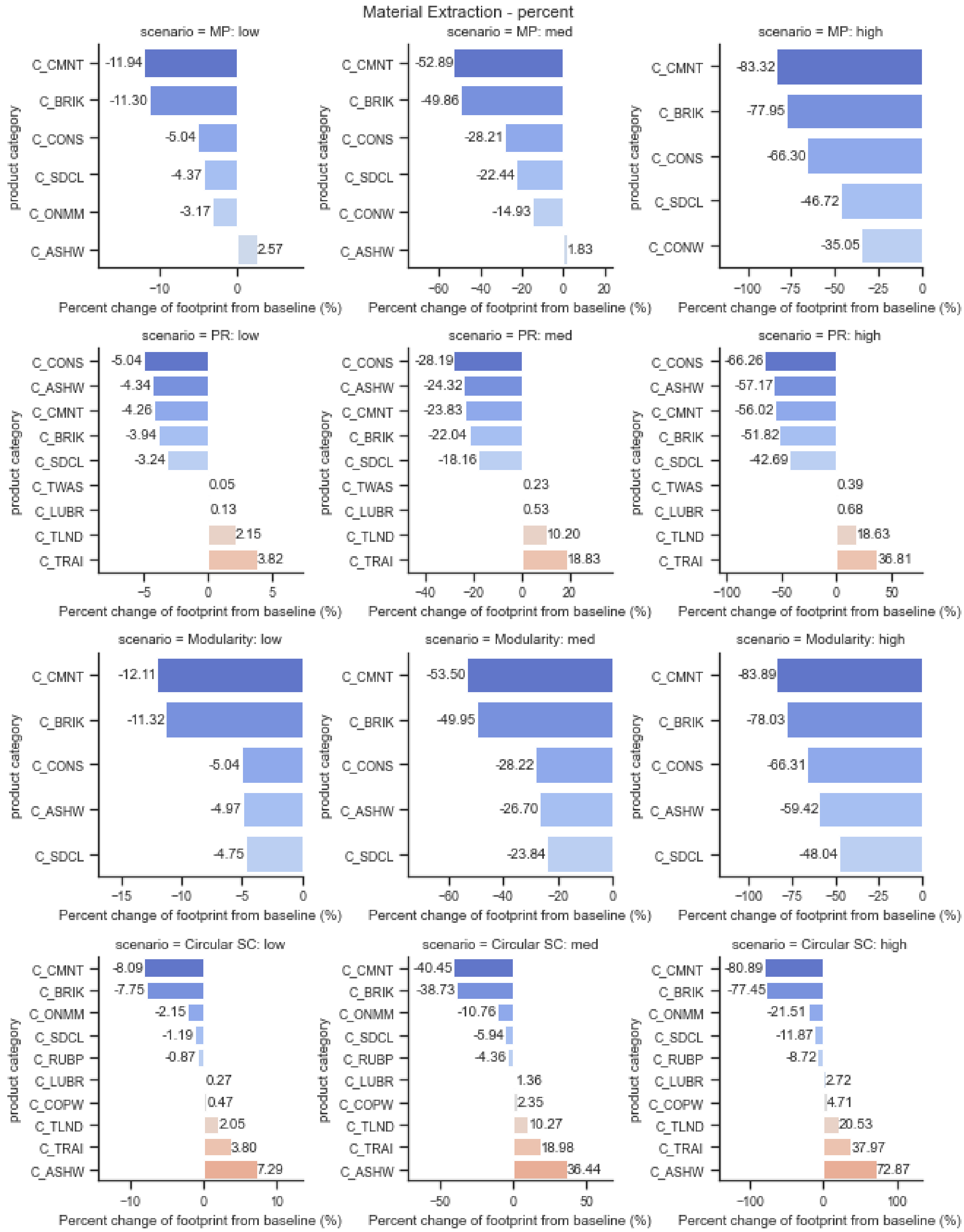

Figure 5.6: Percentage change in raw material extraction ranked and compared across impact categories, for each construction scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter

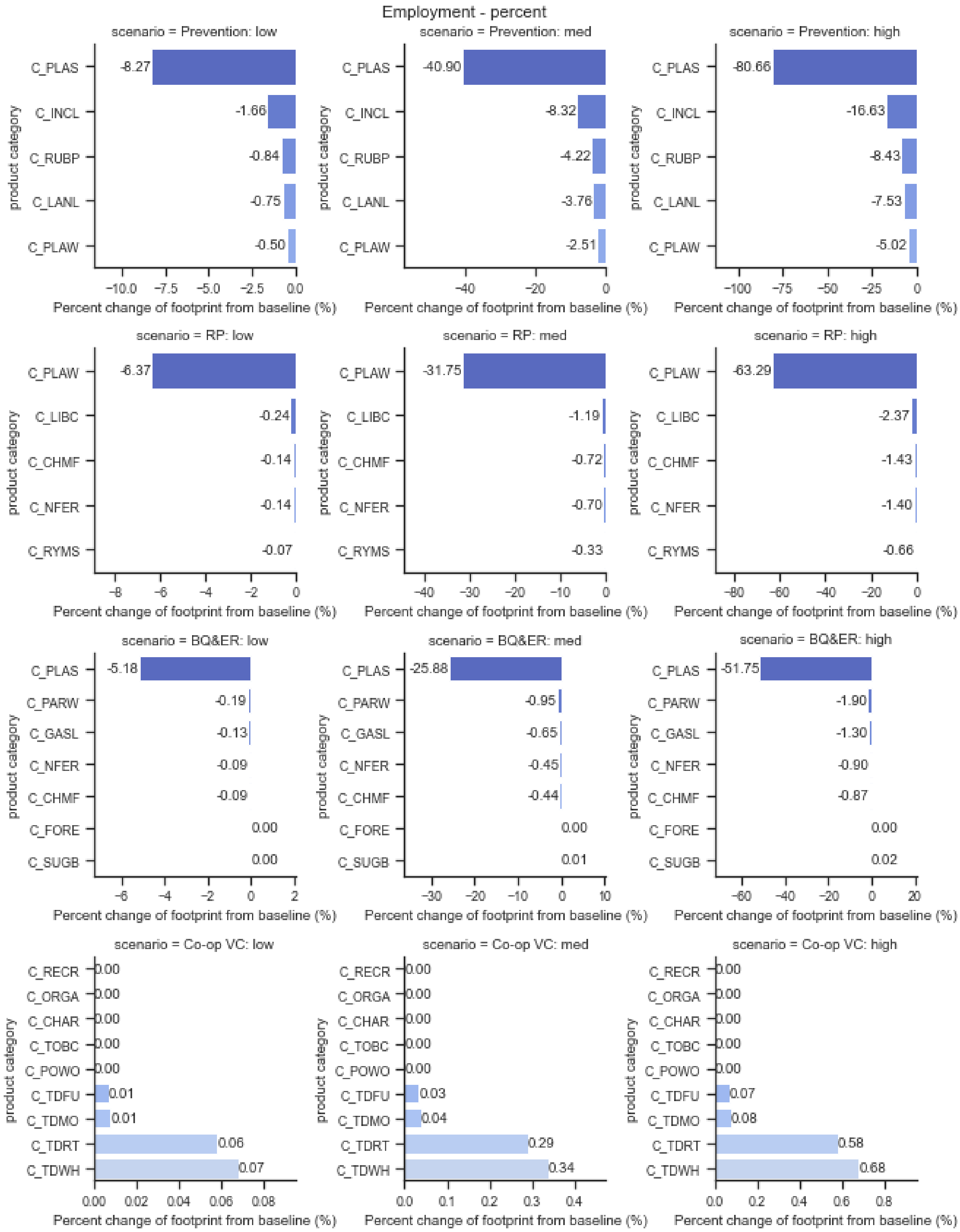

Figure 5.7: Percentage change in employment ranked and compared across impact categories, for each plastics scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter

5.5.2. Plastics

From figure 5.7 employment related products (primary plastics (C_PLAS) and secondary plastics (C_PLAW)) face the biggest reduction, depending on the specific intervention. All other reductions faced by the other products are relatively insignificant as compared to the scale of the changes for the plastics product categories.

For the intervention *co-operation across the value chain,* 4 product sectors (C_TDFU, C_TDMO, C_TDRT, C_TDWH) show an increase in employment, but the size of the increases (0.01% to 0.68%) are not significant.

There are some trade-offs experienced for the intervention, *Better quality and environmental returns*, in the sectors of Products of forestry, logging and related services (C_FORE) and Sugar cane, sugar beet (C_SUGB). As noted in an earlier paragraph, these trade-offs are insignificant as compared to the scale of the changes for the plastics product categories.

From figure 5.8, for the intervention *better quality and environmental returns*, the rubber product category has a significant reduction of global warming potential, which is not present in the other impact categories. This is due the reduction in global warming emissions used for the modelling of the intervention.

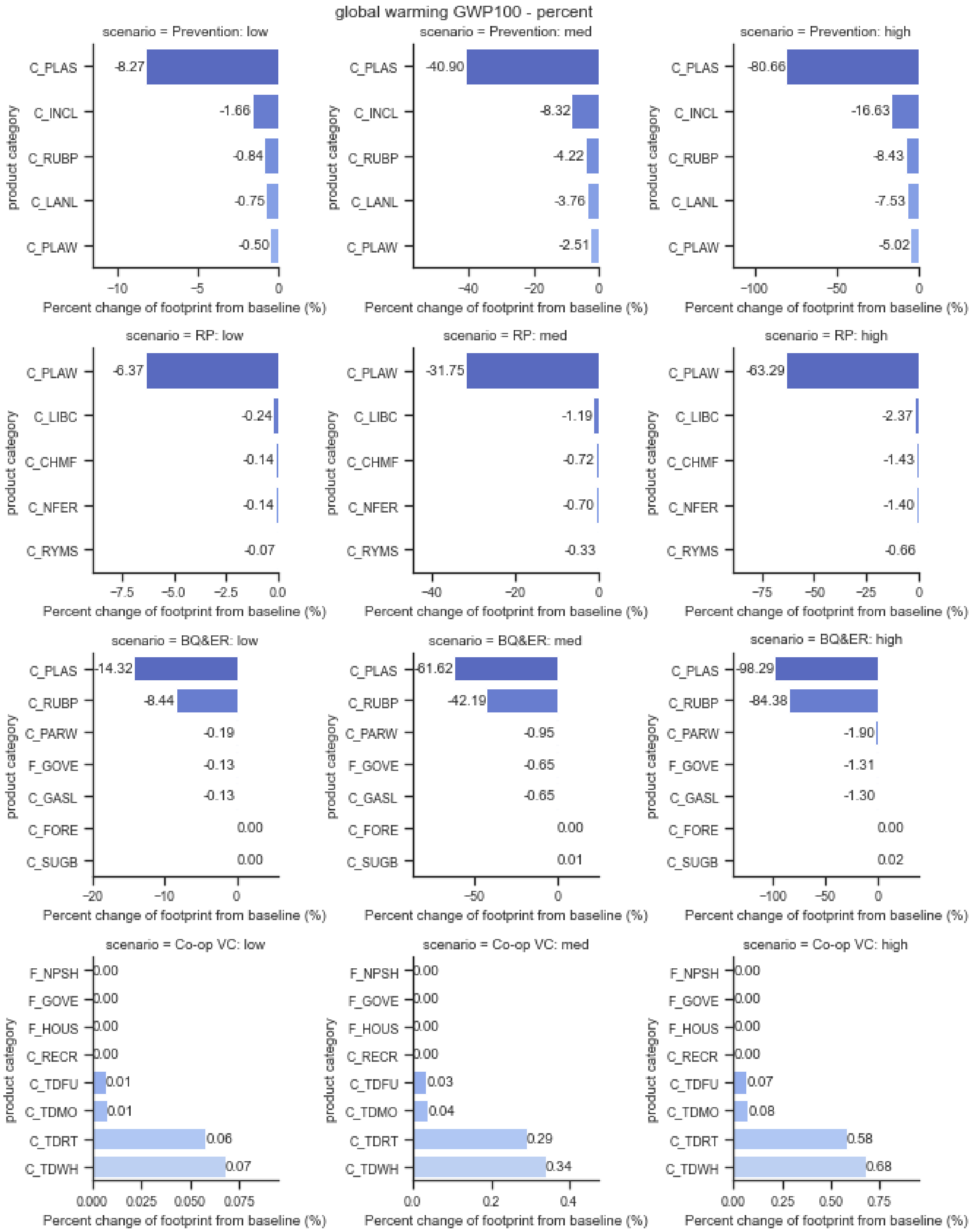

Figure 5.8: Percentage change in employment ranked and compared across impact categories, for each plastics scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter

6

Discussion and Conclusions

6.1. Evaluation of Trade-offs

From the results, it can be concluded that the implementation of the Dutch NPCE does result in trade-offs between the different dimensions of economy, society and environment. Examining impact dimensions, a general trend in the trade-offs is reflected in the results: positive impacts on environmental, material and energy indicators, while negative effects in economic and social indicators. Therefore trade-offs for the Dutch CE implementation programme, more specifically the plastics and construction priority chains, will be between improvements in the environment dimensions, at the cost of socioeconomic dimensions.

The results of the this report also matches the general consensus amongst literature (de Boer et al., 2021; Donati, 2021; Hart & Pomponi, 2021). While CE is sometimes propositioned as a step towards decoupling of the economy from resource use and environmental degradation, the trade-offs point towards the fact that simultaneous progress in all three dimensions cannot be meaningfully achieved with CE transition. For our study, even if there is simultaneous progress, the effects are typically marginal, as seen in the case of the intervention *Circular Supply Chains*.

Examining across product categories in the Dutch economy, most strategies higher up the R-ladder (R2, R3) tend to produce an effect of shrinking the economic sector, whereby all affected product categories in the Dutch economy see a reduction across all footprint categories. Strategies lower down the R-ladder (R4, R5) tend to produce trade-offs between product sectors, especially between resource extraction and manufacturing sectors against the transportation sector. This is due to the importance of the transportation sector in closing supply chain loops, enabling the movement of materials, either for ex-situ reuse, or for additional processing into new products or materials.

Three factors determine the effectiveness of CE intervention: the sector or priority chain targeted, R-ladder position of the intervention and the level of implementation. The target sector affects the underlying potential for the effectiveness of the CE intervention. The inherent differences between the size of the sector and the types if supply chain activities within each sector determines the intensity of the impacts across footprint categories. In the 2 case-study priority chains, the plastics chain was proportionally more energy intensive, whereas the construction sector was overall larger in size. The position of the R-ladder determines the shape of the footprint. As discussed previously, higher R-ladder strategies achieves their impacts through a reduction of size of economic sectors, while lower R-ladder strategies achieve their impact through trade-offs between economic sectors. As a consequence of the trade-offs, the scale of the change in impacts is typically reduced across all footprint categories as compared to higher R-ladder strategies as the wins in one sector are offset by losses in other. The level of implementation determines to what extent the potential for reduction of the CE intervention is achieved.

6.2. Implications for Sustainable Development

Considering the trade-offs in a broader context of sustainable development, the findings of this research seem to imply two things: with a transition towards a circular economy, the concept of green growth may not be feasible, and the sustainable development goals (SDGs) might be at odds with each other.

Green growth proclaims that economic growth can be decoupled from increasing resource use and environmental emissions (Hickel & Kallis, 2020), but the results show that oftentimes, especially for the most effective r-ladder strategies, contraction of the economic system is warranted, along with the loss of employment. While some interventions modelled in this study produced ”green growth” where win-wins were achieved in almost all impact categories, the underlying trade-offs between product sectors means that the resultant overall growth is marginal at best.

For SDGs, socio-economic indicators of value added and employment fall under goal 8: decent work and economic growth, whereas other impact indicators in this study fall under goal 6: clean water and sanitation for blue water withdrawal; 7 for energy use, goal 12: responsible production and consumption for material extraction, and goal 13: climate action for global warming potential (United Nations, n.d.). With the tradeoffs found in this study, goal 8 will be the loser as a result of the circular economy transition.

However, it is also possible to go one step further to challenge the inherent assumptions made when deciding the desirability of the trade-offs made in Chapter 6. With our model, footprint categories are also aggregations where the source or nature of the footprint is obscured. For example, not all forms of employment is necessarily good, as exploitative or dangerous employment is undesirable to sustainable development. Additional caution needs to be taken when drawing conclusions, especially when there is a high level of aggregation.

6.3. Research Contribution

This research adds to the existing body of scientific research on circular economy and input-output analysis. It builds on the theoretical model to execute assessments of the socio-economic and environmental impacts of CE strategies with EEIOA, first presented in Donati et al. (2020). Beyond the modelling of singular CE strategies in EEIOA, it provides an approach to create CE scenarios from complex CE projects that employ a combination of CE strategies for EEIOA modelling.

There has been limited research on the expected effects of ongoing national CE policies, especially comparing across impact dimensions, This research provides an early look into examining the effects and trade-offs that would result from the implementation of the Dutch nation CE agenda, NPCE. Most national CE transitions being at an early stage, are small-scale and have insufficient data to model these interventions scaled to national-level. This research highlights the potential modelling issues as a result of early stage CE transitions and proposes suitable adaptations to modelling method to address the data uncertainties.

This research contributes to the greater societal awareness of the overall macroeconomic effects as a result of a transition to circular economy. Different impact dimensions beyond the typical focus of circular economy, resource use, were compared to determine the winners and losers of the transition. This research can guide the development of future CE policy by focusing on supporting the losers of the CE transition or promoting the winners of the transition. This research can also support decision-making of industrial actors by identifying sectors of the economy that are the biggest winners and losers of the CE transition.

6.4. Limitations and Further Work

6.4.1. Nature of Implementation Programme

The Dutch NPCE, especially the existing implementation programme, provides the foundation for the modelling of the Dutch CE. However, as covered in Chapter 4, the implementation programme possesses 3 traits that make IOA modelling challenging:

1. Exploratory projects and pilot projects make up majority of the implementation programme
2. Innovation
3. Specificity of the projects

With exploratory and pilot projects, these projects are early-stage, small-scale and currently in the midst of being implemented. The full extent of the potential effects are not understood, since these projects have not had the opportunity to scale up beyond a niche. Information on the existing projects are limited, especially numerical data to model the changes to the Dutch economy as a result of the implementation of these projects nation-wide as a

CE intervention. The current approach attempts to address this issue by modelling 3 levels of implementation of these projects to the Dutch economy, but does not accurately represent the practicality and feasibility of achieving these levels of implementation, especially at the higher levels. The accuracy of the model can be improved through the use of better estimates of the potential effects of the CE interventions, either from complimentary studies or literature, or the outcomes from these exploratory and pilot projects as they become available.

The transition to a circular economy is driven by innovation, and as seen from the implementation programme, a significant portion of the projects involve new products and processes. The underlying assumption of the IO model is that the economic structure remains relatively constant before and after the economic shock. When these projects are scaled-up to a national level, the innovative products and processes are no longer a niche and will form a significant portion of economic transactions within an economy. This necessitates the use of an rebalanced IO dataset that captures the technological change and market shifts that will result with increased adoption of innovation.

The projects in the implementation programme affect specific products or industries. Due to the high level of aggregation of economic activity to create the product categories used for EXIOBASE, the CE interventions embodied by the projects can affect transactions of products and services that form a subset of a particular product category in EXIOBASE, or involve a mix of multiple product categories. This high level of aggregation produces 2 issues:

1. Complexity in accurately modelling CE interventions to very specific product types
2. High levels of aggregation increases the complexity of modelling intra-category substitutions

Very specific product types were common in the projects covered in the implementation plan, especially in the agenda areas of manufacturing and consumer goods. When these specific product types only form a fraction of the transactions in a product category, it was challenging to discern significant impacts or trade-offs of the entire economy. For modelling, the effects of the interventions had to be generalised and magnified to apply across the entire product sector. However, this approach disregards of the feasibility of applying product-specific CE interventions across the entire product sector. Product substitutions are also challenging to model with highly aggregated datasets because aggregation increases the likelihood that substitute products and services are grouped together in the same category since they have similar applications. To address this issue, an IO dataset that goes into the necessary resolution for specific product types to be studied has to be used, such that there exists disaggregated data for the specific product types for IO analysis.

6.4.2. Software

The pycirk package provides a powerful tool to model the CE scenarios, but comes with its limitations. Pycirk requires on an input spreadsheet for the modelling of CE scenarios. In this spreadsheet, the outputs of the CE modelling are specified. The current input spreadsheet is designed to take in specified regions, product categories, and emissions categories. This limits the types of outputs that the programme can calculate. This creates restrictions in two aspects:

1. The level of aggregation that can be performed for the calculations
2. The type of accounting method used for the calculation of impacts

Pycirk allows footprint calculation at two different levels of aggregation: at an individualised level for regions, product categories, impact categories or characterised impact categories; or an existing set of aggregations built into the package. Taking the example of regions, the only available levels of aggregation are region level (49 regions in EXIOBASE), EU-28 and rest of world (RoW) level, and global level (49 regions aggregated). This prevents the creation of customised aggregations, e.g. the aggregation of the regions into the Netherlands and RoW, which could be used to perform further trade-off analysis. The accounting method defaults to consumption-based footprint accounting. This prevents the model from producing production-based emissions accounting which provides another perspective for the analysis of trade-offs.

To circumvent the limitations of the input spreadsheet, the underlying IO tables for the baseline scenarios and the counterfactual scenarios are exportable from the pycirk model. This allows the modeller to directly manipulate the IO tables for additional calculations or to extend the pycirk model with other packages such as pymrio, which supports user-specified aggregation levels for EE MRIO modelling. However, the process of exporting the IO tables requires much time and storage space since each counterfactual scenario produces a unique IO dataset. Further work can be done on expanding the capabilities of pycirk to accept user-specified aggregations and output results of production-based accounting.

6.5. Conclusions and Recommendations

Conclusion

The objective of this study was to understand the trade-offs between socio-economic and environmental dimensions as a result of a CE transition. This is done in the context of the Netherlands, which as adopted a CE transition agenda in the form of the NPCE.

Based on the aforementioned objective, the main research question is formulated:

> ”What are the potential trade-offs in environmental and socio-economic impacts of the Dutch National Programme for Circular Economy (NPCE)?”

Given that the NPCE is a national level agenda, the CE transition is approached at a macro-level to allow for top-down examination of the macroeconomic effects of the NPCE on the Dutch economy and its constituent sectors. To perform macroeconomic modelling of the Dutch economy, the following sub-questions were asked:

1. What are the current state-of-the-art methods for modelling the trade-offs of the circular economy?
2. What are the macroeconomic models most suitable for the assessment of circular economy trade-offs?
3. What are the approaches to create a circular economy scenario out of a set of national circular economy strategies for modelling?
4. What are the effects of the Netherlands' circular economy strategies?

To answer the first sub-question, a literature review of the current macroeconomic modelling methods was performed. Three state-of-the-art macroeconomic model- ling approaches were found in existing literature: MRIOA, CGE and IAM.

To answer the second question, a comparison of the strengths and weaknesses of the modelling approaches was performed. MRIOA was found to have three benefits over the other competing modelling approaches. Firstly, it was an established modelling approach for modelling the macroeconomic effects of CE. Secondly, it has a high level of data resolution, making it suitable for modelling trade-offs between environmental and socio-economic indicators. Lastly, the availability of publicly available datasets and modelling tools provides convenience in extending existing models and datasets for the purposes of our research. Hence, MRIOA was ultimately selected as the modelling approach for this study.

To answer the third sub-question. The paper presented a novel approach to create CE scenarios from complex CE projects that employ a combination of CE strategies. First, general CE strategies are identified that best represent the project to be modelled. Next, sectors affected by the project are identified. Third, based on the general CE strategies identified, changes are made to the elements of the MRIO dataset to represent the effects of the CE project on the economic structure. A blueprint is created to aid the modelling of a CE project into CE intervention scenarios by identifying the required elements in the MRIO dataset to change.

Subsequently, the method was applied to the latest Dutch CE implementation programme. With the current state of Dutch CE agenda, national CE strategies were found to be at an exploratory or pilot stage. To address this, adaptations were developed to model Dutch CE strategies within the framework presented in this report.

Overall, a method of modelling national CE interventions as scenarios was synthe sised based on the available EE MRIOA literature and tools. This report also highlights the potential modelling issues and suitable adaptations to the method to model early stage CE transitions.

To answer the forth sub-question, this study provided a formal definition of wins and losses for each footprint category based on the desired direction of changes in footprint categories.

The formal definition provides the foundation for evaluating trade-offs between different footprint dimensions. Next, two priority chains in the implementation programme, *plastics* and *construction*, were chosen. Their subagendas were modelled at 3 levels of implementation: low, medium and high.

In general, most of the modelled CE scenarios led to impacts in the form of reduction of footprints across 6 footprint categories: Global Warming Potential, Total Energy Use, Material Extraction footprint, Blue Water Extraction, Value Added and Employment.

For the construction sector, the biggest reduction of footprints are seen in the manufacturing sectors for construction components, whereas the biggest increase in footprints are seen in transport and freight sectors. The scale of wins in material extraction footprint is potentially -17.96%, double the size of losses in value added and employment.

For the plastics sector, the biggest reduction of footprints are seen in the plastics manufacturing sectors. The scale of wins in energy use footprint is potentially -4.46%, greater than other footprint categories by around five times.

Overall, the biggest potential wins were found in the construction sector, and the best interventions modelled, in decreasing order, being Modularity, Material Pass- ports, and Producer Responsibility.

To answer the main research question, it was found that the trade-offs of the Dutch CE transition occur between improvements in the environment dimensions, at the cost of socioeconomic dimensions. For the case study, wins were observed in the global warming, material, and energy indicators, while losses were observed in the value added and employment indicators. Depending on the type of CE intervention, trade-offs can also be expected between economic sectors. In terms of economic sectors, transportation is the sector expected to gain the most from the transition to a circular economy, and manufacturing of construction components and plastics are sectors expected to lose.

Recommendations

Addressing the trade-offs as a result of the Dutch CE agenda, Dutch policymakers should take action on 2 fronts: tackling the costs to society and economy, and enhance growing economic sectors from the CE transition.

The implementation of CE interventions is expected to reduce the size of targeted economic sectors and with it the revenue generated and the jobs created by companies under those sectors. At a policy-level, the government should encourage an economic shift towards growth industries, such that the Dutch national economy relies less on non-circular industries and companies. As part of the economic shift, the government also needs to facilitate the transition of manpower away from the industry, by creating opportunities for workers to reskill into and find employment in growth industries. At an industrial level, companies need to either adopt CE business models, being a part of the CE transition; or find other business opportunities in the post-CE transition economy.

For sectors that are expected to grow as a result of the implementation of the CE agenda, policymakers and industry leaders should help to steer the growth of these sectors such that the impacts of growth can be managed. The impacts of the growing economic sector has be in line with the desired directions of change as given in table 5.1.This is especially true for the transportation sector which is an integral part of closing the loops in a circular economy. Since the transportation sector relies heavily on shared or public infrastructure, policy makers have greater direct influence over investment into the sector. Policy makers and infrastructure providers should examine ways in which to make this infrastructure circular as well, i.e. applying circular economy strategies to transportation infrastructure.

As shown with the existence of trade-offs, the Dutch government should be wary of potential rebound effects when pursuing the transition to the circular economy. In the current implementation programme, CE projects still form a niche in the economy, but the effects of the transition will be felt once these CE interventions are scaled to nation-wide level. With increasing levels of implementation of CE interventions, the relative importance of the impacts have the potential to change. Policymakers need to take a proactive stance in monitoring and managing the transition of the economy.

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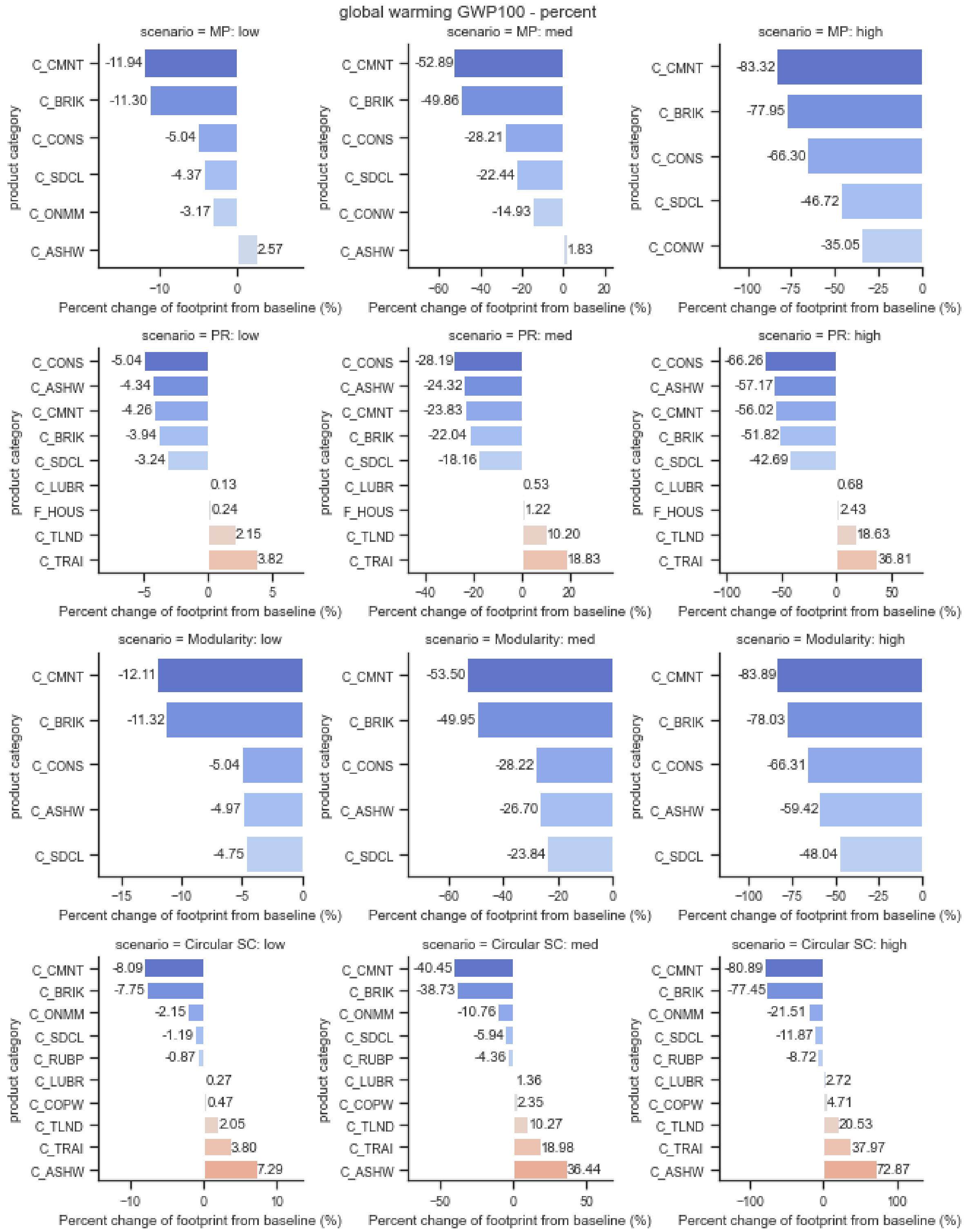
A

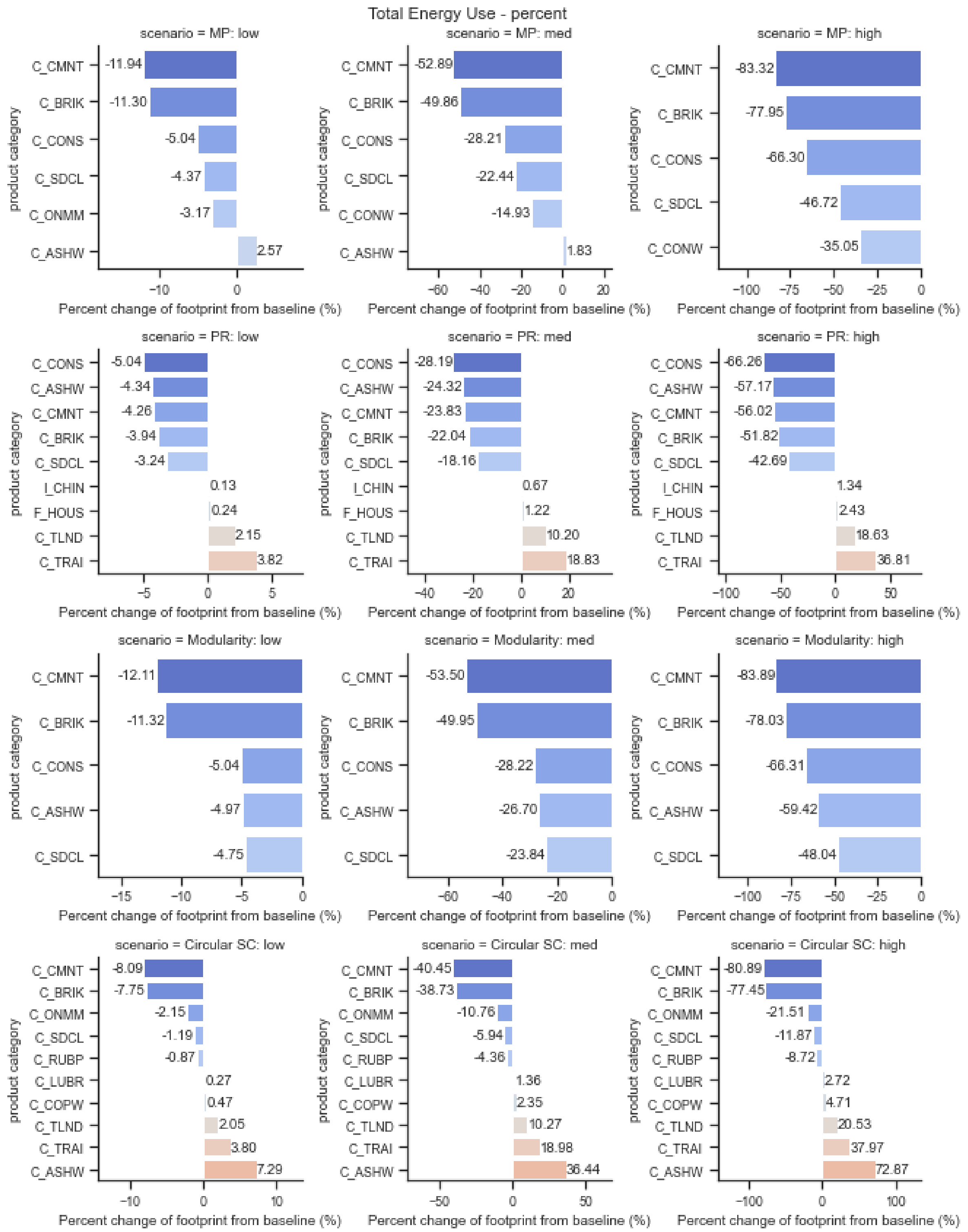
Appendix A

construction



*

Percentage change in GWP ranked and compared across product categories, for each construction scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.



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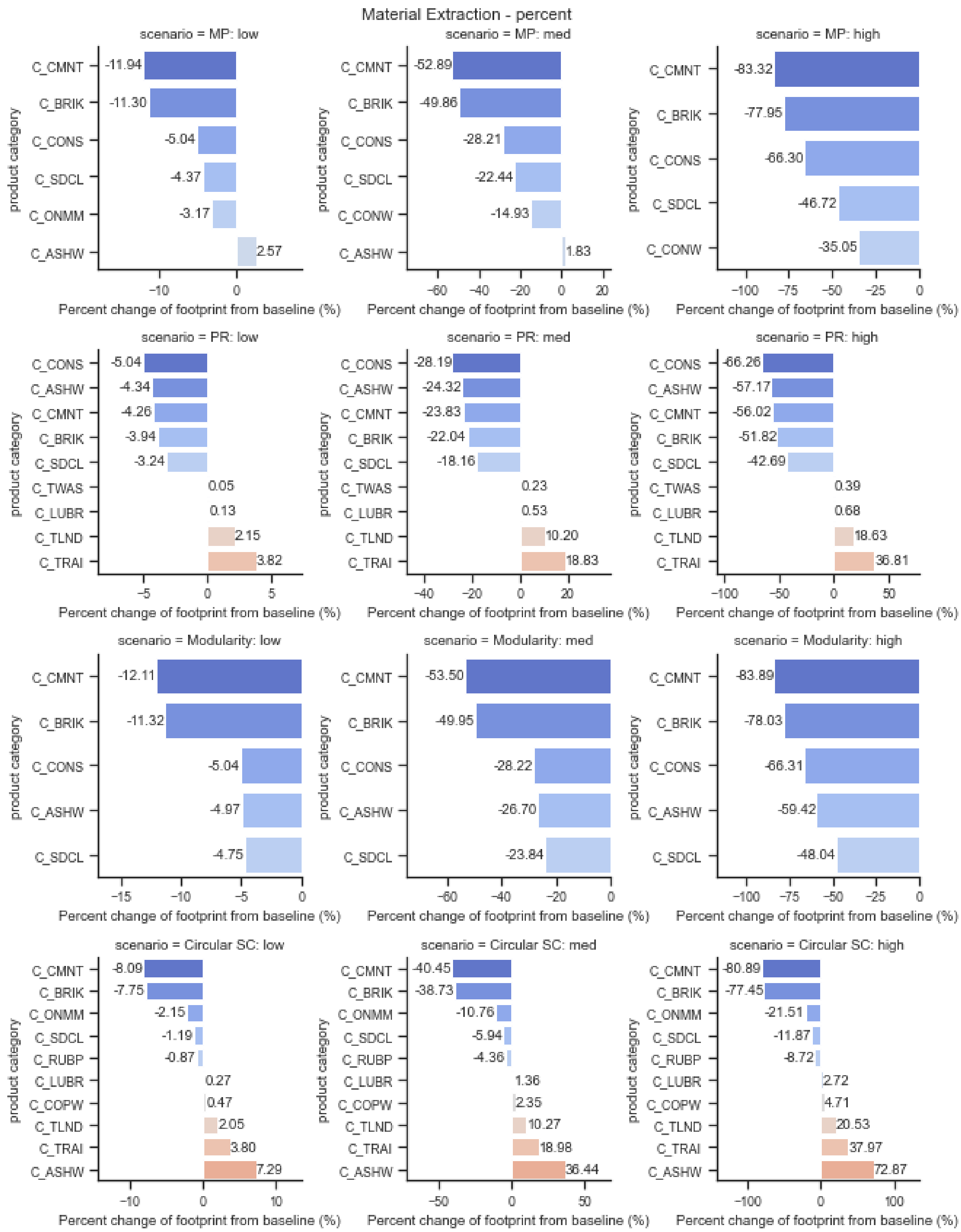
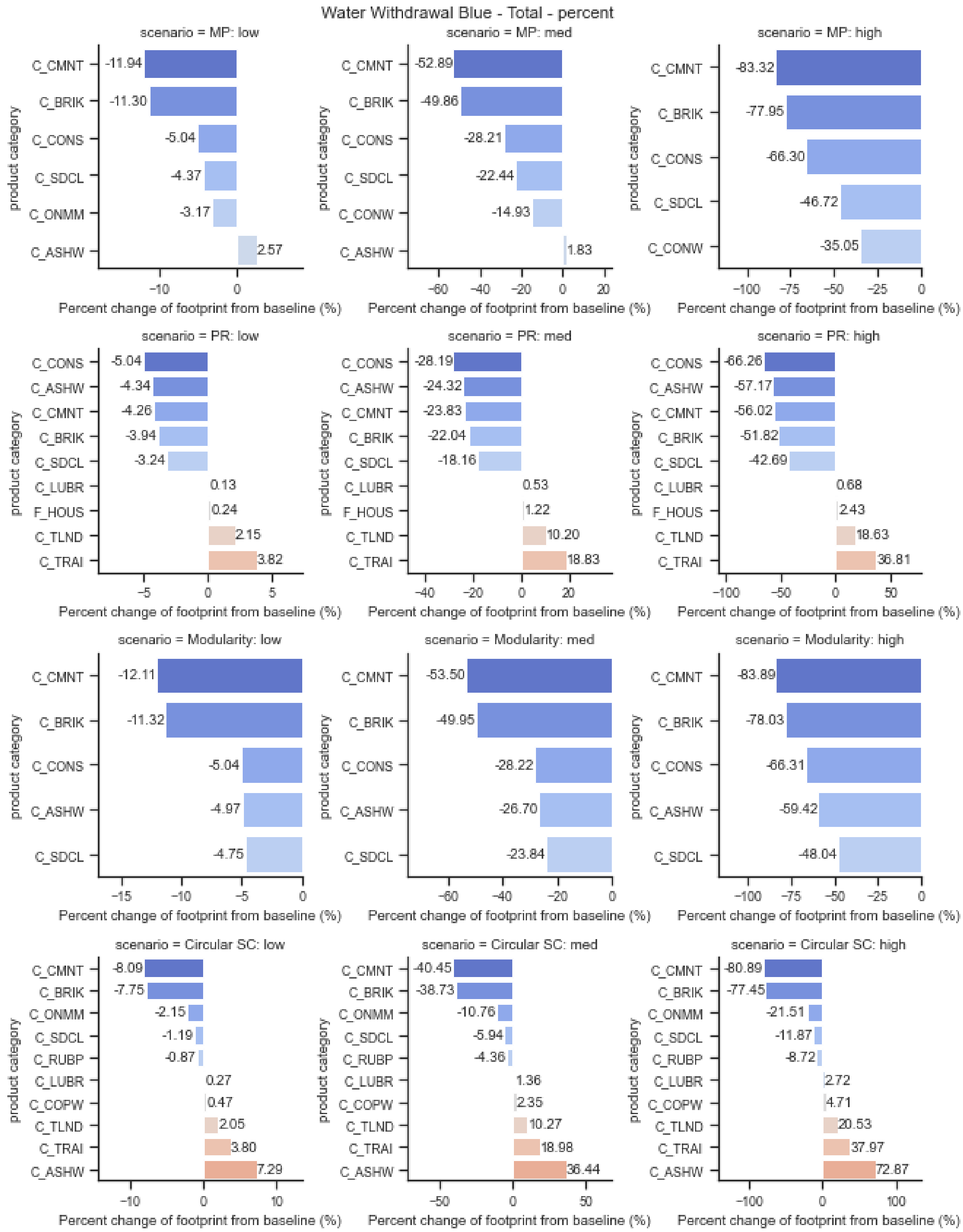
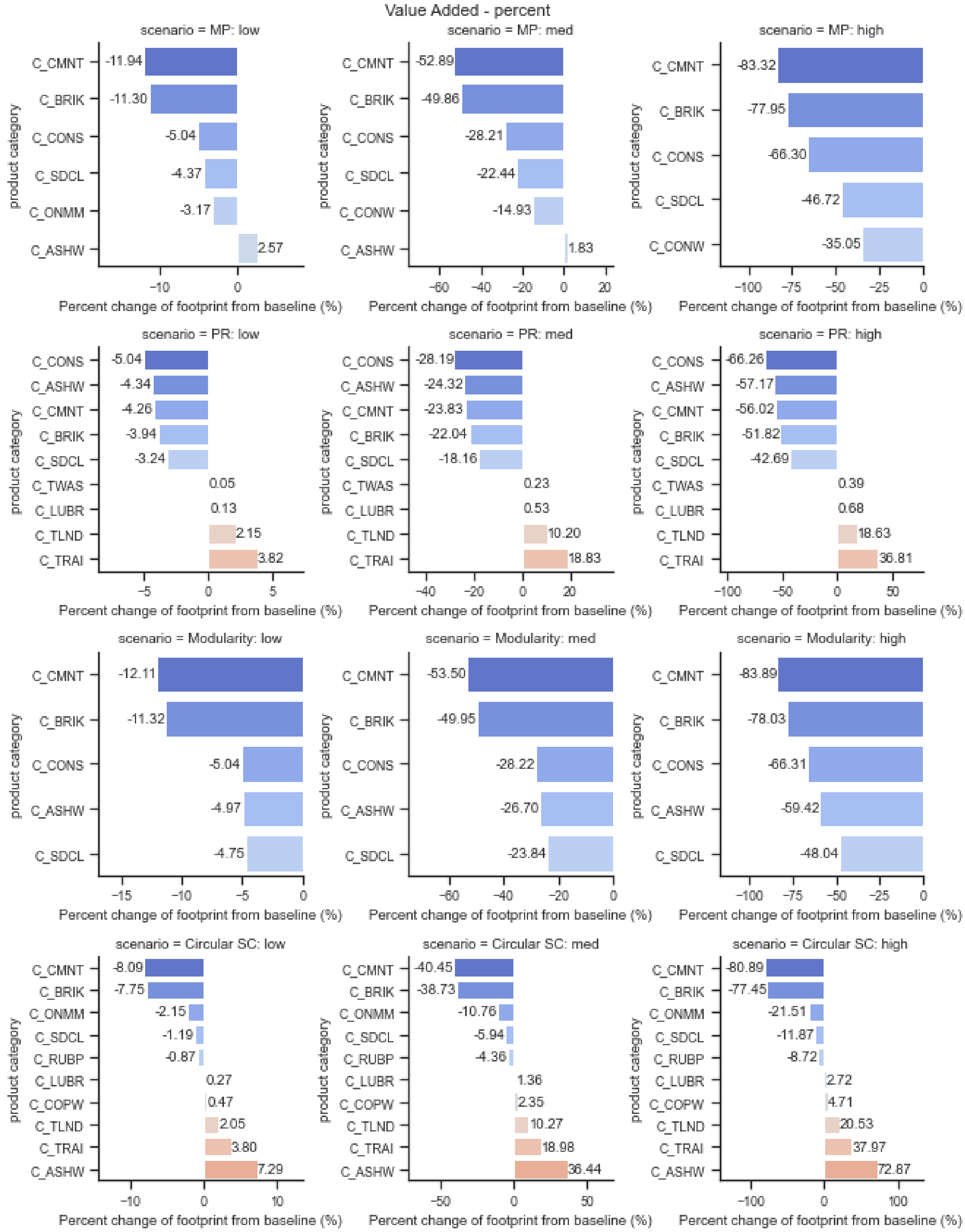
Percentage change in Total Energy Use ranked and compared across product categories, for each construction scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.



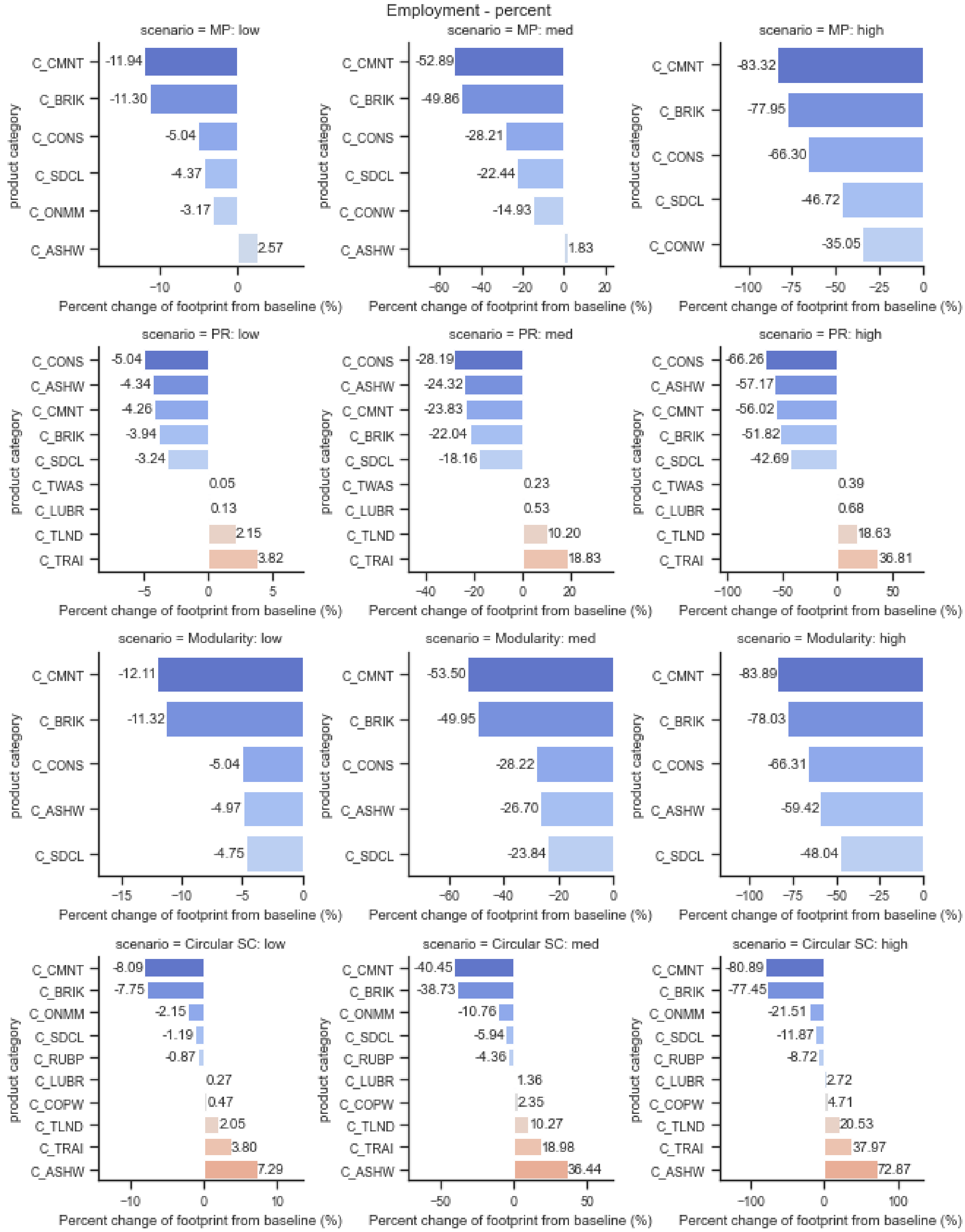
Percentage change in Total Material Extraction ranked and compared across product categories, for each construction scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.



Percentage change in Blue Water Extraction ranked and compared across impact categories, for each construction scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.

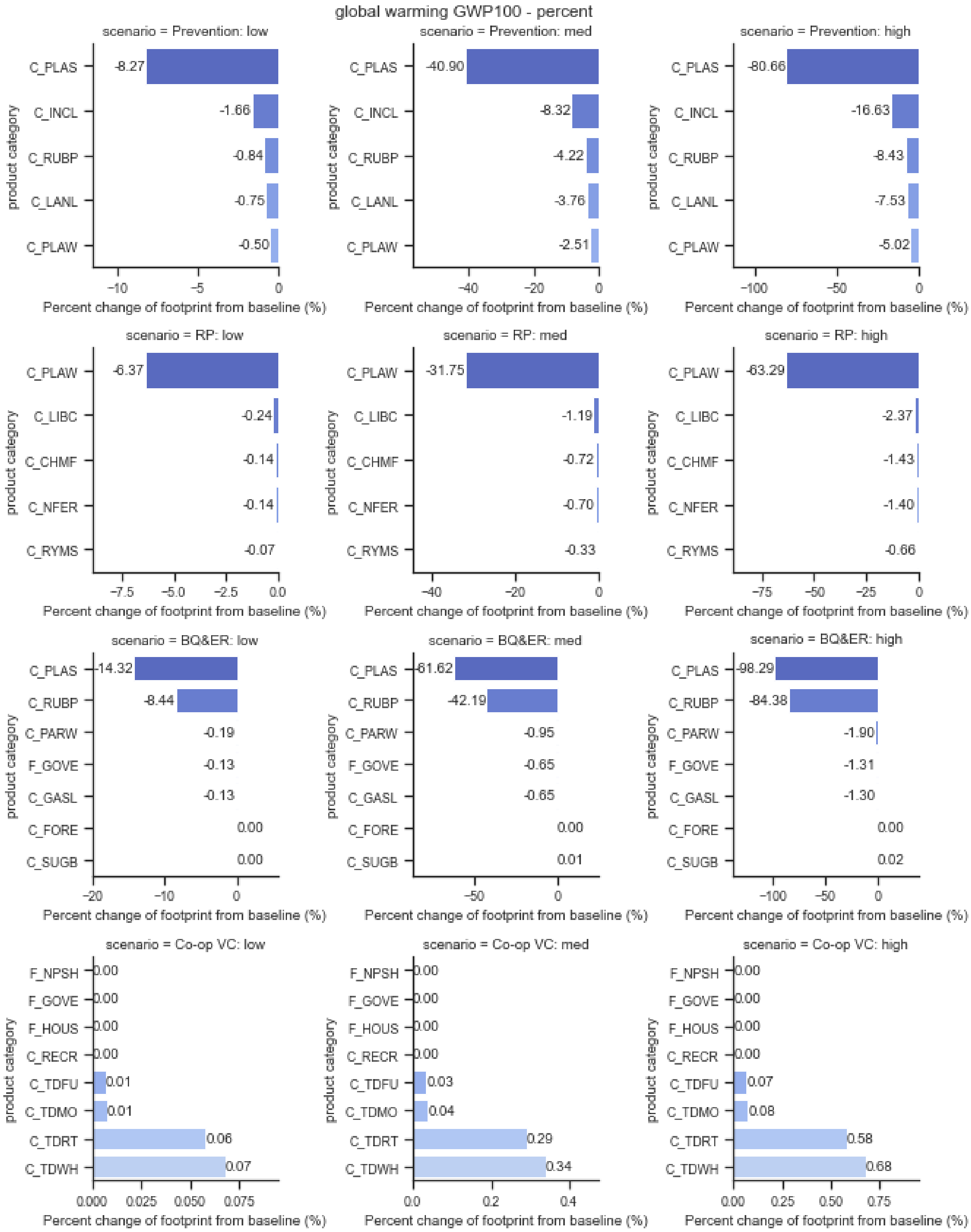


Percentage change in Value Added ranked and compared across impact categories, for each plastics scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.

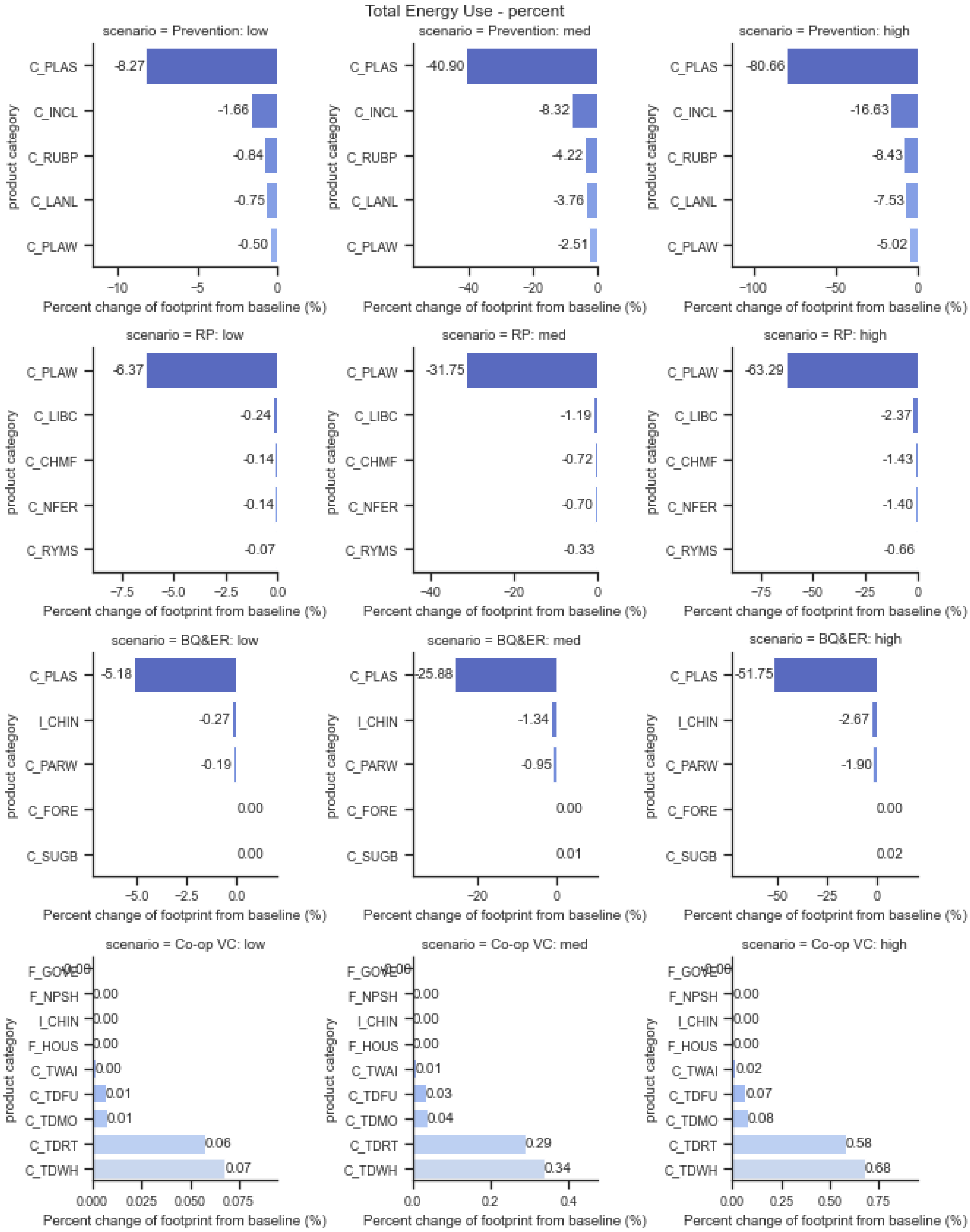


Percentage change in Employment ranked and compared across product categories, for each construction scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.

plastics



Percentage change in GWP ranked and compared across product categories, for each plastics scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.



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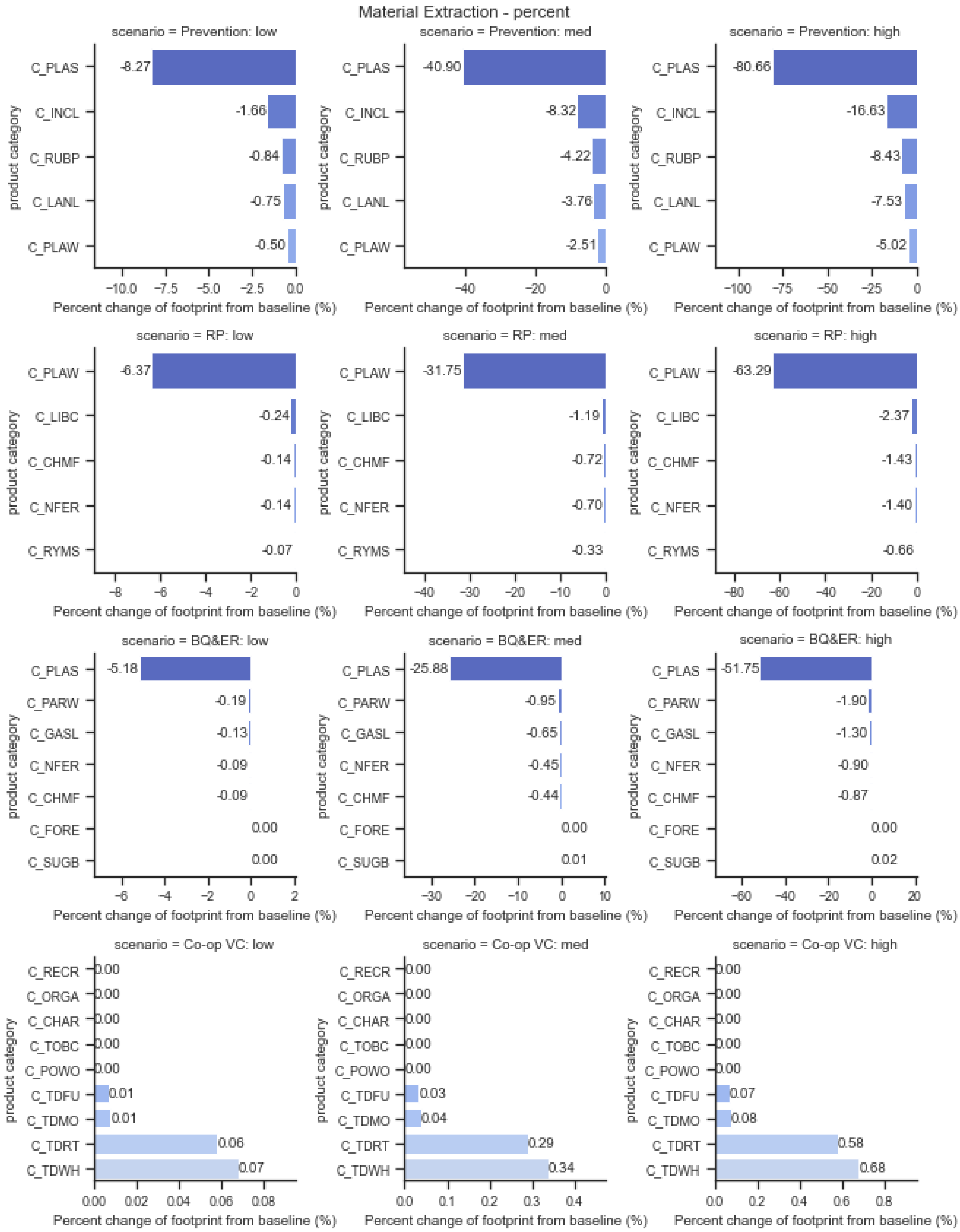
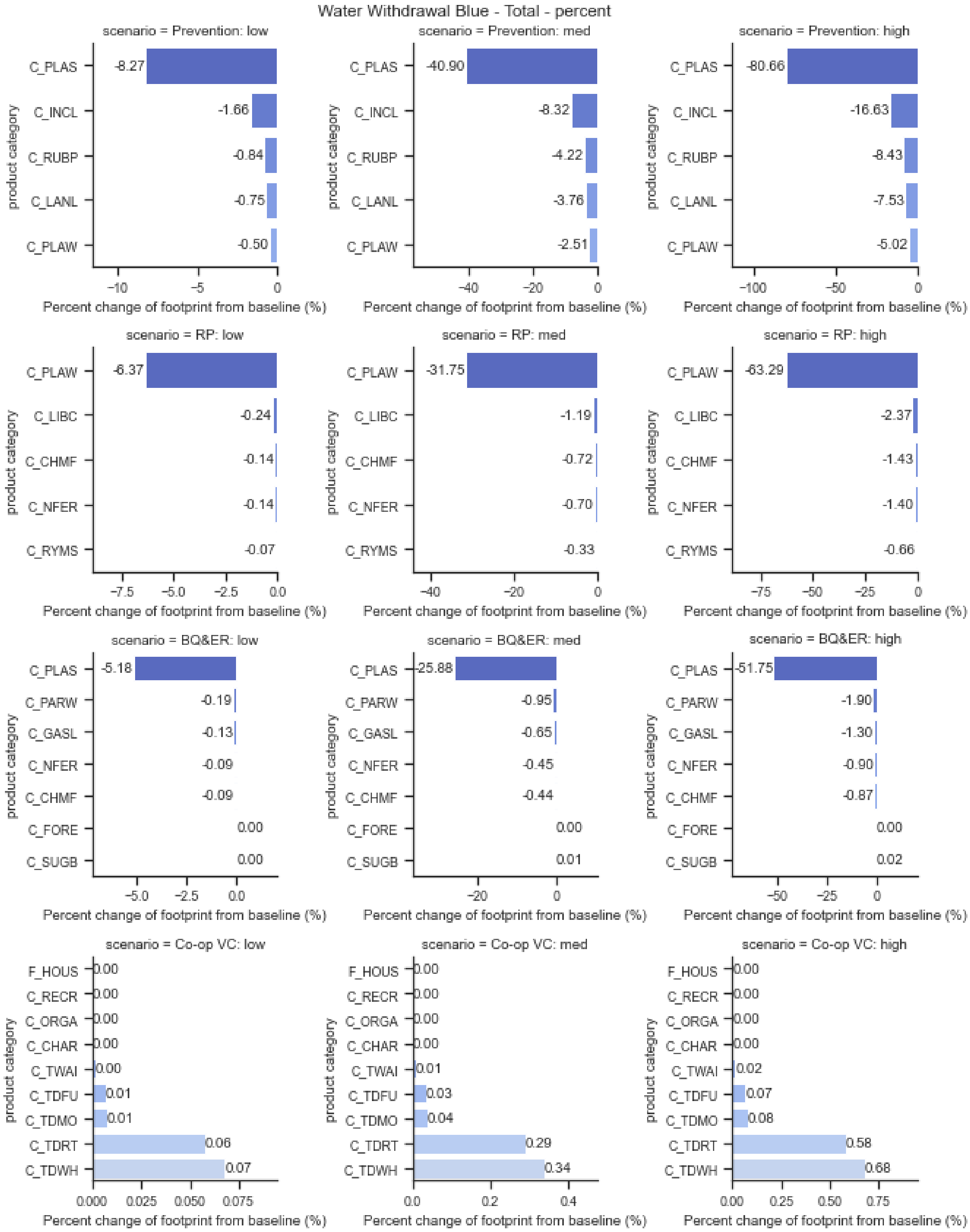
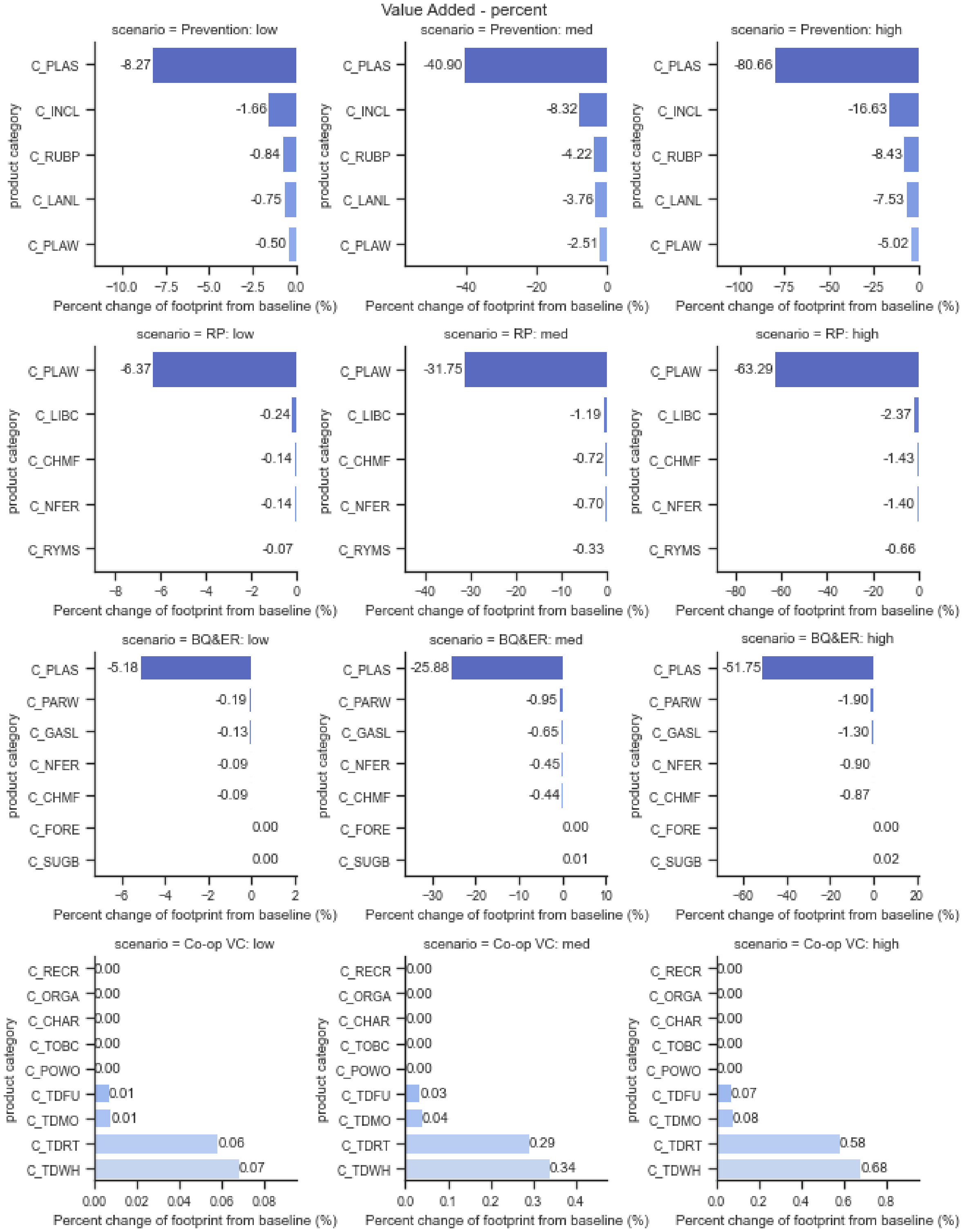


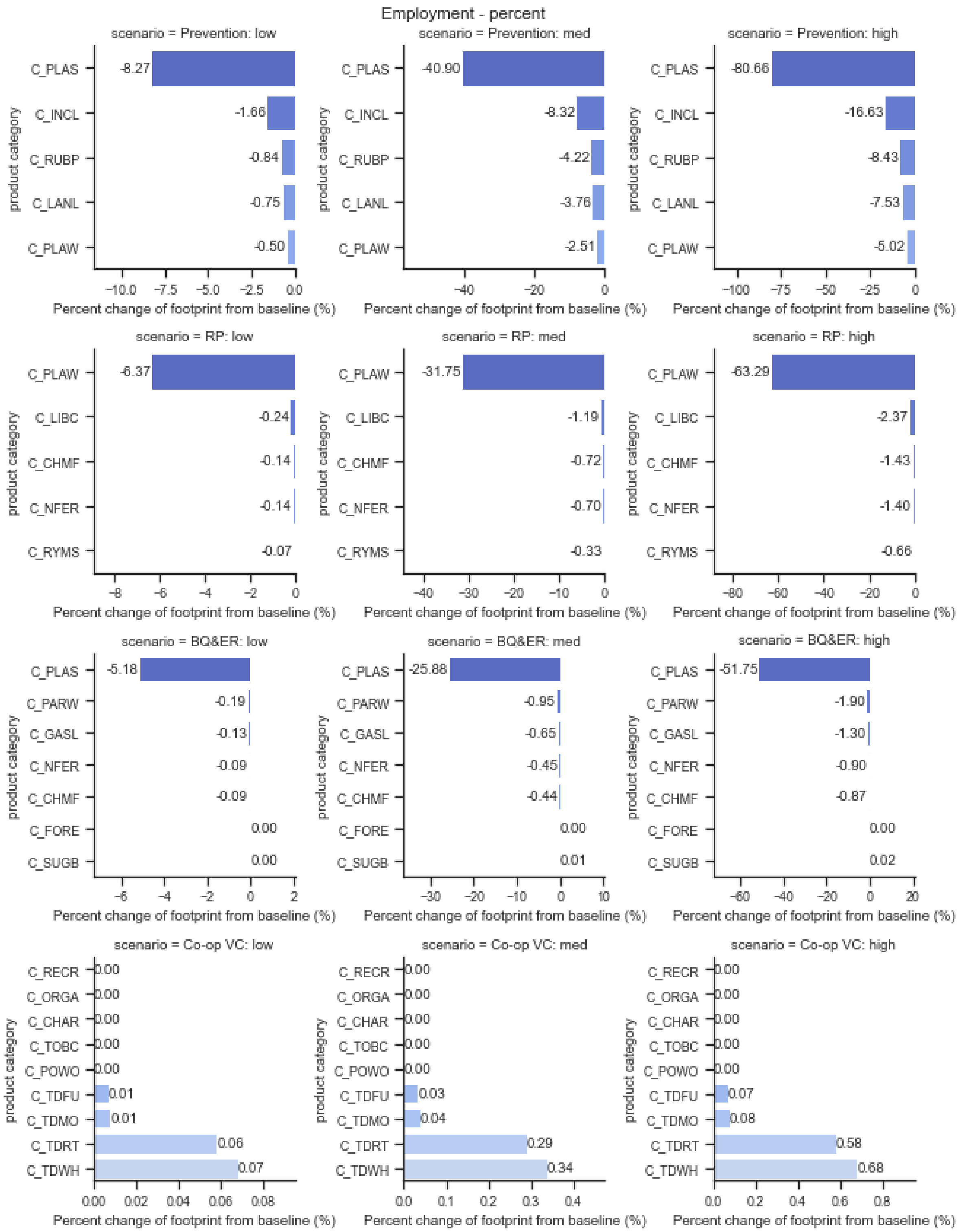
Percentage change in Total Material Extraction ranked and compared across product categories, for each plastics scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.



Percentage change in Blue Water Extraction ranked and compared across impact categories, for each plastics scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.



Percentage change in Value Added ranked and compared across impact categories, for each plastics scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.



Percentage change in Employment ranked and compared across product categories, for each plastics scenario (only top 5 winners and losers (if applicable) shown). Abbreviations for the tracks/subagendas can be found in the Abbreviations chapter.

B

Appendix B

The files used for the modelling of the CE scenarios in Pycirk is provided in the repository: https://github.com/cwtan-delft/circular-tradeoffs. The file structure is as follows:

- .\outputs\
  Contains export of the pycirk scenarios EXIOBASE tables
- .\ref\
  Contains refernce tables, datasets, and concordance tables for EXIOBASE and pycirk.
  - .\ref\Concordance Cat Mat.xlsx
    This file provides the concordance matrix for matching product/sector categories with the correct matrices for analysis.
- .\tests\
  Contains subfolders for each priority chain (plastics, construction)
  - .\tests\plastics\& .\tests\construction\
    Contains the scenario.xls file and the outputs folder for each priority chain.
    - .\tests\(priority chain)\scenario.xlsx
      This file contains the analysis and scenario information for the modelling that priority chain in pycirk
    - .\tests\(priority chain)\output\
      Subsubfolder containing the plots generated by the ce-main.py script
- ce_pycirk.py

This file contains a collection of functions used for modelling with the Pycirk software.

- ce_main.py
  This file contains the code that constructs the scenarios for the plastics and construction priority chains and produces the results and plots used in this report.