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A Just Transition to Circular Economy

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A Just Transition to Circular Economy

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JUST2CE

A Just Transition to Circular Economy

PROJECT No. 101003491

JUST2CE will assess the current state of transition towards the circular economy in relevant economic sectors and analyse possible transition scenarios, as well as their outcomes and impacts. It will identify the key factors that can stimulate or hinder this transition. Natural resources are extracted and transformed into products, which are eventually discarded. As many natural resources are finite, it is important to keep materials in circulation for as long as possible. This makes the transition to circular economy more vital than ever but is a responsible, inclusive, and socially just transition to a circular economy possible or even desirable? What technical, political, and social factors can enable or hamper such transformation? The EU-funded JUST2CE project will answer these questions. It will explore the economic, societal, gender and policy implications of the circular economy paradigm. The project’s findings will shed light on how to ensure democratic and participatory mechanisms when designing and managing such technology.

History Chart

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Executive Summary

This study employs an empirically calibrated ecological two-area input-output stock-flow consistent model to analyse various circular economy (CE) policies and practices and their impacts on economic, social, and environmental variables. The research concludes that solely relying on shifts in the behaviour of households and private businesses is not sufficient in order to achieve a *just* green transition. Two key reasons support this conclusion: competition forces driven by private interests may yield unintended consequences, and there is no universally optimal state for CE policies, each involving trade-offs. Therefore, government intervention is crucial. Coordination among national governments is paramount to prevent policies in one area from negatively affecting others. Additionally, a democratic planning system may empower public authorities to pursue the most pressing targets effectively. Findings indicate that CE policies generally lead to small negative impacts on value added, although exceptions exist, such as reductions in consumption levels in the EU or shifts towards service consumption, which can increase value added. CE policies tend to decrease CO_2 emissions and material extraction, demonstrating their potential for environmental sustainability. However, their effectiveness varies depending on consumption patterns and production processes. While CE policies typically result in small negative impacts on employment, certain policies, such as those promoting the use of recycled inputs, may increase employment despite reduction in value added. Positive economic effects are also observed for female employment in CE policies oriented towards the care economy and social reproduction. The study also highlights changes in functional income inequality, government deficit, and current account balance resulting from CE policies, emphasising the importance of considering distributional and macroeconomic implications, especially for countries in the Global South. Overall, the findings emphasise the necessity of government intervention and policy coordination to achieve a just green transition, ensuring equitable outcomes across economic, social, and environmental dimensions.

JUST2CE
A Just Transition to Circular Economy

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List of abbreviations

BSM	*Balance-Sheet Matrix*
CE	*Circular Economy*
IO	*Input-Output*
IOM	*Input-Output Matrix*
PFM	*Physical Flow Matrix*
PSM	*Physical Stock-Flow Matrix*
SFC	*Stock-Flow Consistent*
TFM	*Transactions-Flow Matrix*

[1] Introduction

[1.1] Background and objectives

In recent years, the concept of circular economy (CE) has gained significant attention as a means to address pressing environmental challenges while fostering economic growth and social equity. The transition towards a CE entails rethinking traditional linear production and consumption models to minimize waste and maximize resource efficiency. To evaluate the potential of CE policies and practices, the work developed within this strand of activity of the JUST2CE project employs an empirically calibrated two-area input-output stock-flow consistent model. The aim is to assess the impact of these policies and practices on economic, social, and environmental variables, with a focus on achieving a *just* green transition. The primary objective of this study is to analyse the effectiveness of various CE policies and practices in achieving sustainable economic development while minimising environmental degradation and promoting social equity. Specifically, the study aims to:

- Evaluate the economic impacts of CE policies on value added, employment, and income distribution.
- Assess the environmental implications of CE policies, particularly in terms of reducing CO_2 emissions and material extraction.
- Investigate the social dimensions of CE policies, including their effects on gender equality and income inequality.
- Examine the macroeconomic consequences of CE policies, such as changes in government deficit and current account balance.
- Highlight the importance of government intervention and policy coordination in driving the transition to a just green economy.

[1.2] Scope and limitations

While this paper provides valuable insights into the potential benefits and challenges of implementing CE policies, it is essential to acknowledge its scope and limitations. Firstly, the analysis is based on a two-area input-output model, which may not capture all nuances and complexities of real-world economies. Additionally, the study focuses primarily on the European Union and the rest of the world, limiting its generalizability to other regions. Furthermore, the analysis assumes certain behavioural responses to CE policies, which may vary in practice. Finally, the study does not account for potential feedback effects or dynamic adjustments over time, which could influence the long-term outcomes of CE initiatives. Despite these limitations, we believe that our findings may contribute to our understanding of the potential pathways towards achieving a more sustainable and equitable economy through circularity.

[2] Literature review

[2.1] CE scenarios

The term ‘circular economy’ (CE) lacks a universally accepted definition; however, most of the proposed conceptualisations share a common theme of decoupling natural resource extraction and use from economic activity, with increased resource efficiency and reduced demand (Bocken et al., 2016; McCarthy et al., 2018). This concept contrasts with the conventional linear economic system, emphasising the closure of resource loops. The transition to a CE holds potential for re-industrialisation, job creation, and economic growth, offering new opportunities across industries, including secondary material production, repair and remanufacturing, the service sector, and the sharing economy.

Despite substantial attention in scientific literature, a comprehensive systematic review of key contributions on circular economy practices and strategies, considering macro-level societal impacts beyond aggregate employment, is lacking (McCarthy et al., 2018). An exception is the work by Bimpizas-Pinis et al. (2022), who conducted a systematic analysis using the SCOPUS database, identifying nearly 50,000 articles and narrowing it down to 405 relevant ones. It turns out that, among macroeconomic models, input-output (IO) models emphasise the CE concept the most, followed by CGE and non-CGE macroeconomic models and system dynamics.

The typology proposed by Aguillar-Hernandez et al. (2018) categorizes CE strategies simulated in the literature. CGE models scenario analyses tend to concentrate more on 'resource efficiency' (RE) and 'resource waste management' (RWM) strategies, which are often modelled through tax policies. In contrast, IO models have a broader focus. They encompass a wider range of CE strategies, such as 'product life extension' (PLE) and 'closing the supply chain' (CSC). In general, results in the literature tend to advocate that adoption of CE strategies can produce 'win-win' situations, i.e. reduction in environmental impact coupled with positive socio-economic impact[1]. However, as argued by Fevereiro et al. (2023) results are intrinsically related to the assumptions embedded in each modelling framework and the size of relative changes in technical coefficients, demand composition and required investment needed assumed by each specific scenario simulated.

Among recent works in this research strand, we can highlight the contributions by Wiebe et al. (2019) and Donati et al. (2020), who use environmentally extended multi-regional input-output model, with exogenous final demand model (among other interventions) the impacts of PLE practices in the environment and in socio-economic variables. Both papers find a reduction in environmental impacts. However, while Wiebe et al (2019) report a small positive impact in employment, while Donati et al. (2020) finds negative impacts in employment and GDP. PLE practices slow down resource depletion by lengthening the useful life of a product, e.g. changing the way products are designed, improving resistance of materials and components, and facilitating maintenance and repair. These can affect durable consumption goods and (or) capital goods. The direct impact of these change is a reduction in consumption and (or) investment for these goods. However, to make increase the lifetime goods may require more (or larger quality) material inputs and (or) increased expenditure on repair and maintenance. This can help make sense of the of the differences in results obtained by Wiebe et al. (2019) and Donati et al. (2020), as the former study assumes that all saved expenditure on durable goods is diverted to repair and maintenance services, while the latter assumes that only a fraction is diverted to repair and maintenance services.

Increased resource efficiency, which reduces material consumption, can also be considered as CE strategy. In terms of scenario modelling, technological changes that increase the material efficiency in production can be represented as a reduction in the amount of material inputs. Different studies make varying assumptions regarding whether material efficiency gains can be obtained without any additional expenditure in other services, such as consulting or R&D, or through higher investment in fixed capital goods. For instance, Meyer et al. (2007) uses a Macroeconometric input-output model to simulate the effect of a linear increase in material efficiency in production in Germany over a period of 11 years. However, this is due to an increase in expenditure in consulting costs and in investment in fixed capital, which is worth 6 years in material costs savings. Wiebe et. al (2019) assume that reduction in material costs are completely offset by increased expenditure with (R&D), thus total demand is kept constant. Donati et al. (2020) do not include any compensating increase in technical coefficients from consulting or increased investment, finding a negative impact on the socio-economic variables considered; contrarily, Meyer et. al. (2007) and Wiebe et. al (2019) find positive impacts.

A key point of difference between different methods is the assumption regarding market structures. Most Neoclassical CGE models, such as Skelton et al. (2020), assume full pass-through of cost savings to prices, in line with the perfect competition assumption. Other approaches allow for imperfect competition, such as the Macroeconometric IO models proposed by Giljum et al. (2008), Meyer et al. (2012) and Distelkamp and Meyer (2019), which, based on empirical estimates, derive only a partial pass-through. As such, part of the cost efficiency gains are redistributed as higher value added per unit of output, either as higher wages, profit, or tax rates.

Most CGE studies have been applied to analyse the impact of environmental taxes to stimulate shifts in consumption and production patterns that lead to higher resource efficiency. Hatfields-Dodds et al. (2017) simulate the impact of a resource

[1] See Aguillar-Hernandez et al. (2021) for a meta-analysis.

extraction tax, estimating impacts. While Schndal et al. (2016) analyse the impact of different global carbon prices, results indicate negligible impacts on GDP and employment, compatible with a slow-down material use and reducing carbon emissions. Ljunggren Soderman et al. (2016) and Brusselaers et al. (2022) simulate changes in tax rates, such as reductions of VAT for services related to manufactured goods, in Sweden and Belgium respectively. Despite similarities in the policies simulated, Ljunggren Soderman et. al. (2016) report a fall in GDP (-0.1%), while Brusselaers et al.(2022) report an increase (1.6%). Both papers find that the tax policies lead to significant reductions in emissions. This result can be linked to the type of consumption functions adopted in CGE models being more or less sensitive to relative price changes (substitution effect). In general the higher the (cross-)price elasticity of demand, the higher the shift in consumption away from resource intensive manufactured goods, which become relatively more expensive. In a CGE model with a Keynesian 'closure' results might differ, as consumption tends to be more affected by income effects than by substitution effects (changes in relative prices). However, no CGE model adopting a Keynesian 'closure' was found in the review process.

Nevertheless, some studies use a Macroeconometric IO framework with a more Keynesian inspiration such as Giljum et al. (2008), Meyer et al. (2012) and Distelkamp and Meyer (2019). These studies model the impacts of the combination of increased resource efficiency with a range of environmental taxes. Although the effect of taxes tend to be much stronger in CGE than in MEIO models, all approaches indicate that the introduction of such policies reduce economic activity and environmental impacts. Hence, results indicate that both policies can deliver a substantial reduction in environmental impacts, without reducing economic activity, if well-coordinated.

CSC practices imply replacing materials from virgin sources with secondary ones through recycling, reuse, and remanufacturing strategies. One key assumption for results in these cases is the difference in prices between recycled inputs and re-used or remanufactured products. Cooper et al. (2016), among other CE practices, estimate positive employment impacts in the UK for an increase of the use of steel sections. The study assumes that 10% (25/kt) of steel sections extracted from demolition sites in the UK in 2011 can be reused, and that prices of re-used steel sections are 50% (£225/t) cheaper than those based on primary raw materials (£450/t). Final demand is kept constant; as such, the analysis does not capture secondary rebound effects associated with potential income effects on employment.

Peng et al. (2019) CGE model analyse the impact of stimulating the use remanufactured engines in China by comparing scenarios of using a (i) government a subsidy in the purchase of remanufactured engines; (ii) an increase in the energy efficiency of remanufactured engines of 15%; and (iii) of combining the two measures. Results indicate that, while the subsidy considerably lowered prices of re-manufactured engines and had a positive, although small, effect on GDP, increased energy efficiency in remanufactured engines had almost no impact on prices and, consequently, did not affect GDP. Winning et al. (2017) use a CGE model to consider the effects of a doubling in steel scrap availability worldwide. Results point to minor gains in GDP and lower environmental impacts at a global level. However, there are important regional imbalances, with negative GDP effects for commodity exporters from the global south.

Papers from the RWM category have typically analysed environmental and socio-economic impacts of alternative waste disposal strategies, such as landfilling, incineration and recycling. Ferrao et al. (2014) assesses the environmental and socioeconomic impact (in terms of gross value added, employment, wages and total revenue) of the Portuguese packaging waste management system by means of a Waste IO model and a IO multiplier analysis. Authors conclude that moving up in the waste hierarchy – from landfilling to recycling – creates jobs and boosts the economy. Freire-Gonzalez et. al (2022) analyse, through a CGE model, the impact of incineration and landfill taxation in the case of Spain, modelling different waste tax tariffs and including subsidies to recycling activities. Contrasting scenarios where (a) only the extension of the waste tax, or (b) waste tax revenues are used to subsidize recycling activities allows the author to assess the differences in impact revenue recycling schemes of environmental taxation. Results show that although both scenarios yield negative GDP results, despite better outcomes in the revenue recycling scenario.

One last important aspect of CE scenarios modelling is to analyse different scenarios analysing whether the CE policy is adopted by the entire world or only one (or some regions), comparing the results. Diestelkaamp and Meyer (2019), for instance, analyse three different types of transition – 'global cooperation', 'EU-goes ahead, and 'civil society leads' – to a resource-efficient and low-carbon production in EU-25 countries through different policy mixes. In the 'global cooperation' scenario, all countries co-operate through international agreements on harmonised economic and regulatory policy instruments. Results indicate that it is possible to achieve an absolute decoupling of GDP and environmental impacts globally, without reducing GDP growth relative to the baseline scenario. Both in the 'EU goes ahead' and in the 'civil society leads' scenarios, the EU pursues a low-carbon, resource-efficient economic strategy unilaterally. However, in the 'EU goes ahead' scenario change is obtained through strong EU-level economic and regulatory policy instruments instituted by the member-states. By contrast, in the 'civil society leads' scenario, resource-efficiency is driven by voluntary changes in preferences and behaviours of European consumers and businesses, such as a reduction in working-hours (through an increase in the share of part-time employment) and a reduction in the average propensity to consume of households. These voluntary behavioural changes end up affecting negatively GDP growth relative to the baseline scenario, whereas the GDP is shown to increase under the 'EU-goes ahead' scenario. Overall, the last two scenarios shows that a joint effort of EU member-states could suffice to achieve an absolute decoupling of their material footprint from economic growth, independently of what the rest of the world does.

As reviewed in this section the macroeconomic modelling literature on environmental and socio-economic impacts of CE strategies scenarios has been developing fast, with a range of frameworks and scenarios being analysed. Our work intends to contribute to this literature, by analysing CE scenarios using a new macroeconomic modelling framework, using a two region Input-Output SFC (IO-SFC) model developed within the JUST2CE project. In the next section we provide a brief overview of this approach and the emerging literature on ecological IO-SFC models.

[2.2] IO-SFC Models

In recent years, several authors (e.g., Hardt and O'Neill 2017; Bimpizas-Pinis et al., 2023; Fevereiro et al., 2022, 2023) have identified the combination of input-output (IO) analysis and stock-flow consistent (SFC) modelling as the most promising approach for developing models assessing the economy-ecology nexus, including Circular Economy (CE) transition scenarios.

IO models are analytical tools used to represent and quantify the interdependencies between different industries of a capitalist economy (e.g., Leontief 1936, 1941). More specifically, IO models illustrate how changes in one industry, such as increased production or consumption, affect other industries through a system of interconnected inputs and outputs, providing insights into the overall economic impact of alternative shocks and policies.

On the other hand, SFC models can be considered a specific class of system dynamics tools that replicate the functioning of a financially sophisticated economy (e.g., Godley and Lavoie 2007, Caverzasi and Godin 2015, Nikiforos and Zezza 2017). In the last decade, SFC models have gained traction in ecological macroeconomics too, due to their ability to integrate consistently and comprehensively the flows and stocks of the real economy, the financial sector, and the ecosystem (Dafermos 2017, 2018; Carnevali et al., 2019, 2020, 2023).

Due to the complexity of an integrated approach, only a few attempts have been made so far to include explicitly the IO structure of the economy into an SFC dynamic model (e.g., Berg et al., 2015, Valdecantos and Valentini 2017). However, progress has been made in recent years. Notably, Veronese Passarella (2022) has transformed a standard 'aggregative' SFC model into a model that disaggregates the economy both vertically (by social sectors) and horizontally (by production industries). The model is then used to analyse simple CE scenarios. More recently, Fevereiro et al. (2023) have expanded on Veronese Passarella (2022)'s analysis by applying it to a two-area economy. This extension explicitly considers the effects of international trade, supply-chain interdependencies, cross-border portfolio investments, and exchange rate fluctuations.

In Section 3.1, we outline the main features of the model. The complete set of accounting identities, equilibrium conditions, and behavioural equations is provided in the Appendix, while the identification of the model is discussed in Section 3.2. Alternative transition scenarios focusing on CE trajectories are outlined in Section 3.3, and thoroughly presented in Section 4.

[3] Methodology

[3.1] Model's features

We employ an empirically calibrated ecological open-economy input-output stock-flow consistent dynamic model to design and evaluate various CE policies and practices. The model has the following characteristics:

- First, the model is *dynamic*, allowing for reproducing the emerging behaviour of the system over time.
- Second, the model is *stock-flow consistent*, meticulously defining the relations between stocks and their related flows, expressed in monetary, real, and even physical terms.
- Third, the model has an *input-output* structure, accounting for cross-industry interdependencies in the production sector within each area and across areas.
- Furthermore, the model is an *open-economy* model, dividing the world economy into two areas: the European Union and the rest of the world.
- The model is also *ecological* as the relationships of economic and social variables with the ecosystem are explicitly modelled.
- Lastly, the *empirical calibration* implies that model's coefficients are calculated based on available time series data (e.g., technical coefficients) or defined to match current observed values of key variables (e.g., GDP components) for the two areas considered.

In formal terms, the model comprises a system of accounting identities and difference equations that describe the relationships between socio-economic sectors and between industries. Ideally, the model structure is subdivided into three major blocks, concerning the economy, the society, and the ecosystem, respectively.

[3.1.1] Economic and Financial Block

Each area consists of five domestic macroeconomic sectors: a) households; b) private production firms; c) the government sector; d) commercial banks; and e) the central bank. Each area shares the same pre-institutional economic structure, and there are no barriers to trade or restrictions on capital flows in the baseline scenario.

Households (equations A.1 in the Appendix, 1-5) receive both labour incomes (wages) and capital incomes (distributed profits, capital gains, and interest payments). They purchase a variety of services and consumption goods based on their disposable income and net wealth. In addition, they can acquire personal loans to fund the purchase of durable goods or to cover consumption exceeding their current disposable income. Households' net savings consist of cash (currency), bank deposits, domestic and foreign government bills, domestic and foreign shares. Their portfolio investment decisions are based on *Tobinesque* principles, as they depend on the relative return rates of financial assets and liquidity preference. Firms manufacture goods and services that are offered for sale in the market. As such, households' consumption is dependent on their disposable income and net wealth. Households consume a fixed proportion of their disposable income, and, as such, such consumption is assumed to be independent of changes in the interest rate. However, interest rate changes may affect consumption indirectly through its effects on net wealth.

To carry out their production, private firms (equations A.2 in the Appendix, 6-14) require labour (currently assumed to be homogenous by skill level), inputs (which will be consumed throughout the production process in each year) and fixed capital goods (purchased as final demand investment). Following the input-output structure, the model assumes the firms' production function with constant returns to scale, without substitution possibilities between factors of production (labour and fixed capital) and between inputs, in the baseline scenario. Firms in each sector use a single technology to produce a homogenous product. Private firms use a markup rule over costs to set prices. More precisely, they set industry-specific costing margins over their unit costs of production, including fixed capital costs. However, actual market prices are allowed to fluctuate above or below the prices of production if demand is higher than potential output.

Private firms demand for fixed capital determines real gross private investment (equations A.3 in the Appendix, 15-24). It is assumed that each industry has its own capital requirements and, as such, set a target stock of fixed capital which is dependent on the level of total output (i.e., firms target to keep a constant capital-output ratio). Moreover, fixed capital goods are assumed to depreciate at a constant rate. Therefore, in each period, industries must undertake a positive real private gross investment to keep the capital stock level adjusted to the target, even when total output remains constant. When total output increases, industries increase their real gross investment expenditure in order to gradually adjust their stock of capital goods to the target level. In order to fund its investment plans, private firms rely on amortisation funds (retained profits), loans (obtained from domestic banks) and issuance of shares (which can be bought by domestic and foreign households). Non-retained profits are then distributed as dividends to households.

Real government consumption (equations A.5 in the Appendix, 30-44) grows according to an exogenous rate, reflecting the political nature of the variable. Government also undertakes public investment, which is exogenous, and capital goods are assumed to depreciate at a constant rate, like it happens with private investment. Government can fund its expenditure based on revenue obtained from income taxes paid by households on their labour and non-labour income, VAT, import tariffs and any profits obtained by the central bank. The government issues government bills whenever it runs a budget deficit - meaning its spending is higher than its revenues. The interest rate on government bills is determined based on a mark-up over the policy rate set by the central bank, based on its monetary policy objective. Central banks are responsible for issuing the currency of each area and supply cash on demand, implying that they buy any government bills that the private sector does not wish to hold. In addition to domestic government bills, the central bank of zone-2 would also hold foreign bonds in its balance sheet.

Commercial banks (equations A.4 in the Appendix, 25-29) supply loans on demand, meaning that commercial banks are always ready to finance firms' production plans and to fund private investment and consumption expenditures, implying that there is no credit rationing. They pay an interest rate on deposits held by households. The interest rate on loans and deposits is also determined based on a mark-up over the policy rate set by the central bank, with interest rates charged on loans being set higher than those paid for deposits. When deposits collected by the banks may exceed those created by granting loans to the firms, commercial banks hold government bills as the asset counterpart of extra-deposits. Conversely, if loans exceed deposits, banks request (and obtain) advances from the central bank.

The baseline scenario involves four traditional industries (manufacturing, agriculture, services, and waste management), where three outputs (and waste) are produced using the same products as inputs; in the Circular Economy scenario, part of the waste is diverted to the recycling industry and is re-processed into inputs which substitute inputs originally obtained from traditional industries.

[3.1.2] Social Block

While households are treated as an aggregated sector, the model enables the tracking of income and wealth distribution dynamics, both pre- and post-tax. This distinction allows for the differentiation of policies and shock effects on income flows for wage earners and rentiers (equations A.6 in the Appendix, 45-52).

In this preliminary version of the model, the unemployment rate is a linear function of labour demand by production firms in each industry and area. The population, and consequently the available labour force in each area, is determined by an autonomous growth rate and net immigration inflow. Cross-area immigration, in turn, is influenced by three factors:

- the population size of the other area (larger population leading to a higher outflow of workers);
- the unemployment rate in the other area (higher unemployment motivating workers to leave their own area);
- the wage difference between the two areas (higher wages attracting workers from the other area).

Additionally, high-salary industries are assumed to be male-dominated (Blau and Kahn, 2017). This results in a tendency for female workers to be concentrated in lower-salary industries, even when other factors are equal. This threefold division of the labour force, albeit simplified, facilitates an intersectional analysis of social discrimination in relation to various shocks and policies.

[3.1.3] Ecological Block

The model includes a set of ecological equations that resemble those utilised in recent literature on ecological SFC models (see Dafermos et al., 2017, 2018; equations A.11 and A.12 in the Appendix, 82-104). Firstly, waste is generated in each industry during the production process. In the baseline scenario, traditional waste management is among the industries considered. However, when circular economy policies are implemented (as detailed in section 6), a recycling-reuse-repair industry is introduced as a one-off process innovation by changing the input-output coefficients accordingly (see Appendix A.13).

Secondly, another undesirable output of production is industrial CO_2 emissions. These emissions are contingent upon the quantity of non-renewable energy utilised. In turn, this non-renewable energy use is a direct linear function of the industry-specific energy-intensity coefficient, the industry's specific percentage of non-renewable energy, and a uniform CO_2 intensity coefficient of non-renewable energy.

Thirdly, the model gauges the impact of anthropogenic production on atmospheric temperature. This impact is determined by global CO_2 concentration in the atmosphere, the non-CO_2 fraction of total anthropogenic forcing, and the transient climate response to cumulative carbon emissions.

Fourthly, both matter and energy resources are depleted with the production of new goods (and services). The amount of matter extracted depends on both the produced output in each industry and the quantity of socioeconomic stock that is recycled in each period.[2] Likewise, energy from renewable sources can be regenerated periodically, whereas non-renewable energy becomes dissipated. Lastly, matter and energy reserves expand as new resources are converted into reserves and contract as natural reserves are employed for production purposes.

[3.2] Data collection and analysis

The model is coded and simulated in an *R* environment. Data have been retrieved from the EXIOBASE 3 database. More specifically we retrieved data from EXIOBASE 3 for the base year of 2011, which contains multiregional input-output data disaggregated for 164 sectors for 45 countries and 4 rest of the world regions 164 products. To make the data compatible with the model structure, the data was aggregated into two regions, European Union (defined as Zone 1) and the rest of the world (Zone 2); and to 5 sectors, namely Agriculture, Manufacturing, Services, Waste Management Services, and an aggregate CE sector[3]. The CE aggregated sector contains the 13 reprocessing manufacturing sectors (existent in EXIOBASE 164-sector disaggregation); the recycling of waste and scrap and recycling of bottles by direct re-use sectors[4].

From EXIOBASE 3, some variables were used to calibrate parameters regarding the structure of the economy. These include variables like technical coefficients, real wages, labour productivity which are essential to calculate unitary costs of production and, therefore, obtain production prices. We also take from EXIOBASE 3 sectoral shares in employment (with a sectoral breakdown by gender) and final demand components (such as private consumption, investment government consumption, exports and imports), and sectoral coefficient of CO_2 emission and material use.

[2] The socio-economic stock of each economy is here defined as the quantity of durable goods that are available for the society.
[3] The resulting Input-Output table for this disaggregation is presented in appendix B.2
[4] A table with translator bet ween EXIOBASE 3 164-sectors and the 5-sector disaggregation used are provided in Appendix B.1.

Other variables describing the overall size and composition of the economy (such as total output, GDP, final demand components and trade flows) were also taken from EXIOBASE but were used as targets to be reached in the calibration of the model baseline. The target values of these variables are presented in Table 1 below.

The remaining coefficients and variables have been calibrated. For this purpose, we identified a number of parameters and exogenous variables to be used as *instruments*. An evolutionary random-search algorithm was developed to assign values to those instruments in such a way as to minimize the gap between the values of endogenous variables under our model's baseline scenario – that is, our *targets* – and the observed data.

The remaining step in the empirical calibration of the model consists of finding a baseline set of instrumental variables $x_i$that ensure the steady state of the system is located on the expected values of target variables y_i for both regions 1 and 2 starting from initial conditions equal to zero. Table 1 shows the target values of a total of 14 variables, with 7 variables per region, shown in table 1. Initial balance sheets configurations (i.e. initial combination of stocks of assets and liabilities) can also be tested as instrument variables.

Table 1: Target variables values

	Consumption	Investment	Government	Exports of final goods	Imports of final goods	GDP	Gross Output
EU (Area 1)	626.32	245.77	239.46	102.78	66.36	1130.67	2153.60
RoW (Area 2)	2370.71	1135.84	675.33	66.36	102.78	4162.75	8424.52

Note: Values are expressed in €10 billion euros. Source: Author's own elaboration based on EXIOBASE 3.

Then, the goodness of fit R can be defined as:

$$R = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{y_i}{\langle y_i \rangle} - 1\right)^2$$

where y_i and $\langle y_i \rangle$ are the observed and expected values for target variables $i = 1, \ldots, N$, so that the goodness-of-fit ratio for variable i is

$$\frac{y_i}{\langle y_i \rangle}$$

with an expected value $\left\langle \frac{y_i}{\langle y_i \rangle} \right\rangle = 1$.

According to this definition, a better fit, with y_i are closer to expected values $\langle y_i \rangle$, has $\frac{y_i}{\langle y_i \rangle}$ ratios closer to 1; a lower value for R indicates a better fit, where $R = 0$ is the perfect fit. As a first step in the algorithm, an initial simulation $k = 1$ is run from a specific set of initial parameters and variables, x_1 and its goodness of fit R_1 is computed. Then, at each step k of the algorithm, a simulation is run slightly changing the initial set of parameters and variables from a random Gaussian distribution with average x_k and standard deviation σ as hyperparameters,

$$x_k = N(x_{k-1}, \sigma^2)$$

computing new goodness of fit R_k. Then, the algorithm accepts the new set of parameters of values x_k if the goodness of fit improves (being $R_k < R_{k-1}$) and proceeds to the next iteration $k + 1$, until the goodness of fit reaches a reasonable and satisfactory value for the particular target variables. New target variables of interest can be added in order to further expand and sophisticate the goodness of fit. Figures 1 and 2 visualize a particular sample run of the random-search algorithm for the instrument variables x_k to stabilize the government deficit and public debt, which added initial values of the balance sheet to the instrument variables. With this process, we find empirically meaningful and realistic baselines on which the experiments can be conducted. Additional constraints have been applied to ensure the realism of values attributed to instruments and the achievement of a quasi-steady-state condition at the period the economy is shocked by the implementation of CE related policies, such as, for example, restricting marginal propensity to consume out of profits and out of wealth to values below the marginal propensity to consume of workers ($\alpha_1 > \alpha_2 > \alpha_3$) (Kaldor, 1955-56).

Figure 1: Calibration of instruments

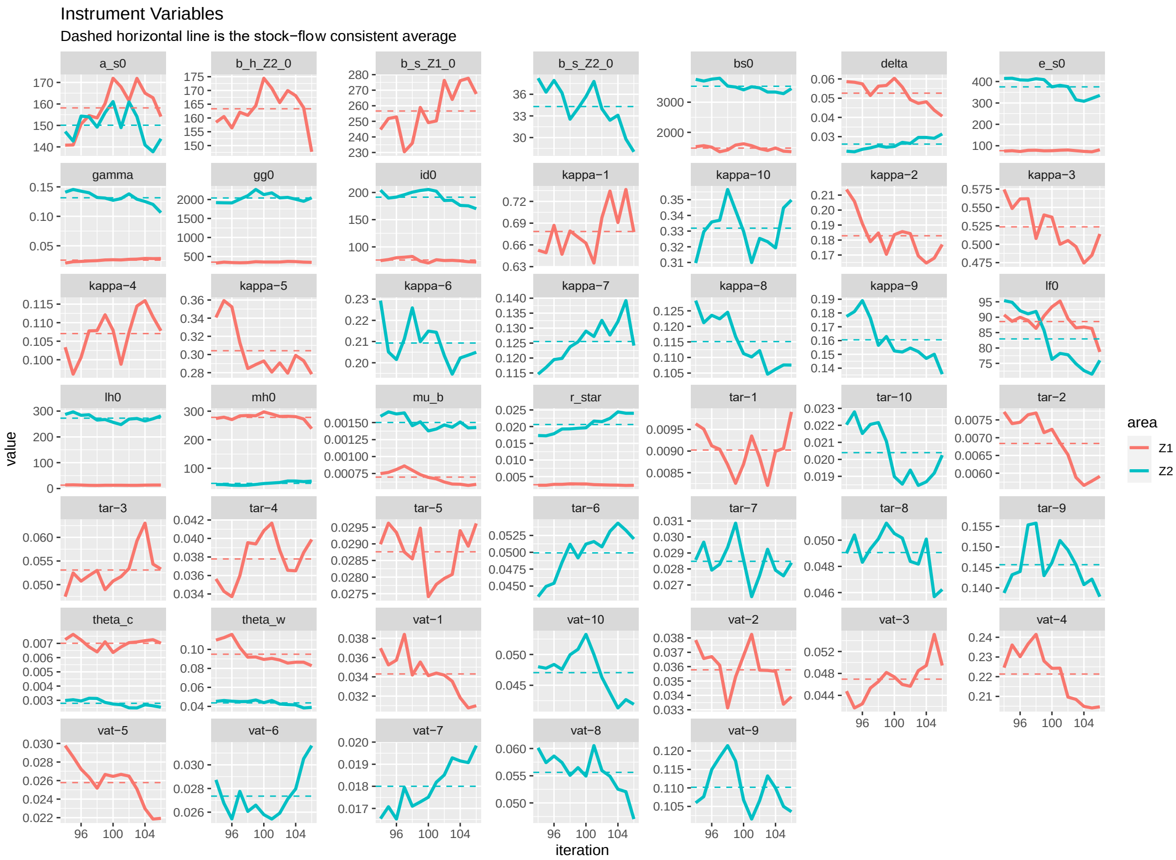
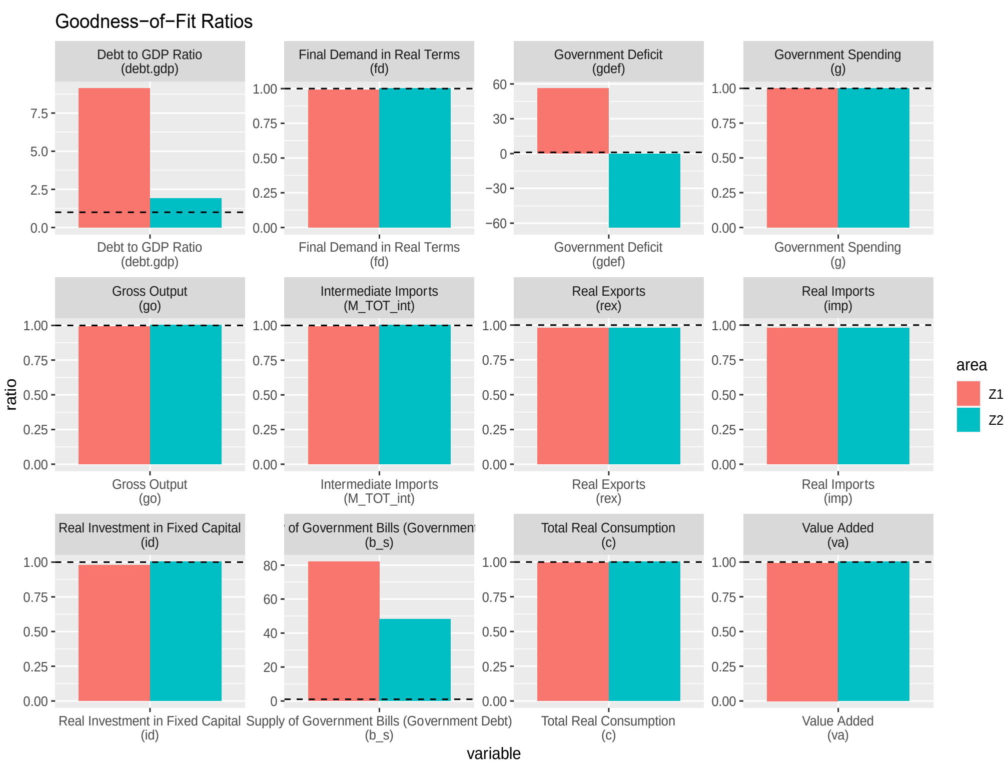


Figure 2: Goodness-of-fit ratios for selected targets



Before implementing a policy scenario analysis, it is essential to stabilize the model, ensuring that no further changes occur in relevant variables such as GDP, total output, current account balance, and government deficit. At the same time, it is necessary to obtain economically relevant values for non-targeted variables, verify the stability of balances between institutional sectors (households, non-financial corporations, banks, government, and central bank), and ensure coherence in stock-flow norms of variables analysed within the Balance Sheet and TFM tables (included in Appendix B.1). This ensures that the outcomes of shocks are not influenced by ongoing trends but can be attributed solely to the effects related to the scenario shock.

To achieve this, parameter values are further adjusted to balance calibration fitness and model stability. Table 2 presents the target ratios used in the model simulations. Overall, the model demonstrates a good fit to observed values for the selected variables, with an overall fitness value of 0.02. However, there is room for improvement with additional work. Specifically, the fit of investment in both regions can be enhanced, as the current model calibration generates only 74.9% of the observed total (private + public) investment for the EU (Zone 1) and 70.2% for the rest of the World (RoW, Zone 2) compared to the values in the EXIOBASE 3 input-output tables.

Additionally, consumption in the EU is currently being overestimated in the model calibration (117.2% of the target value), leading to a slight overestimation of EU imports of final goods (108.3%). While the fit of Gross Output for the EU is satisfactory (101.5%), there is a slight underestimation for the Rest of the World, with the model estimating only 90.9% of the observed value. This discrepancy has implications for the estimation of total employment and environmental impacts in the model baseline, which will consequently be slightly underestimated in the initial period of the shock.

Table 2: Target ratios of the calibration relative to observed values (2011)

	Consumption	Investment	Government	Exports of final goods	Imports of final goods	GDP	Gross Output
EU (Area 1)	1.172	0.749	1.000	0.997	1.083	1.164	1.015
RoW (Area 2)	0.998	0.702	1.000	1.083	0.997	1.055	0.909

Note: A value of 1 indicate that in period 75 (when the policy shocks are introduced) the size of the economy projected by the model is equal to the data retrieved.

To initialize the model, a shock to an exogenous variable is selected to initiate the model. In our case, government consumption and investment were chosen, constituting 100% of government consumption and 20% of total investment targets in each area. In the baseline scenario, this generates a 20% debt-to-GDP ratio for the EU, while the rest of the world has a debt-to-GDP ratio of 15%. This is lower than the current observed stock of debt (for example, the overall debt-to-GDP ratio of European Union countries, which has fluctuated around 80% in the past decade before the pandemic). Therefore, this aspect requires further attention in subsequent rounds of model calibration and scenario analysis, to be conducted in the next few months.

[3.3] Baseline and alternative scenarios

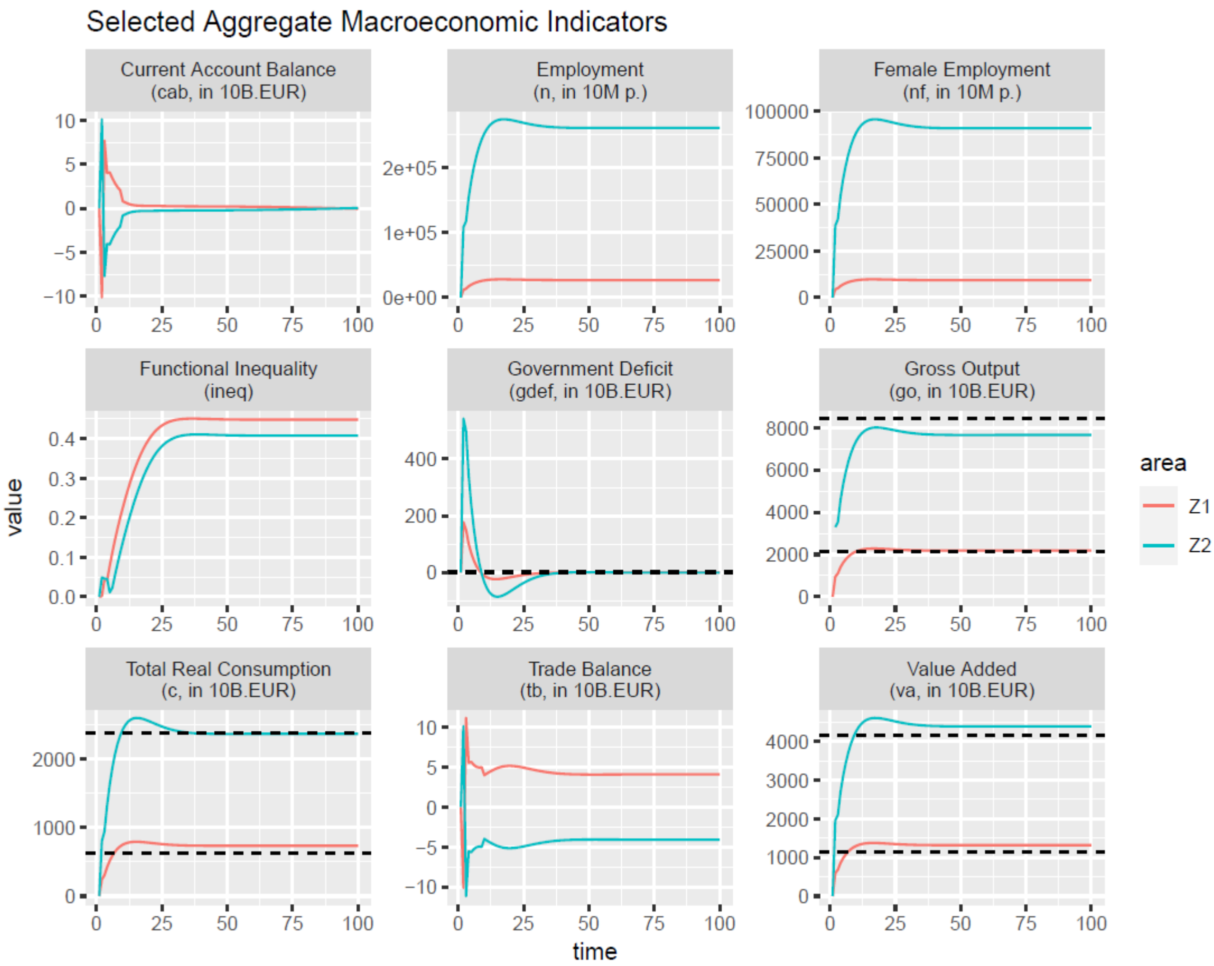
Figures below depict a specific simulation run displaying a rapid dynamic transition to the steady state, with the model stabilising after 30 periods. The figures also illustrate a reasonable goodness of fit for the target variables in both regions, as well as selected aggregate economic indicators. Additionally, industry-level labour-market indicators, including empirical values for gender employment shares, and empirically calibrated ecological indicators are included. Monetary variables are denoted in tens of billions of euros.

Figures 3 to 5 present the results for the calibrated baseline of selected macroeconomic, labour market, and ecological indicators. All monetary units are expressed in €10 billion. Figure 3 displays: (i) the current account balance between the two regions (Zone 1 representing the EU and Zone 2 the rest of the world); (ii) total employment; (iii) female employment, (iv) functional income inequality[5], (v) government deficit; (vi) gross output; (vii) total real government bills (government debt stock); (vii) total real consumption; (viii) the trade balance; and (ix) the value added. Figure 4 presents the results for

[5] Calculated as the 1 minus the ratio between workers and capitalist disposable income: $ineq = |1 - \frac{yd_w}{yd_c}|$

the calibrated baseline of labour market indicators, including (i) total employment, (ii) female employment, (iii) the size of the labour force (all expressed in 10 million people), and (iv) the total wage bill. In Figure 5, we track the evolution of the following indicators: (i) Annual CO_2 emissions (in 10t CO_2 equivalent); (ii) CO_2 concentration (in 10t CO_2 equivalent); (iii) energy required for production (10000eJt); (iv) extraction of matter (in 10Mt); (v) non-renewable energy used (10000eJt); (vi) recycled matter (in kt); (vii) renewable energy (10000eJt); (viii) Socio-Economic Stock (in 10Mt); (ix) waste produced (in 10Mt). Once the model baseline is empirically calibrated, CE policies can be simulated to assess their impact on economic, social, and ecological indicators.

Figure 3: Simulation of selected macroeconomic indicators.



Note: Dashed horizontal line corresponds to the target values.

Figure 4: Simulation of industry-related labour market indicators

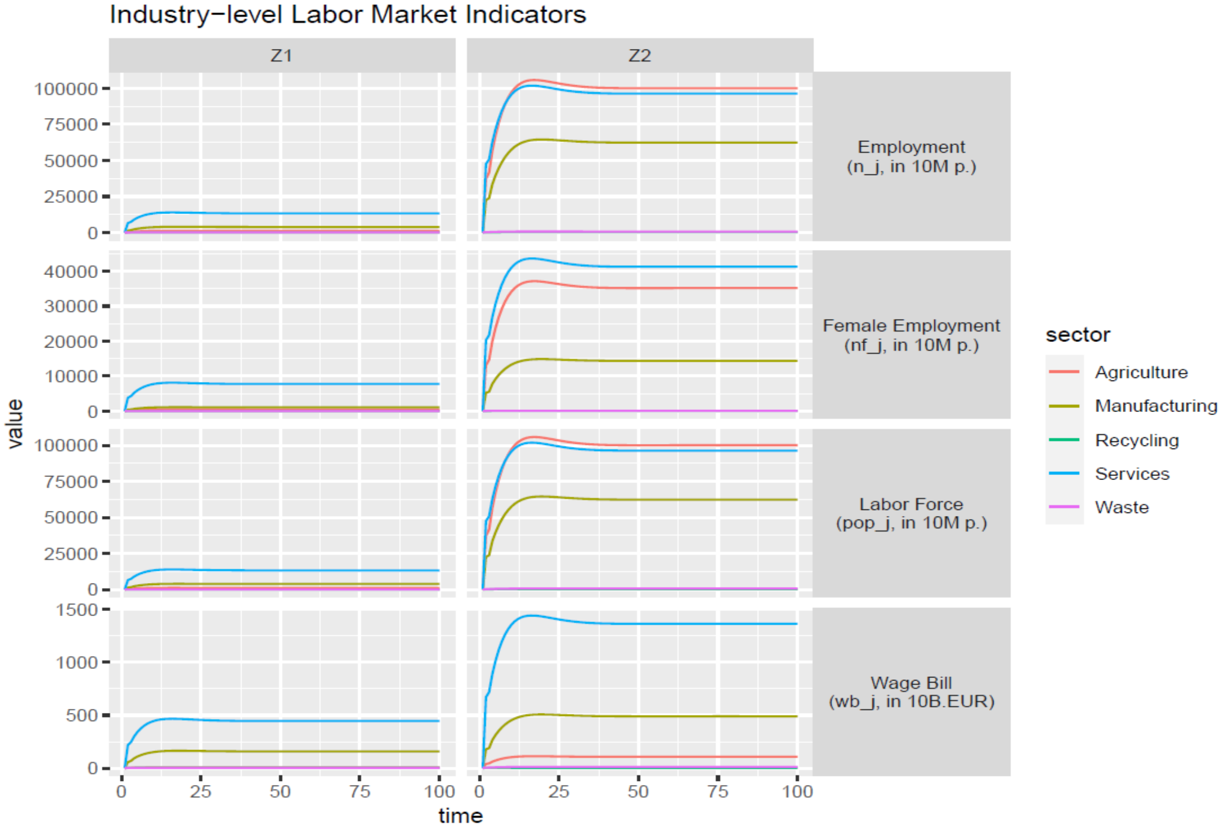
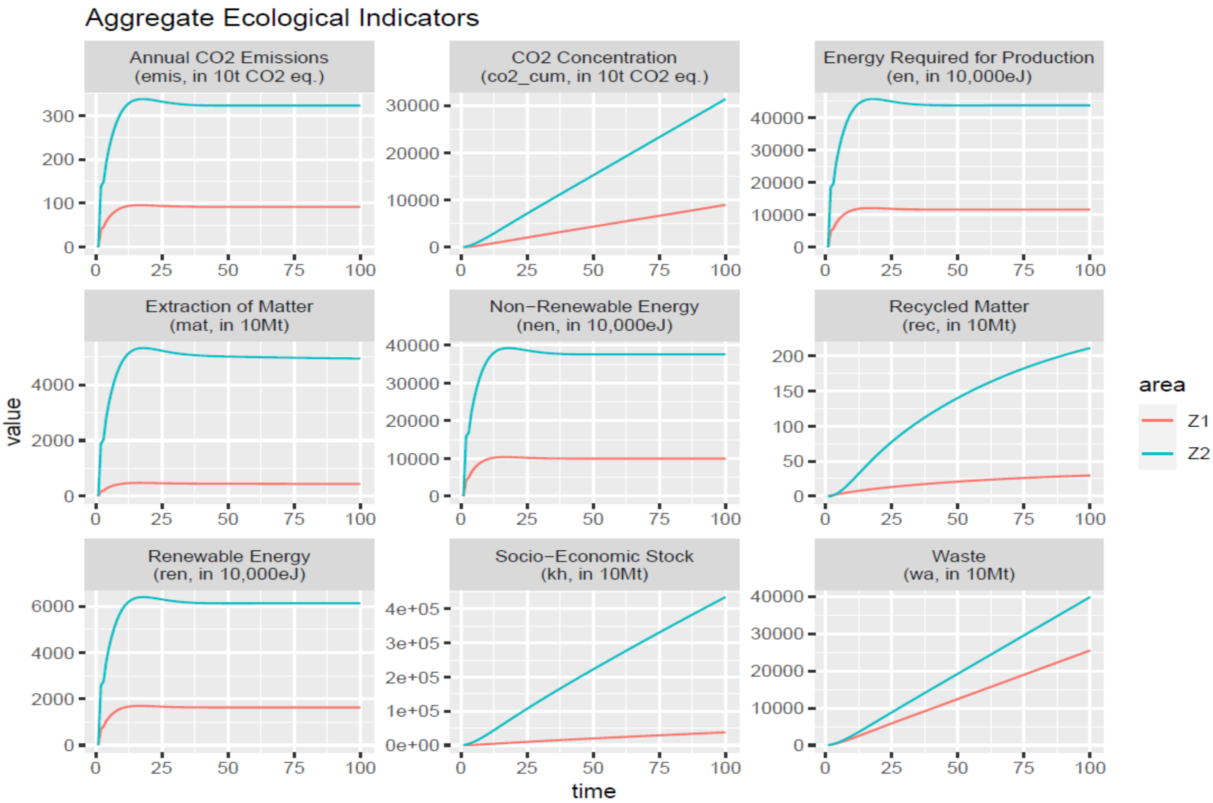


Figure 5: Simulations of ecological indicators



At the current stage, a table of CE experiments that can be conducted in the model is provided in Table 3. It is divided into three categories: private practices by households and firms, direct government policies, and indirect CE effects from other practices and policies. All scenarios, unless indicated otherwise, are implemented in Zone 1, the European Union, with a common shock intensity S for all shocks. For each alternative scenario, the absolute difference and percentage difference between the value of selected variables under the baseline scenario and their value under the alternative scenario at the end of the simulation are computed, providing descriptive informative statistics of the impacts of CE policies and practices on macroeconomic, social, and ecological indicators.

Scenario 1.1 aims to achieve a reduction in consumption level by reducing the marginal propensity to consume out of wages (α_1), profits (α_2) and wealth (α_3). This aligns with a 'post-growth' strategy. Scenario 1.2 involves the effects of continuous structural change towards the service sector, changing the sectoral shares in the final consumption vector ($\Delta\beta_i$).

In scenario 1.3, to test impacts of product life extension (PLE), we increased the depreciation rate (δ) of capital goods. This implies a lower investment and, without ancillary changes in higher expenditure in R&D investment or higher spending in consumption of repair services by firms, is expected to lead to lower final demand and income. Scenario 1.4 involves a substitution of primary inputs for recycled, re-processed or remanufactured inputs, by increasing (decreasing) input-output coefficients of CE (other) inputs ($\Delta a_{CE,j}\ and \downarrow a_{i,j}, for\ i \neq CE$). As such, this can be classified as a closing the supply loop (CSC) strategy.

Scenarios 1.5 and 1.6 involve 'resource efficiency' measures. Scenario 1.5 implies a higher propensity to consume green products and services through a reduction in waste coefficients (ζ), which involves higher efficiency in packaging and discarding of other inputs materials. Scenario 1.6, which corresponds to a lower extraction rate of matter, involves fewer raw materials being used per unit of output ($\downarrow \mu_{\mathrm{mat}}$). However, this requires further elaboration with a counter-shock explaining how this change in technology is determined, which should involve increased expenditure in R&D.

Scenario 1.7, representing a lower discarding rate of socio-economic stock, can be also related to a product lifetime extension (PLE) CE strategy, but it acts on durable consumption goods. However, a compensating increase in demand for repair and maintenance services still needs to be implemented in order to achieve more realistic results. Scenario 1.8 is related to the energy sector, involving an increase in the share of renewable energies in energy generation. However, as the energy & electricity sector is not disaggregated at this current stage, the input structure does not change.

Scenarios 2.1 and 2.2 involve government fiscal policy. Higher government spending towards efficiency (Scenario 2.1) also entails a substitution of primary inputs for recycled, re-processed, or remanufactured inputs, but this is now a consequence of increased government expenditure ((Δg). Scenario 2.2 involves a change in the composition of government expenditure towards the circular economy sector. Lastly, scenario 3.1 involves increased taxation on distributed profit income. It can be combined with other shocks to provide a source of funding for other initiatives.

Table 3: Alternative scenarios and shocks

No.	Scenario	Shock
1	**CE practices by households and firms**	
1.1	Reduction in consumption level	Fall in propensities to consume $\alpha_1, \alpha_2, \alpha_3$
1.2	Change in consumption composition towards services	Increase in consumption share of services β_s at the expense of manufacturing β_m
1.3	Product lifetime extension	Fall in depreciation rate δ for capital goods
1.4	Higher recycling rate	Higher input-output coefficients $a_{CE,j}$
1.5	Higher propensity to consume green	Fall in waste coefficients ζ
1.6	Lower extraction (or conversion) rate of matter	Fall in μ_{mat}
1.7	Lower discarding rate of socio-economic stock	Fall in percentage of durable consumption goods discarded ζ_{DC} by households
1.8	Higher renewable energy share	Increase in η_{en}
2	**Direct CE policies by the government**	
2.1	Higher government spending towards circular economy efficiency	Increase in g, and CE transition to B matrix with smaller IO coefficients
2.2	More selective government spending towards circular economy efficiency	Increase in σ_{CE}
3	**Indirect effects on CE from other practices and policies**	
3.1	More progressive taxation	Increase in θ_c

Source: author's own elaboration

The list of scenarios for the transition to a circular economy is clearly not exhaustive and represents a first attempt to deal with a set of plausible transition trajectories. Modelling some of the scenarios can be further improved by introducing ancillary changes to enhance comparability with other scenarios tested in studies reviewed in literature in section 2. Additionally, combining them with other compensatory policies (e.g., working time reduction, basic income, and/or industrial policies) could be beneficial. Moreover, further CE shocks (and combinations of existing ones) may also be explored, including, for instance:

- A higher portfolio share of equity issued by firms producing green or CE-friendly products (e.g. based on average recycling rate of firms in each area, etc.).
- Selective value-added tax favouring green or CE-friendly products or industries (e.g. based on the recycling rate).
- Selective import tariff tax favouring green or CE-friendly products or industries (e.g. based on the recycling rate).
- Gender rebalancing policies, to be implemented through government spending.
- Changes in immigration flows, population growth rate, and interest policy rate.
- Limits on waste to be landfilled and/or landfills capacity.
- Introduction of specific CE sub-industries (such as 'repairing' or 'sharing') and changes in their input-output coefficients.
- Government spending aimed at reducing matter and energy intensity ratios.

[4] Findings

[4.1] Key results

In general, CE policies generate small negative impacts on value added, with a few exceptions such as a reduction in consumption level in the EU or a shift in consumption towards services, which increases value added. The former can be attributed to wealth effects leading to higher consumption in the long run, while the latter is associated with lower import coefficients related to the consumption of services relative to agriculture and manufacturing. Consequently, higher value added in the EU comes at the expense of lower value added in the rest of the world.

Environmental impact results, such as CO_2 emissions and material extraction, tend to correlate with economic activity and, therefore, decrease in most scenarios in both areas. An exception is scenario 1.2 (Change in consumption towards services), where there is a small decrease in CO_2 emissions and material extraction in the EU, despite the increase in value added.

In terms of employment, CE policies also generate small negative impacts, consistent with the decline in economic activity. Exceptions are CE policies involving a shift towards the use of recycled, reprocessed, or remanufactured inputs in production (scenario 1.4 and 2.1), where employment increases despite the decline in value added. This is due to the production processes in these activities, which are traditionally more labour-intensive than in traditional sectors. Female employment levels generally follow the same direction of change as overall employment, albeit with smaller positive or negative changes relative to changes in total employment. Scenario 1.2, where the transition of consumption towards services occurs, is an exception to this pattern. Despite the overall decrease, female employment in the EU actually improves, as women tend to be more represented in service rather than manufacturing employment. This demonstrates the positive economic effects of CE policies oriented towards the care economy and social reproduction.

Changes in functional income inequality are measured as one minus the ratio between workers' disposable income and capitalists' income, indicating the gap between the disposable incomes of the two classes. Reductions in this ratio imply a reduction in inequality. In the EU, functional income inequality decreases in scenarios 1.1 to 1.4, as well as in 2.1, but increases in cases of more selective government and more progressive taxation scenarios. In the rest of the world, there are either no impacts or minor increases in income inequality.

Regarding government deficit and current account balance, results indicate a worsening situation for the rest of the world. This is particularly concerning for countries in the Global South, considering ample empirical evidence that the major binding constraint for their development is the balance-of-payments one. In these circumstances, if a country is unable to generate enough foreign currency from exports and foreign direct investment to meet its import and financial outflow requirements, a balance-of-payments crisis may be triggered, especially in countries that already experience large structural trade deficits. This issue is acute in low-income and developing economies, as government debt is typically denominated in foreign currency, creating a vicious cycle between exchange rate devaluation and increases in public debt relative to GDP for affected countries.

Specific private adoption of CE practices among firms and households, simulated in scenarios 1.5 to 1.8, have almost no macroeconomic effect, with limited reduction in environmental impacts. For instance, a higher propensity to consume green or CE-friendly products (scenario 1.5) induces only a reduction in waste. Similarly, a lower extraction rate of matter (scenario 1.6) reduces the amount of waste produced, but also reduces recycled matter. Scenario 1.7, a lower discarding rate of socio-economic stock, also reduces the amount of recycled matter. A higher share of renewable energy (scenario 1.8) shifts energy consumption from non-renewable to renewable sources, resulting in reduced emissions. A more progressive taxation, in the form of an increase in the capital income tax, improves income distribution and emissions, but also reduces employment.

Figures below show the percentage and absolute differences between the value under the baseline scenario and the value under the alternative scenario for selected macroeconomic, social, and ecological indicators. Overall, government-spending policies generally fare better in terms of employment, ecological impact, and international inequality than private changes in behaviour among firms and households, especially in consumption. For instance, private reduction in consumption in the European Union has the most negative effect on employment, especially in the rest of the world, including female employment. Only capitalists disposable income benefits ; when the shock is implemented, due to an increase in wealth, worker disposable income decreases and then increases only to gradually recover its original value. A change in consumption shares towards services also has a negative effect on employment in general, but to a lower extent. However, under this scenario, a better performance across ecological indicators can be observed.

Instead, when the government induces a transition to CE through spending (scenario 1.4, recycling rate increase, Z1_ce = 1), employment increases, especially in the CE-related sectors. Direct government policies, especially oriented towards spending, also compared to indirect policies, are the best in terms of employment, either in absolute terms (higher government spending) or relative (more selective government spending). Most, if not all, CE policies reduce gross output both in absolute and relative terms, which has a positive impact on ecological indicators but a negative impact on employment. However, this can be compensated with more value added and employment accompanied by more selective government spending in the context of the CE transition. Some CE policies, such as a lower discarding rate for socio-economic stock or extraction of matter, have a much more exclusive impact on ecological indicators. We see evidence of a rebound effect in the context of the CE transition, as it improves resource efficiency.

Figure 6: Summary of percentage differences with baseline scenario by shock

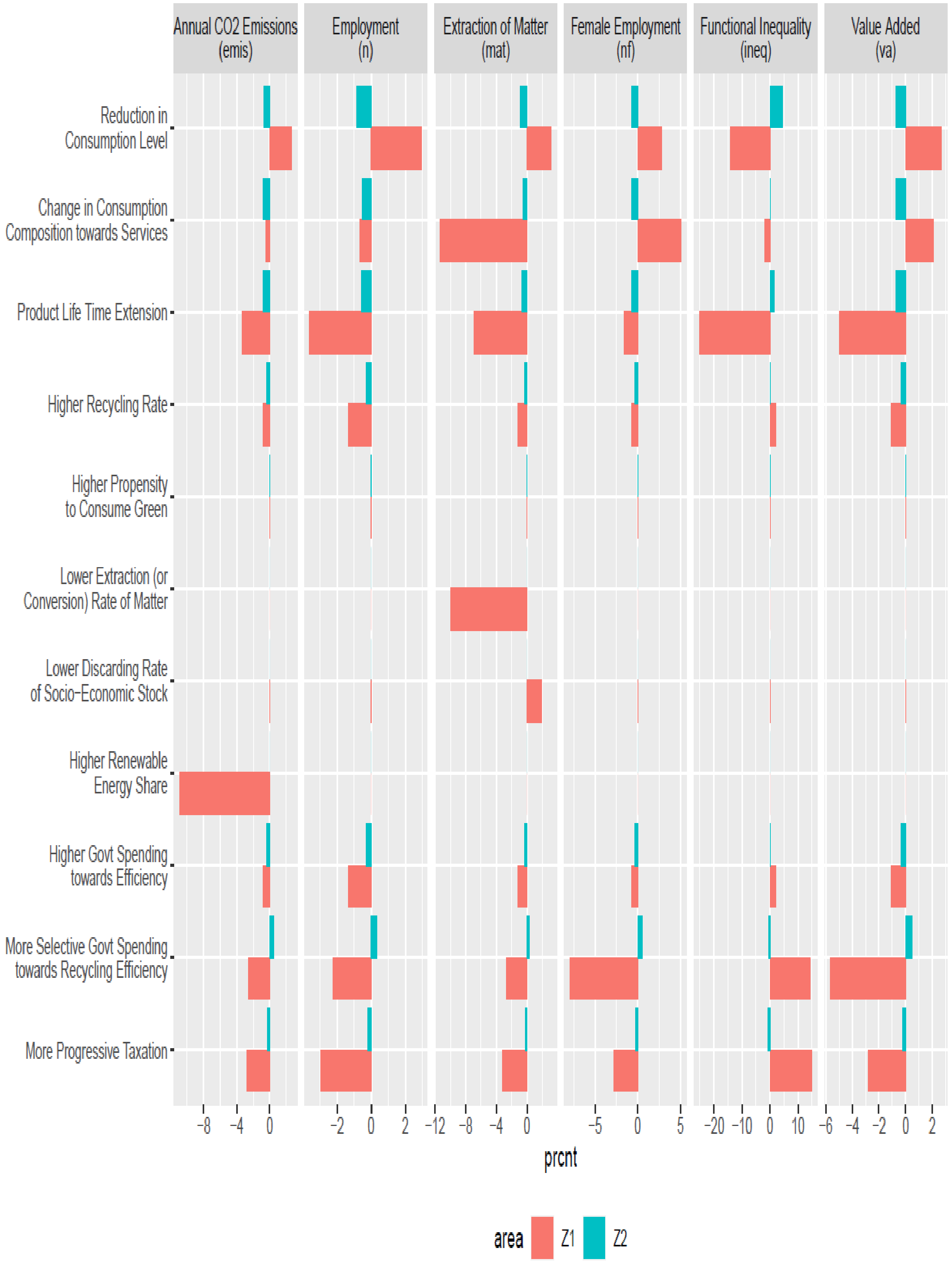
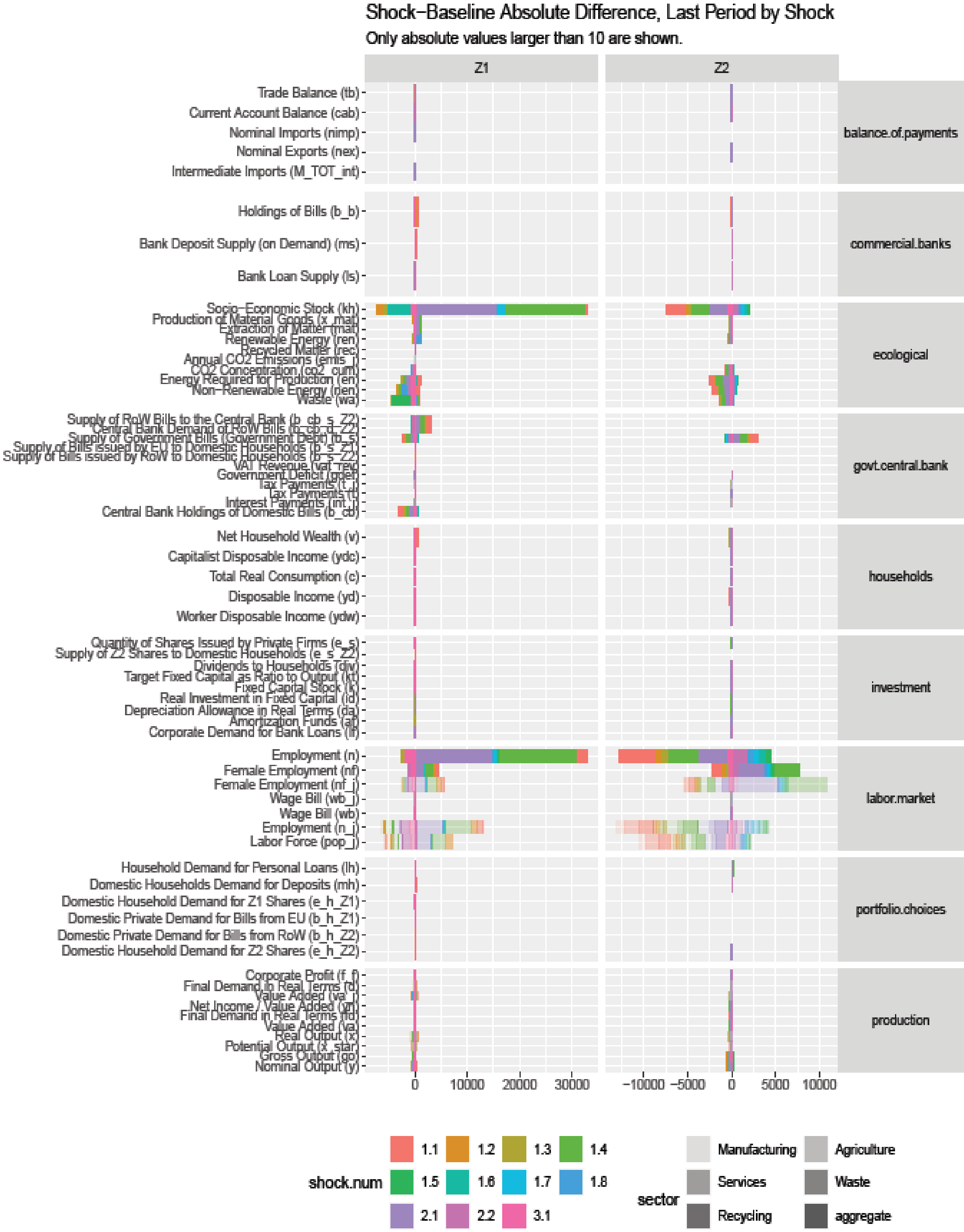


Figure 7: Summary of absolute differences with baseline scenario by shock



[4.2] Discussion of results of specific scenarios

In this section, we delve into more detail on some of the main results of selected scenarios and the associated shocks (1.1, 1.2, 1.3, 2.1, 2.2, and 2.3). Specific private adoption of CE practices among firms and households, simulated in scenario 1.5 to 1.8, have almost no significant impacts. Therefore, their results are not discussed in detail here. A comprehensive compilation of the results of all shocks on various selected macroeconomic, labour market, and environmental variables is included in Appendix C.

Scenario 1.1 – Reduction in the consumption level in the European Union

Initial results indicate that a reduction in consumption due to private CE practices (Scenario 1) induces a rebound effect in Zone 1 (European Union), leading to an ultimate increase in value-added and employment by 2.7% and 2.75%, respectively, after experiencing an initial negative scenario. Due to this rebound effect, ecological impacts, such as CO_2 emissions (+2.4%) and total material extraction (+2.3%), also increase. European Union imports eventually increase over the baseline, worsening its trade balance with Zone 2 (Rest of the World), shifting from an initial surplus to a deficit. Nevertheless, the accumulated net foreign assets by the EU in the transition lead to a continuous deterioration of the current account balance of the Rest of the World (1.1% of GDP), with its government deficit increasing to 1.2% of GDP.

Scenario 1.2 – Shift in consumption composition towards services in the EU

In turn, the shift of consumption shares from manufacturing to services (Scenario 2) induces no significant rebound effect in the EU. However, value-added increases by 2.1%, while employment is 0.5% lower relative to the baseline. These shocks negatively affect the rest of the world economically, as value-added (-0.7%), employment (-0.5%), and government deficit (-1.1% of GDP) are relatively worse than in the baseline. The shift towards services in the EU reduces its imports, leading to an emergent trade surplus (deficit) for the EU (rest of the World). While the EU (rest of the World) trade surplus (deficit) eventually stabilizes at 0.7% of GDP, the current account does not, continuously increasing for the European Union due to increasing interest payments received on its (increasing) holdings of net foreign asset (NAFA). However, the rebound effect in terms of ecological impact is minimal because of the generally smaller impact of services over manufacturing on material extraction and pollution. Despite falling in aggregate figures, female employment in the EU actually improves, as women tend to be more represented in service rather than manufacturing labour markets.

Scenario 1.3 – Product life extension (of capital goods) in the EU

Product life extension of capital goods, implied by a reduction in the depreciation rate, leads to lower investment in the steady state. Without introducing ancillary changes in the intermediate demand for repair and maintenance services (with or without functional upgrading), there is an overall reduction in total output and economic activity. In the EU, value-added is 5% lower than the baseline, while in the rest of the world, it is 0.7% lower. Employment levels are also lower in both regions, with a decrease of -3.6% in the EU and -0.6% in the rest of the world. The reduction of EU's import demand from the rest of the world leads to an increasing current account surplus (deficit) for the EU (rest of the world), which, at the end of the simulation period, reaches 1.2% (-0.4%) of the region's GDP. Lastly, this CE strategy leads to a significant reduction in environmental impacts, with CO_2 emissions falling by -3.4% and material extraction by -6.9%. Another issue to consider is the impact of lower turnover of the capital on productivity. Considering that technical progress, in many circumstances, is embedded in new generations of machine and equipment vintages, the lower investment could be associated with lower growth in productivity. This could have a detrimental impact on the system; these issues should therefore be taken into account in further analyses of this scenario.

Scenario 2.1 – Higher government spending enhancing circularity in the EU

Scenario 2.1 involves an increase in government expenditure compared to scenario 1.4. Although smaller, there remains a minor negative impact on the EU's value-added (-1.1%), total employment (-1.3%), and female employment (-0.7%). Moreover, there is a reduction in environmental impacts relative to the baseline, with a decrease of -0.8% in CO_2 emissions and -1.1% in material extraction. For the rest of the world, value added reduces marginally (-0.3%) relative to the baseline, as it exports fewer material inputs to the EU. This leads to a reduction in emissions and material extraction as well; however, it also results in an emergent current account deficit of 0.3% of GDP at the end of the simulation period.

Moreover, the rest of the world also experiences negative socio-economic outcomes, with reductions in total and female employment (approximately 0.3% each) and a modest rise in income inequality.

Scenario 2.2 – More selective government spending enhancing circularity in the EU

The government-led circular economy transition can also involve an increase in government spending on circularity, making it more selective (Scenario 2.2). In this case, socio-economic effects are negative for the EU, with lower value-added (-5.7%) and employment (-2.3%). This can be attributed to the fact that the circular economy has fewer linkages with other sectors, demanding fewer inputs from other sectors than traditional linear economy sectors, and thus eliminating several indirect jobs created through government expenditure relative to the baseline. In line with the lower economic activity, environmental impacts are also lower (-2.6% in emissions and -2.7% in material extraction). Despite this, the EU would also experience a worsening of the current account balance to 0.8% of GDP. Conversely, the rest of the world in this case would observe minor positive impacts on socio-economic variables such as value-added (0.5%), employment (0.4%), and current account balance, combined with increasing environmental impacts, in line with the macroeconomic variables.

Scenario 3.1 – More progressive taxation in the EU

The introduction of a more progressive taxation leads to lower value-added (-2.8%) and employment (-3.0%), with a greater decline in the disposable income of workers than in capitalists, resulting in worsening functional inequality, contrary to expectations. This is likely related to wealth effects dominating the dynamics of the model in the long run, similar to what is observed in scenario 1.1. Therefore, this should be the subject of further investigation through sensitivity analysis, which involves analysing the effect of the shock under alternative combinations of parameters regarding marginal propensity to consume and portfolio equations. Although significantly smaller, the socio-economic impacts in the rest of the world are also negative, with the exception of income inequality, which improves slightly. While there are lower environmental impacts in both regions in terms of CO_2 emissions and material consumption (-2.7% and -3.2%, respectively, in the EU; and -0.3% and -0.2% in the rest of the world).

Limitations of the analysis and next steps of the research

Our model features a 5-sector disaggregation within a 2-region input-output structure. While this represents a significant advancement compared to single-sector SFC models that produce homogeneous outputs, our results still suffer from aggregation bias. This bias arises from bundling together sectors with vastly different characteristics regarding labour, material, and emissions intensities, as well as input demand structures. Similarly, the aggregation bias applies to the regional disaggregation of the model, where countries with varying levels of economic development and patterns of specialisation are grouped within the 'rest of the world' region. Therefore, future research efforts should prioritize increasing both the sectoral and regional disaggregation of the model. Additionally, there is room for further improvement in the calibration fit to empirical values. This would lead to better estimations of socio-economic and environmental impacts.

As discussed, these scenario results are preliminary. It is essential to explore combinations of some of the shocks presented here and introduce ancillary changes to enhance comparability with scenarios tested in other studies covered in the literature review. Furthermore, comparing scenarios where CE policies are adopted in both regions to scenarios where only the EU implements them, as discussed in this report, is crucial. Moreover, each scenario's analysis should be extended to incorporate more thoroughly the impacts of different CE strategies on immigration, functional income inequality, and gender balance in each area.

[5] Final Remarks

We employed an empirically calibrated two-area input-output stock-flow consistent model to design and evaluate various circular economy (CE) policies and practices. Specifically, our model aimed to assess the impact of these policies and practices on economic, social, and environmental variables. Our experiments lead us to the conclusion that while a shift in the behaviour of households and private businesses is necessary, it is insufficient for achieving a just green transition.

Specifically, our results reveal that CE policies generally generate small negative impacts on value added, although there are exceptions (such as reductions in consumption levels in the EU or shifts towards service consumption, which can increase value added). These findings underscore the importance of considering specific contexts and policy measures when evaluating the economic impacts of CE initiatives.

Moreover, our findings highlight the correlation between environmental impact and economic activity. CE policies tend to decrease CO_2 emissions and material extraction in most scenarios, indicating their potential to contribute to environmental sustainability. However, the effectiveness of these policies varies depending on factors such as consumption patterns and production processes.

In terms of employment, CE policies generally result in small negative impacts, consistent with the decline in economic activity. However, certain policies, such as those involving a shift towards the use of recycled inputs in production, may lead to increased employment despite declines in value added. Additionally, the positive economic effects of CE policies oriented towards the care economy and social reproduction, particularly for female employment, are highlighted.

Furthermore, the results shed light on changes in functional income inequality, government deficit, and current account balance resulting from CE policies. These findings emphasise the need for careful consideration of the distributional and macroeconomic implications of CE initiatives, particularly for countries in the Global South.

Overall, the results highlight the importance of government intervention and policy coordination in achieving a just green transition. While private sector behaviour plays a role, public intervention is essential to address market failures and ensure equitable outcomes across economic, social, and environmental dimensions.

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JUST2CE
A Just Transition to Circular Economy

Appendix A– Memo: Model Equations

This section is largely derived from the Appendix of JUST2CE deliverable D5.1 (refer to Fevereiro et al., 2023). Nonetheless, some modifications have been implemented to align the system of difference equations and their presentation with the updated version of the model utilised for the scenario analysis discussed in this document.

[A.1] Households

If we use the superscript z to define each area and f to define the other area (that is, the foreign sector), households' domestic consumption in real terms is:

$$c^z = \alpha_1^z \cdot \frac{YD_w^z}{E(p_A^z)} + \alpha_2^z \cdot \frac{YD_c^z}{E(p_A^z)} + \alpha_3^z \cdot \frac{V_{-1}^z}{p_{A,-1}^z} \quad (1)$$

where p_A^z is a consumer price index, while α_1^z, α_2^z and α_3^z are the propensities to consume out of disposable labour income (YD_w^z), disposable capital income (YD_c^z) and net wealth (V^z), respectively.[6]

Disposable income is net domestic incomes from firms and banks *plus* received interests on bank deposits and government debt *plus* capital gains on holdings of foreign bills and shares *minus* taxes and interest payments on personal loans:

$$\begin{aligned} YD^z \; &= WB^z + DIV^z + FB^z + \\ &+ r_{m,-1}^z \cdot M_{h,-1}^z + r_{b,-1}^z \cdot B_{s,z,-1}^z + xr_{-1}^f \cdot r_{b,-1}^f \cdot B_{s,z,-1}^f + \\ &+ \Delta xr^f \cdot (B_{s,z,-1}^f + E_{s,z,-1}^f) + \\ &- r_{h,-1}^z \cdot L_{h,-1}^z - T^z \end{aligned} \quad (2)$$

where WB^z is the wage bill, DIV^z is distributed profits of firms, F^z is bank profits (which are assumed to be fully distributed), r_m^z is the interest rate paid on bank deposits (M_h^z), r_b^z is the interest rate on domestic government bills held by domestic households ($B_{s,z}^z$), xr^f is the nominal exchange rate,[7] r_b^f is the interest rate on foreign government bills held by domestic households ($B_{s,z}^f$), $E_{s,z}^f$ is domestic holdings of foreign shares, r_h^z is the interest rate on personal loans granted to domestic households (L_h^z), and T^z is income tax payments.

More precisely, disposable labour income in each area is:

$$YD_w^z = WB^z \cdot (1 - \theta_w^z) \quad (3)$$

where θ_w^z is the average tax rate on income.

$$YD_c^z = YD^z - YD_w^z \quad (4)$$

Total disposable capital income is:

Net private wealth accumulated in each area is:

$$V^z = V_{-1}^z + YD^z - c^z \cdot p_A^z \quad (5)$$

The stock of wealth increases as households save. Portfolio decisions (that is, the way in which net wealth is held) are discussed in the subsection A.7. Consumption composition is discussed in the subsection A.2.

,[6] Purely adaptive price expectations are assumed in the baseline scenario, so that: $E(p_A^z) = p_{A,-1}^z$. Besides, the impact of the so-called 'inflation tax' on real disposable income is ignored.
[7] Exchange rates are quoted indirectly. As a result, xr^z is the price of one unit of domestic currency expressed in foreign currency, whereas, for the 'home' area, xr^f is the price of one unit of foreign currency expressed in domestic currency.

[A.2] Production Firms (Current)

The final demand faced by production firms is made up of household consumption, corporate investment in fixed capital, government spending, and net export. Considering 10 industries and products at the global level, the demand for final goods and services in each area is:

$$\mathrm{d}^z = \beta^z \cdot c^z + \iota^z \cdot i_d^z + \iota^z \cdot i\_g_d^z + \sigma^z \cdot gov^z + \eta_z^f \cdot exp^z + \eta^z \cdot imp^z = \\ = \begin{pmatrix} d_1^z \\ d_2^z \\ \vdots \\ d_{10}^z \end{pmatrix} = \begin{pmatrix} \beta_1^z \\ \beta_2^z \\ \vdots \\ \beta_{10}^z \end{pmatrix} \cdot c^z + \begin{pmatrix} \iota_1^z \\ \iota_2^z \\ \vdots \\ \iota_{10}^z \end{pmatrix} \cdot i_d^z + \begin{pmatrix} \iota_1^z \\ \iota_2^z \\ \vdots \\ \iota_{10}^z \end{pmatrix} \cdot i\_g_d^z + \begin{pmatrix} \sigma_1^z \\ \sigma_2^z \\ \vdots \\ \sigma_{10}^z \end{pmatrix} \cdot gov^z + \begin{pmatrix} \eta_{1,z}^f \\ \eta_{2,z}^f \\ \vdots \\ \eta_{10,z}^f \end{pmatrix} \cdot exp^z + \\ - \begin{pmatrix} \eta_1^z \\ \eta_2^z \\ \vdots \\ \eta_{10}^z \end{pmatrix} \cdot imp^z \tag{6}$$

where i_d^z is real corporate demand for investment, $i\_g_d^z$ real government demand for investment, gov^z is real government consumption, exp^z is real gross export, imp^z is real gross import, β^z is the vector of household consumption shares (with: $\sum_{s=1}^{10} \beta_s^z = 1$), ι^z is the vector of investment shares (with: $\sum_{s=1}^{10} \iota_s^z = 1$), σ^z is the vector of government spending shares (with: $\sum_{s=1}^{10} \sigma_s^z = 1$), η_z^f is the vector of export shares (with: $\sum_{s=1}^{10} \eta_{z,s}^f = 1$),[8] and η^z is the vector of import shares (with: $\sum_{s=1}^{10} \eta_s^z = 1$).

Note that we assume that there is only a direct demand for manufacturing goods, agricultural goods and services. As a result, considering 5 domestic industries per area implies that the demand vectors of the two areas will look like:

$$\mathrm{d}^z = \begin{pmatrix} d_1^z > 0 \\ d_2^z > 0 \\ d_3^z > 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix} \quad \mathrm{d}^f = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ d_1^f > 0 \\ d_2^f > 0 \\ d_3^f > 0 \\ 0 \\ 0 \end{pmatrix}$$

Unlike other spending shares, the composition of household consumption is endogenous. More precisely, the share of services to total consumption is assumed to increase as disposable income (expressed in real terms, using the price of services) increases, whereas the share of manufacturing goods remains constant. Using subscript 1 for domestic manufacturing, 2 for domestic agriculture, and 3 for domestic services, real domestic consumption shares are:

$$\beta_1^z = \bar{\beta}_1^z \tag{7}$$

$$\beta_2^z = 1 - \beta_1^z - \beta_3^z \tag{8}$$

$$\beta_3^z = \beta_{3,-1}^z + \beta_{31}^z \cdot \frac{YD_{w,-1}^z}{p_{3,-1}^z} + \beta_{32}^z \cdot \frac{YD_{c,-1}^z}{p_{3,-1}^z} \tag{9}$$

where β_{31}^z and β_{32}^z are positive coefficients, and so must be β_1^z, β_2^z and β_3^z.

Once final demands are known, the gross output vector can be defined as:

[8] For each area, the vector of export shares mirror the vector of import shares of the other area.

$$\mathrm{x}^z = \begin{pmatrix} x_1^z \\ x_2^z \\ \vdots \\ x_{10}^z \end{pmatrix} = \mathrm{A} \cdot \mathrm{x}^z + \mathrm{d}^z$$

from which:

$$\mathrm{x}^z = (\mathrm{I} - \mathrm{A})^{-1} \cdot \mathrm{d}^z \tag{10}$$

where I is the identity matrix and A is the global matrix of technical coefficients, defined as:

$$\mathrm{A} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{110} \\ a_{21} & a_{22} & \cdots & a_{210} \\ a_{31} & a_{32} & \cdots & a_{310} \\ \cdots & \cdots & \cdots & \cdots \\ a_{101} & a_{102} & \cdots & a_{1010} \end{pmatrix}$$

As usual, a_{ij} (with $i, j = 1,2,\ldots,10$) is the quantity of product i necessary to produce one unit of product j. Therefore, each column j of A is associated with an industry, a the technique of production, and a product.[9] More precisely, columns 1 to 5 are associated with industries of the first area, whereas columns 6 to 10 are associated with industries of the second area. Similarly, rows 1 to 5 shows outputs produced by industries of the first area used as inputs by other industries, whereas rows 6 to 10 shows outputs produced by industries of the second area used as inputs by other industries. We refer to Table 3 for an example.

The monetary value of gross domestic output is the product of the unit price vector and the output vector:

$$Y^z = \mathrm{p}^{zT} \cdot \mathrm{x}^z \tag{11}$$

where p^z is the price vector and the subscript 'T' stands for the transpose of the matrix (hence p^{zT} is a row vector).

The net income or value added for each domestic economy matches aggregate nominal demand for final products and services, net of VAT and tariffs:

$$YN^z = c^z \cdot p_A^z + i_d^z \cdot p_I^z + i\_g_d^z \cdot p_I^z + gov^z \cdot p_G^z + EXP^z - IMP^z - VAT^z - TAR^z \tag{12}$$

where p_I^z is an investment price index, p_G^z is a government spending price index,[10] EXP^z is nominal export, IMP^z is nominal import, VAT^z is VAT revenues, and TAR^z is tariff revenues.

Total corporate profit in each area is:

$$FF^z = YN^z - WB^z - r_{l,-1}^z \cdot L_{F,-1}^z - AF^z \tag{13}$$

where r_l^z is the interest rate on loans obtained by production firms (L_F^z), and AF^z are amortisation funds.

Productions firms can retain a supplementary share of profits, in addition to using funds for amortisation:

$$FF_u^z = \omega^z \cdot FF^z \tag{14}$$

where ω^z is the percentage of (additional) undistributed profits of firms.

[9] Notice that the term $(\mathrm{I} - \mathrm{A})^{-1}$ is a matrix too. It is named the *Leontief inverse* and shows the multipliers, that is, the successive changes in production processes triggered by an initial change in final demands. As is well known, the Leontief inverse matrix can be expressed as a sum of power series (Waugh 1950[@fvw:1950]), that is: $(\mathrm{I} - \mathrm{A})^{-1} = \mathrm{I} + \mathrm{A} + \mathrm{A}^2 + \mathrm{A}^3 + \ldots + \mathrm{A}^t + \ldots = \sum_{t=0}^{\infty} \mathrm{A}^t$.

[10] As we are explaining in subsection A.8, p_I^z is the average price of investment goods and p_G^z is the average price of goods purchased by the government sector.

[A.3] Production Firms (Capital)

Firms need fixed capital (in addition to labour and circulating capital inputs) to produce. It is assumed that each industry has its own capital requirement. The target stock of fixed capital, expressed in real terms, is therefore:

$$k^{z*} = \mathrm{p}_{-1}^{zT} \cdot (\mathrm{h}^z \odot \mathrm{x}_{-1}^z) \cdot \frac{1}{p_{I,-1}^z} \tag{15}$$

where $\mathrm{h}^z = \{h_j^z\}$ is the column vector of industry-specific target capital to output ratios.[11]

The real gross private investment adjusts in such a way to bridge the gap between the actual capital stock (at the beginning of the period) and its target level:

$$i_d^z = \gamma^z \cdot (k^{z*} - k_{-1}^z) + da^z \tag{16}$$

where γ^z defines the speed of adjustment, and da^z is real capital depreciation.

The current private capital stock depreciates according to a constant ratio, δ^z, so that:

$$da^z = \delta^z \cdot k_{-1}^z \tag{17}$$

It follows that the real stock of current fixed private capital stock in each area is:

$$k^z = k_{-1}^z + i_d^z - da^z \tag{18}$$

Amortisation funds are used to fund the replacement of depleted private capital:

$$AF^z = da^z \cdot p_I^z - k^z \cdot \Delta p_I^z \tag{19}$$

The stock of bank loans obtained by production firms is defined as a residual variable:

$$L_F^z = L_{F,-1}^z + i_d^z \cdot p_I^z - AF^z - FF_u^z - \Delta E_s^z \tag{20}$$

where E_s^z is the nominal value of the stock of shares issued by production firms.

For the sake of simplicity, we assume that share issues are completely demand driven:

$$E_s^z = E_{h,z}^z + xr_f \cdot E_{h,f}^z \tag{21}$$

where $E_{h,z}^z$ is nominal stock of domestic shares held by domestic investors and $E_{h,f}^z$ is the portion held by foreign investors.

The supply of domestic shares to foreign investors, expressed in domestic currency, is therefore:

$$E_{s,f}^z = xr_f \cdot E_{h,f}^z \tag{22}$$

The return rate (in addition to percentage capital gains) on shares issued by production firms of each area is:

$$r_e^z = \frac{(1-\omega^z) \cdot FF^z}{E_S^z} \tag{23}$$

Finally, total dividends (from non-financial firms) received by investors in each area are:

$$DIV^z = (1-\omega^z) \cdot FF^z \cdot \frac{E_{h,z}^z}{E_S^z} + (1-\omega^f) \cdot FF^f \cdot \frac{E_{h,z}^f}{E_S^f} \tag{24}$$

[11] Notice that k^* cannot be expressed in physical units. It is calculated by dividing the nominal stock of capital by the average price of investment goods. See subsection 2.8.

[A.4] Commercial Banks

For the sake of simplicity, it is assumed that commercial banks are always ready to finance firms' production plans and to fund private investment and consumption expenditures. Supplied loans are, therefore, demand driven:

$$L_s^z = L_F^z + L_h^z \tag{25}$$

Banks provide deposits on demand:

$$M_s^z = M_h^z \tag{26}$$

Because of cash (or state money), deposits collected by the banks may exceed those created by granting loans to the firms. If this happens, banks hold government bills as the asset counterpart of extra-deposits. Conversely, if loans exceed deposits, banks request (and obtain) advances from the central bank:

$$if\ M_s^z \geq L_s^z\ then\ B_b^z = M_s^z - L_s^z\ and\ A_d^z = 0 \tag{27}$$

$$if\ M_s^z < L_s^z\ then\ B_b^z = 0\ and\ A_d^z = L_s^z - M_s^z \tag{28}$$

where A_d^z are advances obtained by commercial banks from the central bank.

It is assumed that the interest rate on advances is nil, banks have no costs of production, and there are no compulsory reserves. As a result, bank profits equal the difference between perceived interests on loans and bills and interest payments on deposits:

$$F_b^z = r_{l,-1}^z \cdot L_{F,-1}^z + r_{h,-1}^z \cdot L_{h,-1}^z + r_{b,-1}^z \cdot B_{b,-1}^z - r_{m,-1}^z \cdot M_{s,-1}^z \tag{29}$$

Unlike corporate profits, bank profits are entirely distributed to the households.

[A.5] Government and Central Bank

Real government consumption grows according to an exogenous rate:[12]

$$gov\_c^z = gov\_c_{-1}^z \cdot (1 + g_g^z) + gov\_c_0^z \tag{30}$$
(30)

where g_g^z is the growth rate of government spending and gov_0^z is a shock component.

The government gross investment adjusts in such a way to bridge the gap between the actual capital stock (at the beginning of the period) and its target level:

$$i\_g_d^z = da\_g^z + i\_g_c^Z \tag{31}$$

Where $i\_g_c^Z$ is exogenous public investment , and da^z is real public capital depreciation.

The current capital stock depreciates according to a constant ratio, δ^z, so that:

$$da\_g^z = \delta^z \cdot k\_g_{-1}^z \tag{32}$$

It follows that the real stock of current fixed capital in each area is:

[12] However, it is assumed that $g_g^z = 0$ in the baseline scenario.

$$k\_g^z = k\_g^z_{-1} + i\_g^z_d - da\_g^z \quad (33)$$

Income taxes collected by the government can be calculated using the average tax rates on households' labour and non-labour incomes. The corresponding revenue is therefore:

$$T^z = \theta^z_{\mathrm{w}} \cdot WB^z + \theta^z_{\mathrm{c}} \cdot \left(DIV^z + r^z_{m,-1} \cdot M^z_{h,-1} + r^z_{b,-1} \cdot B^z_{s,z,-1} + xr^f_{-1} \cdot r^f_{b,-1} \cdot B^f_{s,z,-1}\right) \quad (34)$$

where θ^z_c is the average tax rate on capital incomes in each area.

Government revenues from VAT and tariffs are, respectively:

$$VAT^z = [\mathrm{p}^z \odot \tau^z_{vat} \oslash (\mathrm{I} + \tau^z_{vat})]^T \cdot (\beta^z \cdot c^z) \quad (35)$$

$$TAR^z = [xr^f \cdot \mathrm{p}^f \odot \tau^z_{tar} \oslash (\mathrm{I} + \tau^z_{tar})]^T \cdot (\eta^z \cdot imp^z) \quad (36)$$

where τ^z_{vat} and τ^z_{tar} are the vectors defining product-specific VAT rates and percentage tariffs, respectively.[13]

The government budget deficit in each area is:

$$DEF^z_g = gov^z \cdot p^z_G + r^z_{b,-1} \cdot B^z_{s,-1} - F^z_{cb} - T^z - VAT^z - TAR^z \quad (37)$$

where F_{cb} is the profit made by the central bank (seigniorage income) on its holdings of (both domestic and foreign) government securities, which is subsequently returned to the government sector.

The government sector issues bills as it runs into deficits:

$$B^z_s = B^z_{s,-1} + DEF^z_g \quad (38)$$

Advances to commercial banks are provided on demand:

$$A^z_s = A^z_d \quad (39)$$

Similarly, the supply of cash adjusts to the demand for cash:

$$H^z_s = H^z_h \quad (40)$$

This is the overall amount of state money that remains in circulation at the end of each period.

The stock of bills supplied to domestic investors is:

$$B^z_{s,z} = B^z_{h,z} \quad (41)$$

whereas the stock of bills supplied to foreign investors is:

$$B^z_{s,f} = xr^f \cdot B^z_{h,f} \quad (42)$$

The profit made by the central bank is:

$$F^z_{cb} = r^z_{b,-1} \cdot B^z_{cb,z,-1} + xr^f \cdot r^f_{b,-1} \cdot B^f_{cb,s,z,-1} \quad (43)$$

where $B^f_{cb,s,z}$ is the amount of foreign government bills held by the domestic central bank, expressed in foreign currency.

[13] Note that $\odot$ and $\oslash$ are the Hadamard multiplication and division, respectively, also called element-wise multiplication and division of matrices.

Finally, interest rates on bank deposits, government bills, loans to firms, and personal loans, are simply defined using different mark-ups (μ_s^z) over the policy rate (r^{*z}) set by the central bank, that is:

$$r_m^z = r^{*z} + \mu_m^z \quad (44)$$

$$r_b^z = r^{*z} + \mu_b^z \quad (45)$$

$$r_l^z = r^{*z} + \mu_l^z \quad (46)$$

$$r_h^z = r^{*z} + \mu_h^z \quad (47)$$

We assume that, in each area, $r_h \geq r_l \geq r_b \geq r_m$ in the baseline scenario.

[A.6] Population and the Labour Market

The employment level is determined by firms' demand for labour in each production process. More precisely, the number of workers hired in each industry is:

$$N_j^z = \frac{x_j^z}{pr_j^z} \quad (48)$$

$\forall j = 1,2,\ldots,5$, where pr_j^z is the product per worker in the j-th industry.

Total employment in each area is:

$$N^z = \mathrm{x}^{zT} \cdot \left[\begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \oslash \mathrm{pr}^z \right] = \mathrm{x}^{zT} \cdot \mathrm{l}^z = \sum N_j^z \quad (49)$$

where pr^z is the vector of industry-specific labour productivities and therefore l^z is the column vector of labour coefficients.

The wage bill paid in each industry is:

$$WB_j^z = n_j^z \cdot w_j^z \quad (50)$$

$\forall j = 1,2,\ldots,5$, where w_j^z is the average money wage rate paid to employees of industry j.

The total wage bill is:

$$WB^z = \mathrm{N}^{zT} \cdot \mathrm{w}^z = \sum WB_j^z \quad (51)$$

where N^z and w^z are the vectors of industry-specific employees and wage rates, respectively. The equation above defines the overall cost of labour faced by private firms in each area.

The available labour force in each area's industries depends on an exogenous growth rate and the net inflow of immigrants from the other area:

$$\mathrm{POP}^z = \mathrm{POP}_{-1}^z \odot \left(I + \mathrm{g}_{pop}^z\right) + \mathrm{IMM}^z - \mathrm{IMM}^f \quad (52)$$

where IMM^z and IMM^f are the vectors defining inflows and outflows of labour-force in each area's industries.

Industry-specific unemployment rates in each area are:

$$un_j^z = 1 - \frac{N_{j,-1}^z}{POP_{j,-1}^z} \tag{53}$$

We assume that immigration inflows depend on three factors: *a*) the size of the population of the other area; *b*) the unemployment rate of the other area; *c*) the wage differential between the two areas. In formal terms, we obtain:

$$\mathrm{IMM}^z = \gamma_{imm,0}^z \odot \mathrm{POP}_{-1}^f + \gamma_{imm,1}^z \odot \mathrm{un}_{-1}^f + \gamma_{imm,2}^z \odot \left(\mathrm{w}_{-1}^z - \mathrm{w}_{-1}^f\right) \tag{54}$$

where $\gamma_{imm,0}^z$, $\gamma_{imm,1}^z$ and $\gamma_{imm,2}^z$ are positive coefficients.

Finally, gender segregation is assumed to be dependent on the wage level. Since men tend to occupy high-salary jobs, the percentage of female employees (ρ_j^z) in each industry reduces as the wage rate increases:

$$\rho_j^z = \rho_{0j}^z - \rho_{1j}^z \cdot \left(w_j^z - w_{j,-1}^z\right) \tag{55}$$

where ρ_{0j}^z and ρ_{1j}^z are positive coefficients.

[A.7] Portfolio Choices

Domestic household holdings of domestic government bills are defined by a Tobinesque portfolio equation:

$$\begin{aligned}\frac{B_{h,z}^z}{V^z} &= \lambda_{10} + \lambda_{11} \cdot r_{b,-1}^z - \lambda_{12} \cdot \left(r_{b,-1}^f + \frac{\Delta xr^f}{xr^f}\right) - \lambda_{13} \cdot r_{m,-1}^z - \lambda_{14} \cdot \frac{YD^z}{V^z} - \lambda_{15} \cdot r_{e,-1}^z + \\ &\quad -\lambda_{16} \cdot \left(r_{e,-1}^f + \frac{\Delta xr^f}{xr^f}\right)\end{aligned} \tag{56}$$

In plain words, the share of domestic government bills to net wealth in domestic households' portfolio increases as the interest rate on domestic government bills increases (this effect is captured by coefficient λ_{11}), and reduces as interest and return rates (including percentage capital gains) on other financial assets increase (coefficients λ_{12}, λ_{13}, λ_{15}, and λ_{16}). Besides, it reduces as the liquidity preference of domestic investors increases (coefficient λ_{14}).

Similarly, domestic household holdings of foreign government bills, domestic shares, and foreign shares, are, respectively:

$$\begin{aligned}\frac{B_{h,z}^f}{V^z} &= \lambda_{20} - \lambda_{21} \cdot r_{b,-1}^z + \lambda_{22} \cdot \left(r_{b,-1}^f + \frac{\Delta xr^f}{xr^f}\right) - \lambda_{23} \cdot r_{m,-1}^z - \lambda_{24} \cdot \frac{YD^z}{V^z} - \lambda_{25} \cdot r_{e,-1}^z + \\ &\quad -\lambda_{26} \cdot \left(r_{e,-1}^f + \frac{\Delta xr^f}{xr^f}\right)\end{aligned} \tag{57}$$

$$\begin{aligned}\frac{E_{h,z}^z}{V^z} &= \lambda_{30} - \lambda_{31} \cdot r_{b,-1}^z - \lambda_{32} \cdot \left(r_{b,-1}^f + \frac{\Delta xr^f}{xr^f}\right) - \lambda_{33} \cdot r_{m,-1}^z - \lambda_{34} \cdot \frac{YD^z}{V^z} + \lambda_{35} \cdot r_{e,-1}^z + \\ &\quad -\lambda_{36} \cdot \left(r_{e,-1}^f + \frac{\Delta xr^f}{xr^f}\right)\end{aligned} \tag{58}$$

$$\begin{aligned}\frac{E_{h,z}^f}{V^z} &= \lambda_{40} - \lambda_{41} \cdot r_{b,-1}^z - \lambda_{42} \cdot \left(r_{b,-1}^f + \frac{\Delta xr^f}{xr^f}\right) - \lambda_{43} \cdot r_{m,-1}^z - \lambda_{44} \cdot \frac{YD^z}{V^z} - \lambda_{45} \cdot r_{e,-1}^z + \\ &\quad +\lambda_{46} \cdot \left(r_{e,-1}^f + \frac{\Delta xr^f}{xr^f}\right)\end{aligned} \tag{59}$$

where λs are all positive coefficients.[14]

In each area, households' demand for cash is proportional to their expected consumption expenditures (proxied by past consumption):

[14] Note that λs are defined in such a way that: *a*) horizontal constraints on coefficients of rates of interest/return for each financial asset are met; *b*) vertical constraints for cross-asset coefficients of rates of interest/return are met; and *c*) the sum of autonomous shares of assets to total wealth (additional vertical constraints) is lower than unity, because households can hold cash and bank deposits in addition to government bills and corporate equity (see Godley and Lavoie 2007, sections 5.6.2 and 5.6.3). These constraints must be verified at the global level.

$$H_h^z = \lambda_c^z \cdot c_{-1}^z \cdot p_{A,-1}^z \quad (60)$$

Households' demand for personal loans is driven by their purchases of durable goods and their consumption in excess of disposable income:

$$L_h^z = L_{h,-1}^z \cdot (1-\psi_1^z) + \max\left(c^z \cdot p_A^z - YD^z, \psi_2^z \cdot \Delta(\mathrm{p}^{zT} \cdot \mathrm{dc}^z)\right) \quad (61)$$

where ψ_1^z is the share of loans repaid in each period, ψ_2^z is the share of consumption funded by bank loans, and dc^z is the vector defining the real stocks of durable goods (we refer to subsection 2.12, equation 92).

In each area, bank deposits are the buffer stock of domestic investors:

$$M_h^z = V^z + L_h^z - H_h^z - B_{h,z}^z - B_{h,z}^f - E_{h,z}^z - E_{h,z}^f \quad (62)$$

[A.8] Price Setting and Production Function

Private firms use a markup rule. More precisely, they set industry-specific costing margins over their unit costs of production, including fixed capital costs. The vector of unit prices of reproduction is:

$$\mathrm{p}^{z*} = \mathrm{w}^z \odot \mathrm{l}^z + \mathrm{p}^{z*} \cdot \mathrm{A} \odot \mathrm{m}^{z*} \odot \mathrm{h}_d^z \quad (63)$$

where $\mathrm{m}^{z*} = \{1 + \mu_j^{z*}\}$ is the vector of normal mark-ups and $\mathrm{h}_d^z = \{1 + h_j^z \cdot \delta^z\}$ is the vector of the portions of fixed capital that are being amortised in each period,[15] from which one obtains:

$$\mathrm{p}^{z*} = \begin{pmatrix} p_1^{z*} \\ p_2^{z*} \\ \vdots \\ p_5^{z*} \end{pmatrix} = \begin{pmatrix} \frac{w_1^z}{pr_1^z} + (p_1^{z*} \cdot a_{11} + p_2^{z*} \cdot a_{21} + \cdots + p_5^{z*} \cdot a_{51}) \cdot (1+\mu_1^{z*}) \cdot (1 + h_1^z \cdot \delta^z) \\ \frac{w_2^z}{pr_2^z} + (p_1^{z*} \cdot a_{12} + p_2^{z*} \cdot a_{22} + \cdots + p_5^{z*} \cdot a_{52}) \cdot (1+\mu_2^{z*}) \cdot (1 + h_2^z \cdot \delta^z) \\ \vdots \\ \frac{w_5^z}{pr_5^z} + (p_1^{z*} \cdot a_{15} + p_2^{z*} \cdot a_{25} + \cdots + p_5^{z*} \cdot a_{55}) \cdot (1+\mu_5^{z*}) \cdot (1 + h_5^z \cdot \delta^z) \end{pmatrix}$$

While this resembles Sraffa (1960), both wage rates and normal mark-ups are allowed to differ across industries here. In other words, we assume no tendency for industry-specific wage and profit rates to level out.

In each industry, potential output is simply defined as a direct, linear, function of the available labour force:

$$\mathrm{x}^{z*} = \mathrm{pr}^z \odot \mathrm{POP}^z \quad (64)$$

Actual market prices grow above (or fall below) reproduction prices if actual outputs exceed (or are lower than) potential outputs.[16] Besides, they include VAT rates and tariffs on imports:

$$\mathrm{p}^z = [\mathrm{p}^{z*} + \Gamma_x^z \odot (\mathrm{x}_{-1}^z - \mathrm{x}_{-1}^{z*})] \odot \left(\begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} + \tau_{vat}^z + \tau_{tar}^f \right) \quad (65)$$

where Γ_x^z is a vector of positive coefficients defining the sensitivity of market prices to output gaps.

The average price level faced by domestic households depends on the basket of goods they consume in each period:

[15] We refer again to subsection 2.2.
[16] It follows that actual marks-ups fall below normal mark-ups as long as $p_j^z < p_j^{z*}$, and they exceed them as long as $p_j^z > p_j^{z*}$, $\forall j = 1,2,\ldots,5$.

$$p_A^z = \mathrm{p}^{zT} \cdot \beta^z \tag{66}$$

Similarly, the average price paid by production firms to buy investment goods is:

$$p_I^z = \mathrm{p}^{zT} \cdot \iota \tag{67}$$

The average price paid by the government is:

$$p_G^z = \mathrm{p}^{zT} \cdot \sigma \tag{68}$$

Finally, the average price of import is:

$$p_M^z = xr^f \cdot \mathrm{p}^{fT} \cdot \eta \tag{69}$$

Notice that these average prices are used to express each component of aggregate demand in real terms, thus avoiding using disaggregated functions for consumption, investment, government spending and foreign trade.

[A.9] The Balance of Payments

In each area, real import is defined by a logarithm function of both the international price gap and the real domestic disposable income:

$$\log(imp^z) = m_0^z - m_1^z \cdot \left[\log\left(p_{\mathrm{M},-1}^z\right) - \log\left(p_{\mathrm{A},-1}^z\right)\right] + m_2^z \cdot \log\left(\frac{YD_{-1}^z}{p_{A,-1}^z}\right) \tag{70}$$

where $m_0^z < 0$, $m_1^z > 0$, and $m_2^z > 0$.

Nominal import is:

$$IMP^z = p_M^z \cdot imp^z \tag{71}$$

The volume of export to the other area is:

$$exp^z = imp^f \tag{72}$$

Nominal export is:

$$EXP^z = xr^f \cdot IMP^f \tag{73}$$

The trade balance of each area is:

$$TB^z = EXP^z - IMP^z \tag{74}$$

The current account balance is:

$$\begin{aligned} CAB^z \quad &= TB^z + r_{b,-1}^f \cdot B_{s,z,-1}^f \cdot xr_{-1}^f - r_{b,-1}^z \cdot B_{s,f,-1}^z + r_{b,-1}^f \cdot B_{cb,s,z,-1}^f \cdot xr_{-1}^f + \\ &+ xr^f \cdot (1-\omega^f) \cdot FF^f \cdot \frac{E_{s,z,-1}^f}{E_{s,-1}^f} - (1-\omega^z) \cdot FF^z \cdot \frac{E_{s,f,-1}^z}{E_{s,-1}^z} \end{aligned} \tag{75}$$

The financial account balance, net of official transactions, is:

$$KABP^z = \Delta B_{s,f}^z - xr^f \cdot \Delta B_{s,z}^f + \Delta E_{s,f}^z - xr^f \cdot \Delta E_{s,z}^f \tag{76}$$

Finally, the net accumulation of financial assets in each area is:

$$NAFA^z = DEF_g^z + CAB^z \tag{77}$$

[A.10] Exchange Rate Regimes

As mentioned, exchange rates are quoted indirectly, that is, the exchange rate is the price of one unit of domestic currency expressed in foreign currency. Obviously, the exchange rate of the foreign area is the reciprocal of the exchange rate of the domestic area:

$$xr^f = \frac{1}{x^z} \tag{78}$$

Following Godley and Lavoie (2007, section 12.4), central bank's holdings of government bills are modelled asymmetrically. The amount of domestic government bills held by the domestic central bank is obtained as an accounting identity from column 7 of the transactions-flow matrix (Table 2, changes in stocks):

$$\Delta B^z_{cb,z} = \Delta H^z_s - \Delta A^z_s - xr^f \cdot \Delta B^f_{cb,s,z} \tag{79}$$

Conversely, column 12 of the balance sheet matrix (Table 1) provides the following identity (vertical constraint) for the other area's central bank:

$$B^f_{cb,f} = H^f_s - A^f_s \tag{80}$$

The balance sheet of the central bank in the first area comprises domestic government bills, foreign government bills, and advances to commercial banks as its assets. On the liability side, cash is the primary component.[17] The balance sheet of the central bank in the second area is similar, but it is assumed that it does not hold government bills issued in the first area.

We consider two different exchange rate regimes: a fixed exchange rate, and a (quasi) floating exchange rate.

[A.10.1] Fixed exchange rate

Under the fixed exchange rate regime, the supply of foreign government bills to domestic households is defined as:

$$\Delta B^f_{s,z} = xr^z \cdot B^f_{h,z} \tag{81}$$

The supply of government bills of the second area to the central bank of the first area is:

$$B^f_{cb,s,z} = B^f_s - B^f_{s,z} - B^f_{s,f} - B^f_{cb,f} - B^f_b \tag{82}$$

Therefore, the hidden or redundant equation is the one that matches the amount of domestic government bills held by the domestic central bank with the horizontal constraint (in terms of cross-sector holdings of bills) defined by the balance sheet matrix:

$$B^z_{cb,z} = B^z_s - B^z_{s,z} - B^z_{s,f} - B^z_b \tag{83}$$

The accounting structure of the model is now complete. However, a few additional model features have been included to allow for a broader range of experiments, which are discussed below.

[A.10.2] Quasi-floating exchange rate

In the alternative regime, the exchange rate is allowed to adjust gradually to reflect the relative demand for national currencies:

$$\Delta xr^z = \chi \cdot \frac{CAB^z_{-1}}{YN^z_{-1}} \tag{84}$$

[17] For the sake of simplicity, we assume away bank reserves.

where χ is a positive parameter defining the speed of adjustment of the exchange rate to the current account balance to total value added ratio. As a result, the domestic currency keeps appreciating (depreciating) as long as the area runs into current account surpluses (deficits).

Note that while the mechanism above increases (reduces) the value of the amount of foreign government bills supplied to domestic households (via equation 78), the domestic central bank is still buying foreign government bills (via 79), albeit in a lower (higher) amount compared with that purchased under a fixed exchange rate regime.[18]

[A.11] Waste, Emissions

In each area, waste accumulates as goods and services are produced. The waste associated with each domestic industry is calculated using the related waste to output ratio, ζ_j^z, that is:

$$wa_j^z = wa_{j,-1}^z + x_j^z \cdot \zeta_j^z - x_j^z \cdot a_{5,j} \quad (85)$$

$\forall j = 1,2,\ldots,5$, where the last component ($x_j^z \cdot a_{5,j}$) shows that, in principle, waste can be reduced by recycling it and using is as an input for the other industries.

Total domestic waste (net of recycling) is therefore:

$$wa^z = \sum_{j=1}^{4} w\,a_j^z \quad (86)$$

If one assumes away land emissions, annual emissions of CO_2 can be calculated for each industry by multiplying their respective output by the industry-specific energy intensity coefficient ($\varepsilon_j^z = Ej_j^z/x_j^z$), the industry-specific share of non-renewable energy ($1 - \eta_{en,j}^z$), and a uniform CO_2 intensity coefficient ($\beta_e^z = Gt/Ej$). Emissions linked with each domestic industry are:

$$emis_j^z = x_j^z \cdot \left(1 - \eta_{en,j}^z\right) \cdot \varepsilon_j^z \cdot \beta_e^z \quad (87)$$

Therefore, total domestic emissions per year are:

$$emis^z = \mathrm{x}^{zT} \cdot \left\{\left[\begin{pmatrix}1\\1\\\vdots\\1\end{pmatrix} - \eta_{en}^z\right]^z \odot \varepsilon^z\right\} \cdot \beta_e^z = \sum_{j=1}^{5} emis_j^z \quad (88)$$

where η_{en}^z is the vector of industry-specific renewable energy percentages.

In each area, cumulative co_2 emissions are:

$$co_2^z = co_{2,-1}^z + emis^z \quad (89)$$

Atmospheric temperature is simply calculated as a function of CO_2 concentration at the global level:

$$temp = \frac{1}{1-fnc} \cdot tcre \cdot \left(co_2^z + co_2^f\right) \quad (90)$$

where fnc is the non-CO_2 fraction of total anthropocentric forcing, and $tcre$ is the transient climate response to cumulative carbon emissions.

[18] In this scenario, the domestic central bank should be purchasing all the unsubscribed foreign bills to maintain exchange rate stability.

[A.12] Matter Extraction and Energy Use

In each area, the material contents of outputs can be defined using the corresponding vector of industry-specific matter-intensity coefficients, ϕ^z, that is:

$$x_{mat}^z = \phi^{zT} \cdot \mathrm{x}^z \tag{91}$$

The quantity of matter actually extracted in each period also depends on recycling:

$$mat^z = x_{mat}^z - rec^z \tag{92}$$

Both the socioeconomic stock and industrial waste can be (partially) recycled:

$$rec^z = \rho_{dis}^z \cdot dis^z + q_5^z \cdot x_5^z \tag{93}$$

where dis^z is the discarded socioeconomic stock, ρ_{dis}^z is the associated rate of recycling, and $q_5^z \cdot x_5^z$ is the matter content of the recycling industry's output.

The discarded socioeconomic stocks is:

$$dis^z = \phi^{zT} \cdot \left(\zeta_{dc,-1}^z \odot \mathrm{dc}_{-1}^z\right) \tag{94}$$

where ζ_{dc}^z is vector of the percentages of durable consumption goods discarded every year by product/industry.

New durable goods equal all produced goods minus discarded goods:

$$\Delta \mathrm{dc}^z = \beta^z \cdot c^z - \zeta_{dc,-1}^z \odot \mathrm{dc}_{-1}^z \tag{95}$$

Finally, the socioeconomic stock accumulates as new material goods are produced and reduces as a share of those goods is discarded every year:

$$\Delta k_h^z = x_{mat}^z - dis^z \tag{96}$$

Like material contents, the energy contents of outputs can be defined using the corresponding vector of industry-specific intensity coefficients, ε^z, that is:

$$en^z = \varepsilon^{zT} \cdot \mathrm{x}^z \tag{97}$$

Renewable energy is just a share of total energy used in each industry:

$$en_R^z = \mathrm{x}^{zT} \cdot (\varepsilon^z \odot \eta_{en}^z) \tag{98}$$

Non-renewable energy is therefore:

$$en_N^z = en^z - en_R^z \tag{99}$$

We can now calculate the global stocks of matter and energy. The annual change in the stock of material reserves is:

$$\Delta k_{mat} = conv_{mat} - mat^z - mat^f \tag{100}$$

Material resources converted into reserves are:

$$conv_{mat} = \sigma_{mat} \cdot res_{mat} \tag{101}$$

where σ_{mat} is the speed of conversion and res_{mat} is the quantity of resources, which reduce as more resources are converted into reserves:

$$res_{mat} = res_{mat,-1} - conv_{mat} \tag{102}$$

Similarly, the equations defining energy depletion are:

$$\Delta k_{en} = conv_{en} - en_N^z - en_N^f \tag{103}$$

$$conv_{en} = \sigma_{en} \cdot res_{en} \tag{104}$$

$$res_{en} = res_{en,-1} - conv_{en} \tag{105}$$

where σ_{en} is the speed of conversion of energy resources into reserves.

Finally, we can calculate the carbon mass of non-renewable energy and the mass of oxygen used for production purposes for each area as follow:

$$cen^z = \frac{emis^z}{car} \tag{106}$$

$$o2^z = emis^z - cen^z \tag{107}$$

where car is the coefficient converting Gt of carbon into Gt of CO_2., while equation (104) can be easily derived from equation (93) and the second column of Table 3.

[A.13] Circular Economy Innovations

The label ‘circular economy’ (CE) denotes a set of policies and practices that aim at reusing, repairing, sharing, and recycling products and resources to create a closed-loop system, thus minimising waste, pollution and CO_2 emissions.[19] A simple way to introduce a CE innovation in the model above is to consider a 5-industry economy, in which the first four industries produce standard goods and services and waste management, whereas the fifth industry deals with waste recycling.

As long as waste is not recycled, the matrix of technical coefficients is:

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & 0 & a_{16} & a_{17} & a_{18} & a_{19} & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & 0 & a_{26} & a_{27} & a_{28} & a_{29} & 0 \\ a_{31} & a_{32} & a_{33} & a_{34} & 0 & a_{36} & a_{37} & a_{38} & a_{39} & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 & a_{46} & a_{47} & a_{48} & a_{49} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{61} & a_{62} & a_{63} & a_{64} & 0 & a_{66} & a_{67} & a_{68} & a_{69} & 0 \\ a_{71} & a_{72} & a_{73} & a_{74} & 0 & a_{76} & a_{77} & a_{78} & a_{79} & 0 \\ a_{81} & a_{82} & a_{83} & a_{84} & 0 & a_{86} & a_{87} & a_{88} & a_{89} & 0 \\ a_{91} & a_{92} & a_{93} & a_{94} & 0 & a_{96} & a_{97} & a_{98} & a_{99} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

All industries generate waste, but no waste is used as input in the domestic economy ($a_{51} = a_{52} = a_{53} = a_{54} = 0$) or in the foreign economy ($a_{106} = a_{107} = a_{108} = a_{109} = 0$). Additionally, no inputs are used in the waste recycling industry of the domestic economy ($a_{15} = a_{25} = a_{35} = a_{45} = 0$) or of the foreign economy ($a_{610} = a_{710} = a_{810} = a_{910} = 0$).

The introduction of a simple CE innovation in the domestic economy implies a change in technical coefficients such that the new matrix is:

[19] For a thorough discussion on the definition of CE, see Bimpizas-Pinis et al. (2021).

$$A' = \begin{pmatrix} a'_{11} \leq a_{11} & a'_{12} \leq a_{12} & a'_{13} \leq a_{13} & a'_{14} \leq a'_{14} & a'_{15} > 0 & a_{16} & a_{17} & a_{18} & a_{19} & 0 \\ a'_{21} \leq a_{21} & a'_{22} \leq a_{22} & a'_{23} \leq a_{23} & a'_{24} \leq a'_{24} & a'_{25} > 0 & a_{26} & a_{27} & a_{28} & a_{29} & 0 \\ a'_{31} \leq a_{31} & a'_{32} \leq a_{32} & a'_{33} \leq a_{33} & a'_{34} \leq a'_{34} & a'_{35} > 0 & a_{36} & a_{37} & a_{38} & a_{39} & 0 \\ a'_{41} \leq a_{41} & a'_{42} \leq a_{42} & a'_{43} \leq a_{43} & a'_{44} \leq a'_{44} & a'_{45} > 0 & a_{46} & a_{47} & a_{48} & a_{49} & 0 \\ a_{51} > 0 & a_{52} > 0 & a_{53} > 0 & a_{54} > 0 & 0 & a_{56} & a_{57} & a_{58} & a_{59} & 0 \\ a'_{61} \leq a_{61} & a'_{62} \leq a_{62} & a'_{63} \leq a_{63} & a'_{64} \leq a'_{64} & a'_{65} > 0 & a_{66} & a_{67} & a_{68} & a_{69} & 0 \\ a'_{71} \leq a_{71} & a'_{72} \leq a_{72} & a'_{73} \leq a_{73} & a'_{74} \leq a'_{74} & a'_{75} > 0 & a_{76} & a_{77} & a_{78} & a_{79} & 0 \\ a'_{81} \leq a_{81} & a'_{82} \leq a_{82} & a'_{83} \leq a_{83} & a'_{84} \leq a'_{84} & a'_{85} > 0 & a_{86} & a_{87} & a_{88} & a_{89} & 0 \\ a'_{91} \leq a_{91} & a'_{92} \leq a_{92} & a'_{93} \leq a_{93} & a'_{94} \leq a'_{94} & a'_{95} > 0 & a_{96} & a_{97} & a_{98} & a_{99} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

In short, the CE innovation entails a reduction in the quantities of products and services used as inputs in the same industries. This is possible because recycled waste now enters their production processes.[20] Besides, outputs from other industries are used as inputs in the waste recycling industry.

The unit price of recycled waste now enters equation (60) in subsection 2.8. It is defined in the same way as the other prices. The mark-up applied by the recycling industry is set using the average mark-up of the economy:

$$\mu_5^z = \mu_{5,-1}^z + \gamma_\mu^z \cdot \left(\bar{\mu}^z - \mu_{5,-1}^z\right), \quad with: \bar{\mu}^z = \frac{\sum_{j=1}^4 \mu_j^z}{4} \qquad (108)$$

where γ_μ^z is the speed of convergence of the initial mark-up value (0 in the baseline scenario) to the average one.

This model assumes that technical change (that is, the value of a'_{ij}) is set by the policy makers, while the average speed of convergence of technical coefficients to their target values is defined as a linear, positive function of government expenditures.

Focusing on the domestic economy (that is, on the first five columns of matrix A′), each coefficient is defined as:

$$a_{ij} = a_{ij,-1} + \gamma_A^z \cdot \left(a'_{ij,-1} - a_{ij,-1}\right) \qquad (109)$$

$\forall\ i = 1,2,\ldots,10$ and $j = 1,2,\ldots,5$, where γ_A^z is the average speed of transition towards a (partial) CE production system, which is defined as:

$$\gamma_A^z = \gamma_{A0}^z + \Gamma_A^{zT} \cdot \sigma^z \cdot gov_{-1}^z \qquad (110)$$

where γ_{A0}^z is a positive scalar, whereas $\Gamma_A^z = \{\gamma_{Aj}^z\}$ is the vector that defines the industry-specific sensitivities (of the speeds of adjustment) to government final demands.[21]

[20] As CE innovation seems to imply some degree of input substitutability, one might notice that *smooth substitutability*, within the *same production function*, is one of the key assumptions of neoclassical general equilibrium models. However, input substitution is only possible here because of a *change in the techniques of production*.

[21] Notice that: $\sigma^z \cdot gov^z = \begin{pmatrix} \sigma_1^z \\ \sigma_2^z \\ \vdots \\ \sigma_5^z \end{pmatrix} \cdot gov^z = \begin{pmatrix} \sigma_1^z \cdot gov^z \\ \sigma_2^z \cdot gov^z \\ \vdots \\ \sigma_5^z \cdot gov^z \end{pmatrix}$.

Appendix B - Tables and Figures

[B.1] Translator between EXIOBASE 3 sectoral disaggregation and the 5-sector disaggregation used in JUST2CE

JUS2CE sector	EXIOBASE 3 sector number	Sector name
Agriculture	1-15, 18-19	
Manufacturing	20-113	(except 51, 53, 60, 66, 70, 73, 75, 77, 79, 81, 83, 94, 95)
Services	138	
Waste Management Services	139-158	
Circular Economy sector	16	Manure treatment (conventional), storage and land application
	17	Manure treatment (biogas), storage and land application
	51	Re-processing of secondary wood material into new wood material
	53	Re-processing of secondary paper into new pulp
	60	Re-processing of secondary plastic into new plastic
	66	Re-processing of secondary glass into new glass
	70	Re-processing of ash into clinker
	73	Re-processing of secondary steel into new steel
	75	Re-processing of secondary precious metals into new precious metals
	77	Re-processing of secondary aluminium into new aluminium
	79	Re-processing of secondary lead into new lead, zinc and tin
	81	Re-processing of secondary copper into new copper
	83	Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
	94	Recycling of waste and scrap
	95	Recycling of bottles by direct reuse
	114	Re-processing of secondary construction material into aggregates

[B.2] Balance sheet, transaction flow matrix, input-output and Sankey diagram table in period 75 (in current prices, in €10's bi).

Table B.2.1 Balance-sheet matrix in period 75 (in current prices, in €10's bi). Area 1 (European Union) and Area 2 (Rest of the World)

	H1	F1	G1	B1	CB1	xr1	H2	F2	G2	B2	CB2	Tot
Money	83.13	0.00	0.00	0.00	-83.13	1	270.40	0.0	0.00	0.00	-270.4	0.00
Advances	0.00	0.00	0.00	0.00	0.00	1	0.00	0.0	0.00	0.00	0.0	0.00
Deposits	554.25	0.00	0.00	-554.25	0.00	1	2163.29	0.0	0.00	-2163.29	0.0	0.00
Loans	-110.50	-371.11	0.00	481.61	0.00	1	-424.54	-1658.9	0.00	2083.44	0.0	0.00
Area 1 bills	87.81	0.00	-255.42	72.64	66.27	1	28.70	0.0	0.00	0.00	0.0	0.00
Area 2 bills	26.34	0.00	0.00	0.00	16.86	1	287.02	0.0	-680.47	79.85	270.4	0.00
Area 1 shares	219.53	-248.23	0.00	0.00	0.00	1	28.70	0.0	0.00	0.00	0.0	0.00
Area 2 shares	17.56	0.00	0.00	0.00	0.00	1	516.64	-534.2	0.00	0.00	0.0	0.00
Capital stock	0.00	619.34	0.00	0.00	0.00	1	0.00	2193.1	0.00	0.00	0.0	2812.45
Net financial wealth	-878.13	0.00	255.42	0.00	0.00	1	-2870.21	0.0	680.47	0.00	0.0	-2812.45
Total	0.00	0.00	0.00	0.00	0.00		0.00	0.0	0.00	0.00	0.0	0.00

Table B.2.2. Transactions-flow matrix in period 75 (in current prices, in €10's bi). Area 1 (European Union) and Area 2 (Rest of the World)

	H1	F1(curr)	F1(kap)	G1	B1	CB1	xr1	H2	F2(curr)	F2(kap)	G2	B2	CB2	Tot
Consumption	-831.32	831.32	0.00	0.00	0.00	0.00	1	-2703.96	2703.96	0.00	0.00	0.00	0.00	0
Investment	0.00	212.26	-154.84	-57.42	0.00	0.00	1	0.00	923.48	-657.93	265.55	0.00	0.00	0
Government spending	0.00	269.91	0.00	-269.91	0.00	0.00	1	0.00	766.98	0.00	-766.98	0.00	0.00	0
Export of Area 1	0.00	217.08	0.00	0.00	0.00	0.00	1	0.00	-217.08	0.00	0.00	0.00	0.00	0
Import of Area 1	0.00	-213	0.00	0.00	0.00	0.00	1	0.00	213	0.00	0.00	0.00	0.00	0
[Value added]	0.00	[1195.75]	0.00	0.00	0.00	0.00	1	0.00	[4018.28]	0.00	0.00	0.00	0.00	0
Wage bill	614.74	-614.74	0.00	0.00	0.00	0.00	1	1976.22	-1976.22	0.00	0.00	0.00	0.00	0
Corporate profit	414.20	-418.75	0.00	0.00	0.00	0.00	1	1338.91	-1334.36	0.00	0.00	0.00	0.00	0
Amortization	0.00	-154.84	154.84	0.00	0.00	0.00	1	0.00	-657.93	657.93	0.00	0.00	0.00	0
Bank profit	4.81	0	0.00	0.00	-4.81	0.00	1	42.45	0	0.00	0.00	-42.45	0.00	0
CB profit	0.00	0	0.00	1.00	0.00	-1.00	1	0.00	0	0.00	5.41	0.00	-5.41	0
Income tax revenue	-207.18	0	0.00	207.18	0.00	0.00	1	-668.56	0	0.00	668.56	0.00	0.00	0
VAT revenue	0.00	-102.09	0.00	102.09	0.00	0.00	1	0.00	-352.69	0.00	352.69	0.00	0.00	0
Tariffs revenue	0.00	-19.73	0.00	19.36	0.00	0.00	1	0.00	-19.36	0.00	19.73	0.00	0.00	0
Interests on deposits	5.54	0	0.00	0.00	-5.54	0.00	1	21.62	0	0.00	0.00	-21.62	0.00	0
Interests on loans	-2.20	-7.42	0.00	0.00	9.63	0.00	1	-12.71	-49.77	0.00	0.00	62.48	0.00	0
Interests on Area 1 bills	0.88	0	0.00	-2.55	0.73	0.66	1	0.29	0	0.00	0.00	0.00	0.00	0
Interests on Area 2 bills	0.53	0	0.00	0.00	0.00	0.34	1	5.74	0	0.00	-13.61	1.60	5.41	0
Change in money stock	0.00	0	0.00	0.00	0.00	0.00	1	0.00	0	0.00	0.00	0.00	0.00	0
Change in advances	0.00	0	0.00	0.00	0.00	0.00	1	0.00	0	0.00	0.00	0.00	0.00	0
Change in deposits	-0.31	0	0.00	0.00	0.31	0.00	1	-0.94	0	0.00	0.00	0.94	0.00	0
Change in loans	0.31	0	0.00	0.00	-0.31	0.00	1	0.94	0	0.00	0.00	-0.94	0.00	0
Change in Area 1 bills	0.00	0	0.00	0.25	0.00	-0.25	1	0.00	0	0.00	0.00	0.00	0.00	0
Change in Area 2 bills	0.00	0	0.00	0.00	0.00	0.25	1	0.00	0	0.00	-0.25	0.00	0.00	0
Change in Area 1 shares	0.00	0	0.00	0.00	0.00	0.00	1	0.00	0	0.00	0.00	0.00	0.00	0
Change in Area 2 shares	0.00	0	0.00	0.00	0.00	0.00	1	0.00	0	0.00	0.00	0.00	0.00	0
Revaluation effects	0.00	0	0.00	0.00	0.00	0.00	1	0.00	0	0.00	0.00	0.00	0.00	0
Total	0.00	0	0.00	0.00	0.00	0.00		0.00	0	0.00	0.00	0.00	0.00	0

Table B.2.3. Multi-area input-output matrix in period 75 (current prices, in 10's billions of EU). Area 1 (European Union) and Area 2 (Rest of the World)

	Area 1 demand for inputs					Area 2 demand for inputs						
	A	M	S	W	R	A	M	S	W	R	Final dem.	Output
Area 1 production												
Agriculture	4.81	22.1	2.34	0.01	0.04	0.23	0.99	0.43	0.01	0	57.58	4.81
Manufacturing	10.9	295.64	94.38	1.17	7.17	1.57	43.8	15.83	0.14	0.28	935.81	10.9
Services	8.26	162.06	373.23	2.28	6.07	0.72	13.13	27.33	0.16	0.1	1450.3	8.26
Waste manag.	0.24	3.44	4.01	1.24	0.36	0.07	0.22	0.2	0.01	0	9.79	0.24
Recycling	0.13	17.4	1.85	0.09	1.84	0.01	2.4	0.21	0	0.04	23.94	0.13
Area 2 production												
Agriculture	0.94	2.62	0.65	0	0.03	47.08	150.77	24.8	0.2	0.11	385.91	0.94
Manufacturing	1.87	73.31	14.39	0.13	2.53	48.55	1702.24	433.82	5.11	5.04	3801.98	1.87
Services	0.37	12.07	29.99	0.14	0.38	51.8	557.64	1186.23	6.91	3.42	4534.49	0.37
Waste manag.	0.02	0.22	0.09	0.02	0.01	2.7	11.48	19.6	1.96	0.09	36.19	0.02
Recycling	0	0.28	0.02	0	0.02	0.82	11.28	0.47	0.02	1.06	13.98	0
Value added												
~ Compensation of employees	5.49	158.07	445.44	1.83	3.92	106.43	490.1	1366.34	10.62	2.74		5.49
~ G.O. surplus and mixed incomes	24.54	188.61	483.91	2.88	1.56	125.92	817.92	1459.25	11.06	1.1		24.54
Output	57.58	935.81	1450.3	9.79	23.94	385.91	3801.98	4534.49	36.19	13.98		57.58

Table B.2.4. Area-specific physical flow matrix in period 75 (matter = 10Mt, energy = 10, 000 EJ). Area 1 (European Union) and Area 2 (Rest of the World)

	Matter			Energy		
	Area 1	Area 2	Global	Area 1	Area 2	Global
INPUTS						
Extracted matter	442.69	4967.12	5409.81			
Recycled socio-economic stock	26.03	182.24	208.27			
Renewable energy			0	1628.69	6124.06	7752.75
Non-renewable energy	25.04	87.86	112.91	9971.55	37619.2	47590.74
Oxygen	66.86	234.6	301.46			
OUTPUTS						
Industrial CO_2 emissions	-91.9	-322.46	-414.37			
Discarded socio-economic stock	-111.88	-911.21	-1023.09			
Dissipated energy				-11600.24	-43743.25	-23200.48
Δ IN SOCIO-ECONOMIC STOCK	356.84	4238.15	4594.99			
DIFFERENCE	0	0	0	0	0	0

Table B.2.5 Global physical stock-flow matrix in period 75 (matter = 10Mt, energy = 10, 000 EJ). Area 1 (European Union) and Area 2 (Rest of the World)

	Material reserves	Energy reserves	CO_2 concentration	Socio-economic stock
INITIAL STOCK	23586028.53	-3243287.67	29526.45	355113.85
Resources converted into reserves	187918.58	1302.72		
CO_2 emissions			414.37	
Production of material goods				5618.07
Extraction/us of matter/energy	-5409.81	-47590.74		
Destruction of socio-economic stock				-1023.09
FINAL STOCK	23768537.31	-3289575.69	29940.82	359708.84
DIFFERENCE	0	0	0	0

Figure B.2.1 Sankey diagram of cross-sector transactions and changes in stocks in $t = 75$

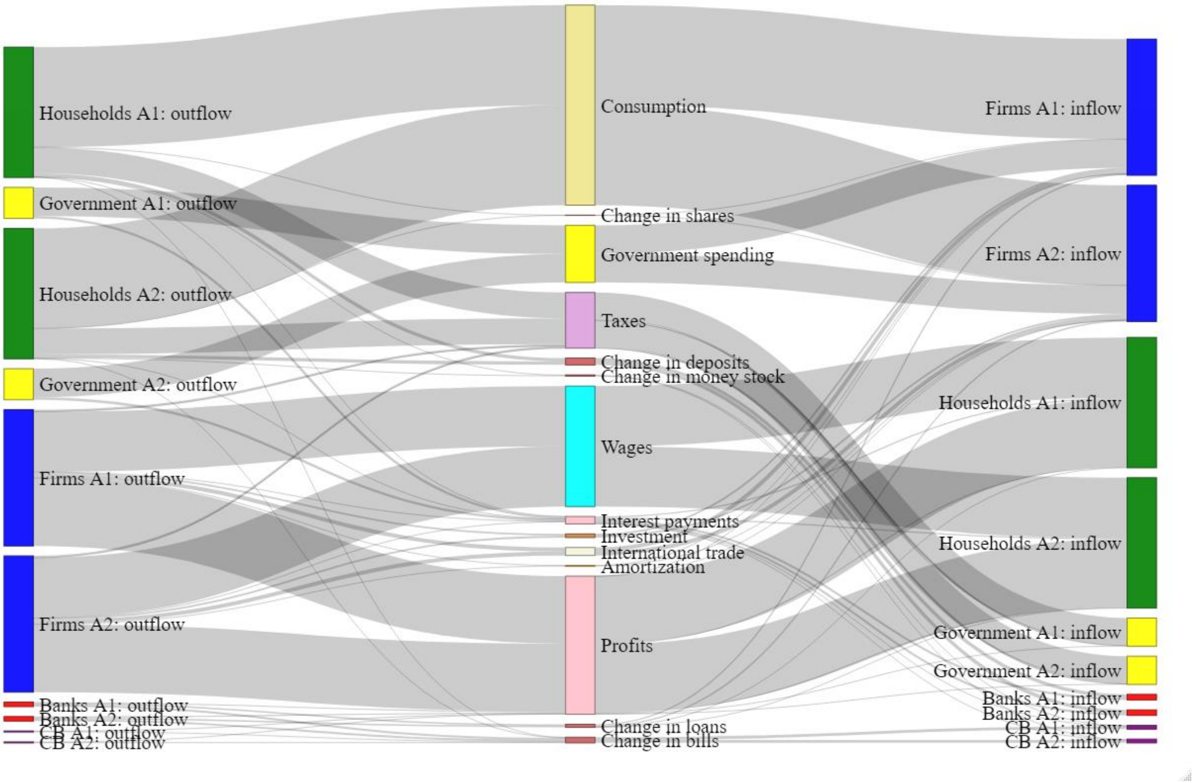


Figure B.2.2. Sankey diagram of cross-industry interdependencies in $t = 75$

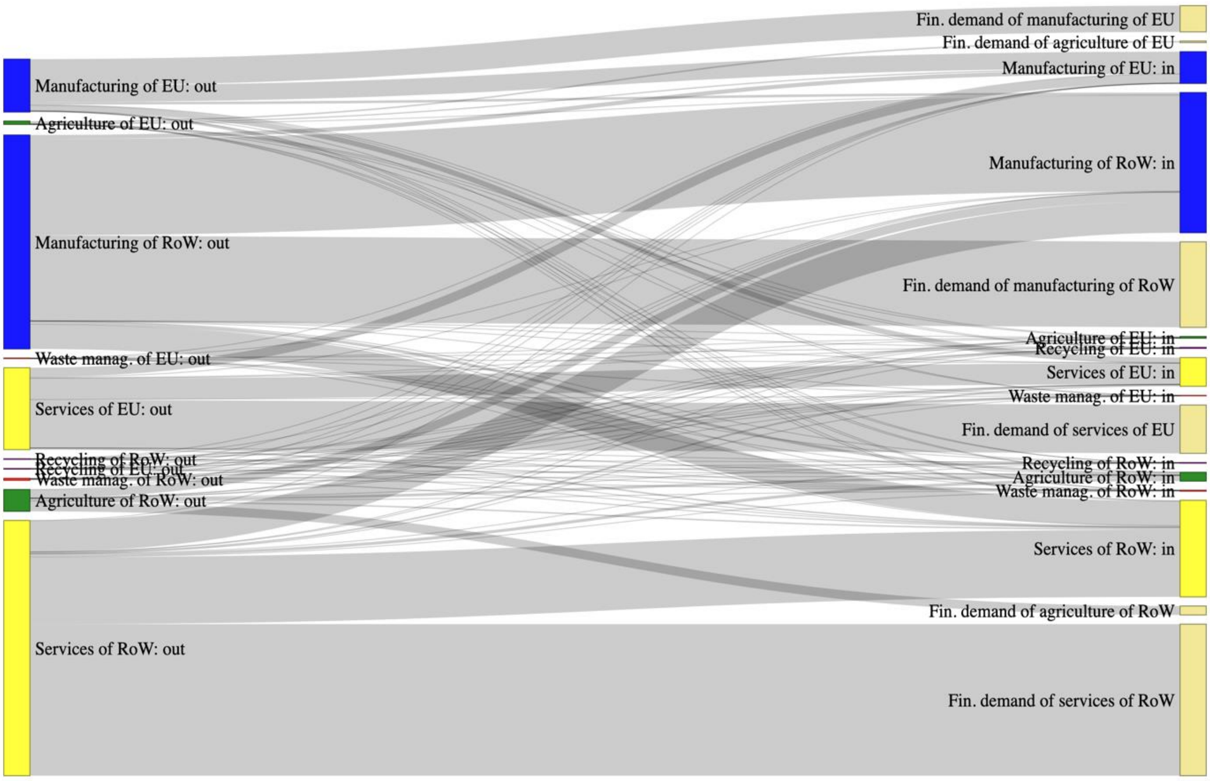
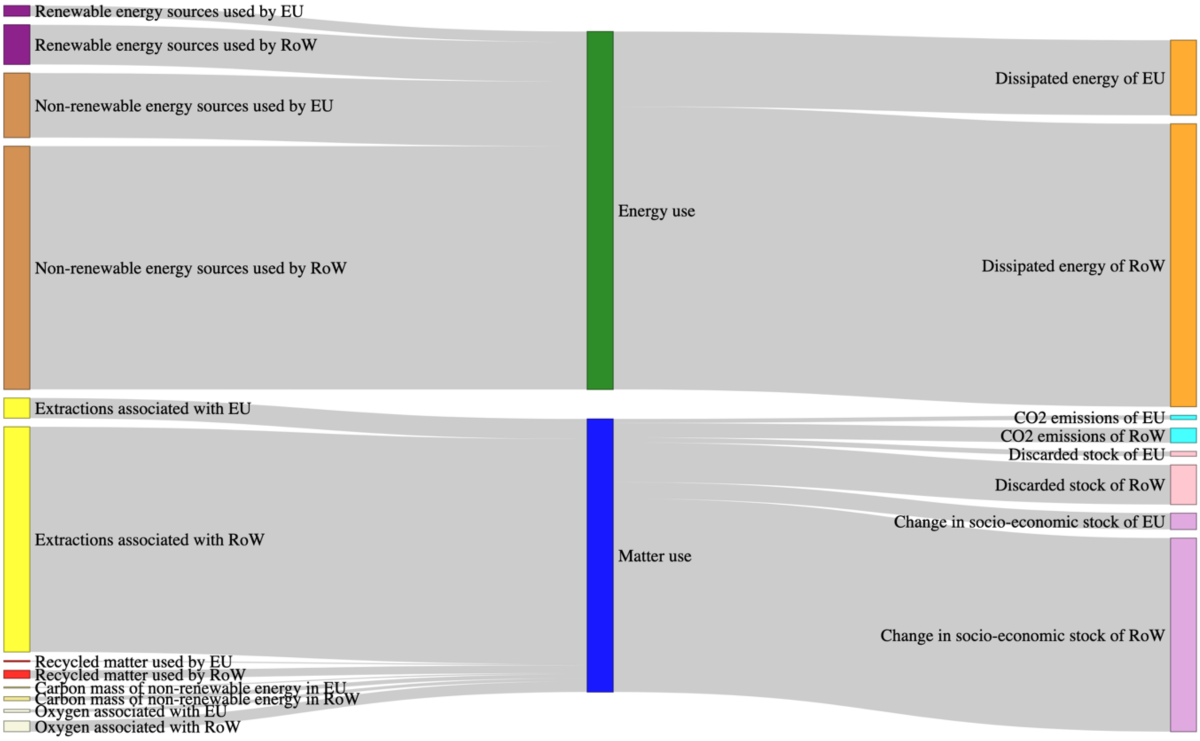


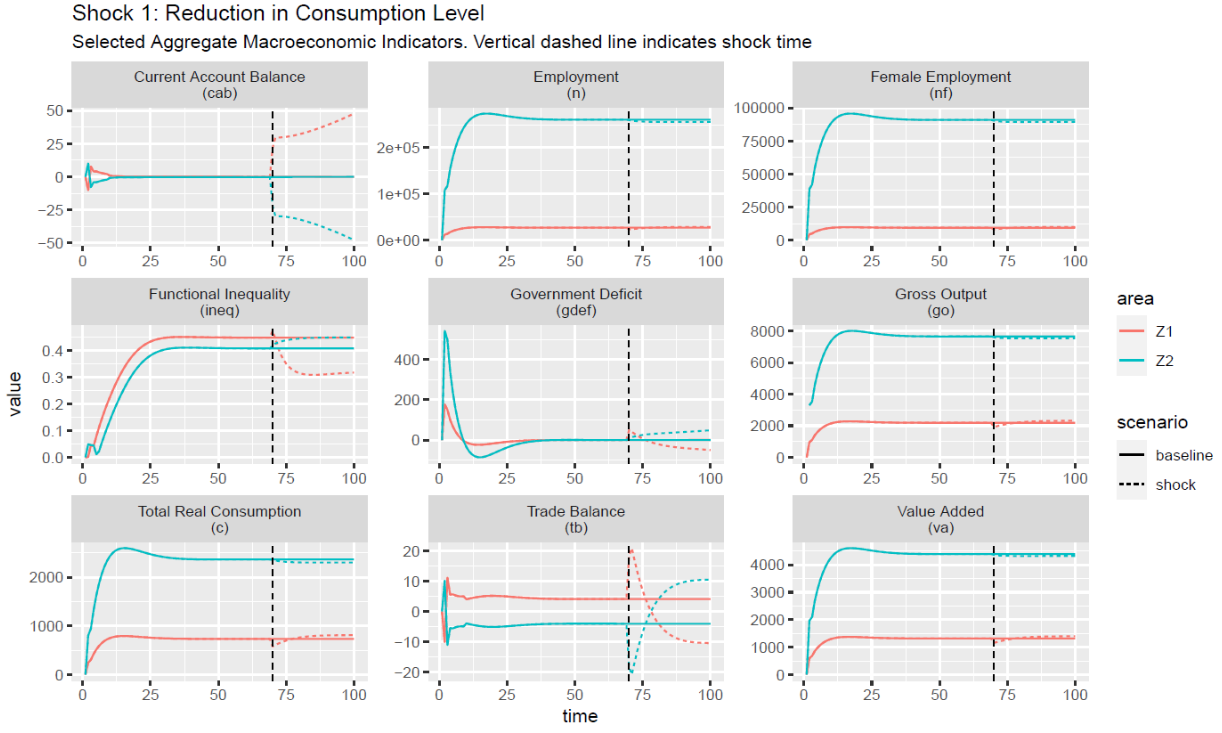
Figure B.2.3. Sankey diagram of material flows in $t = 75$

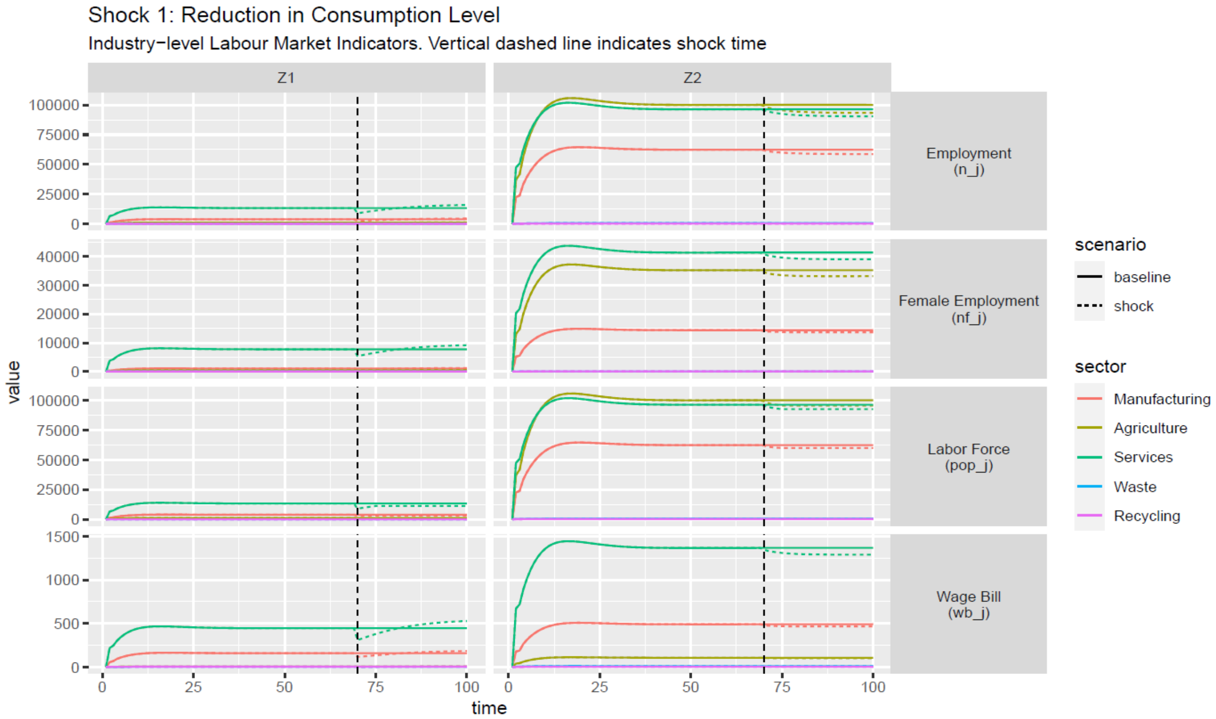


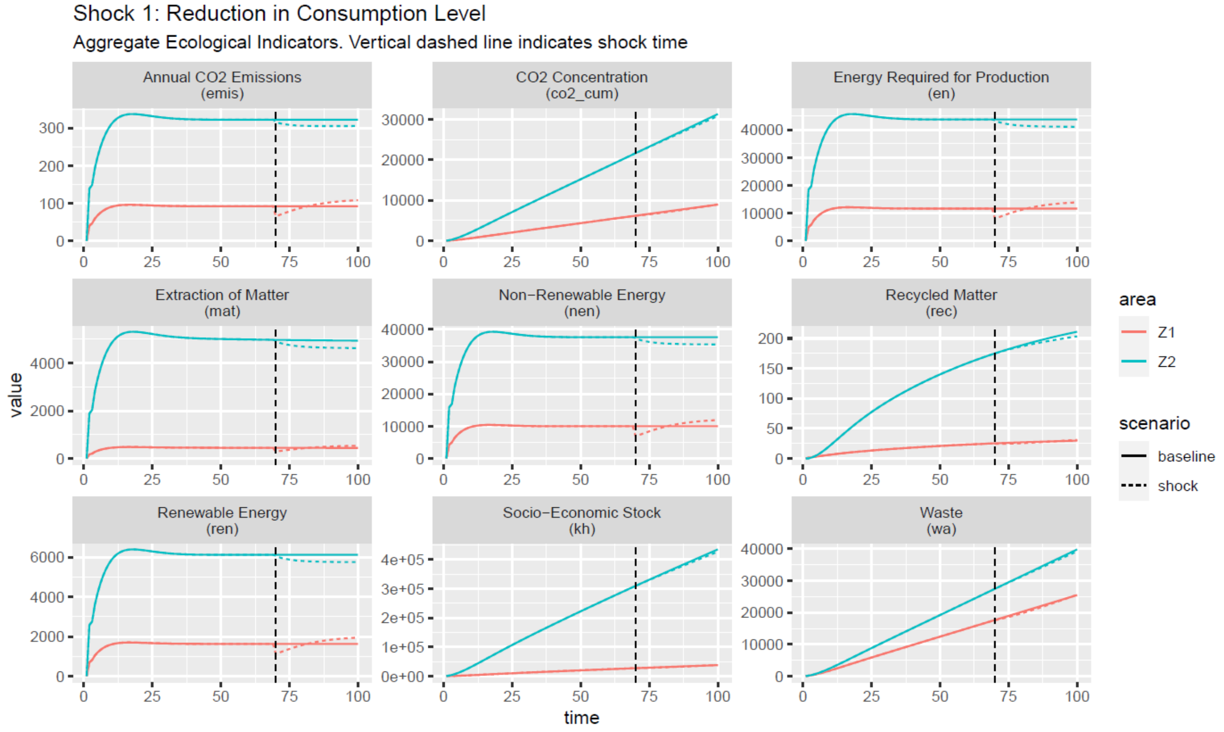
Appendix C– CE Scenarios

This section presents graphs of the evolution of main macroeconomic, labour market, and ecological variables included in the model for each shock.

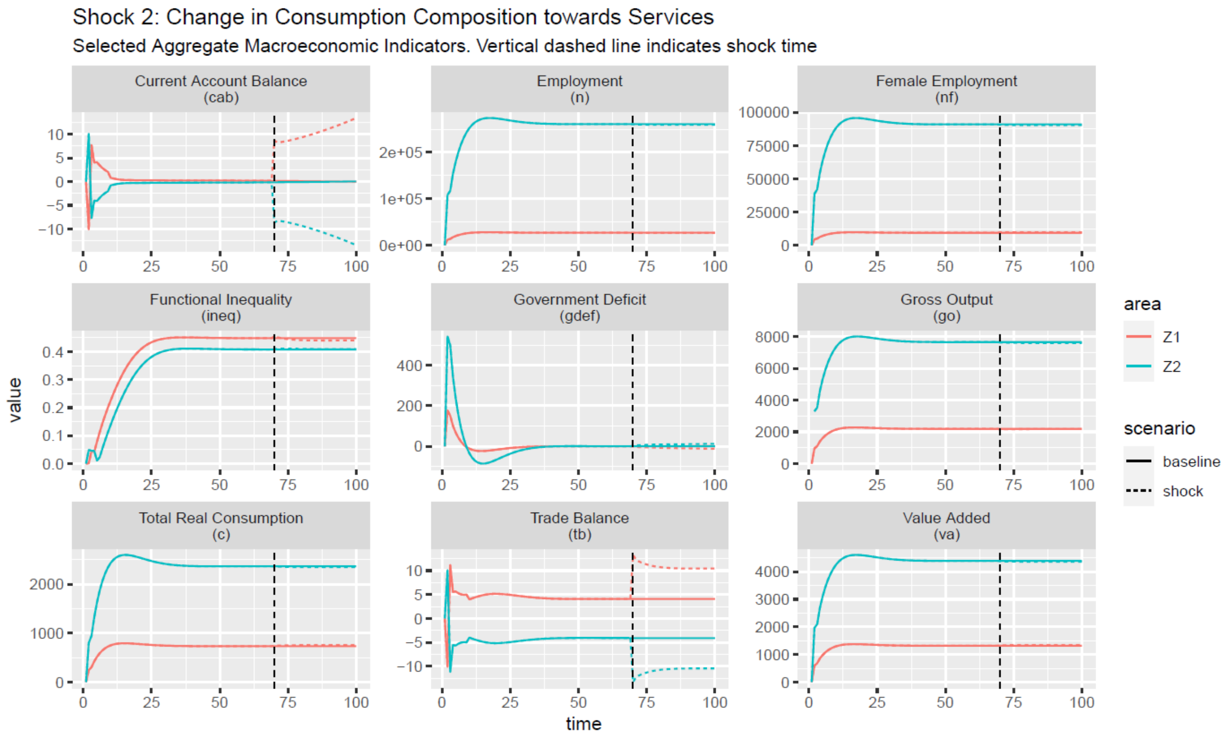
[C.1] Shock 1.1



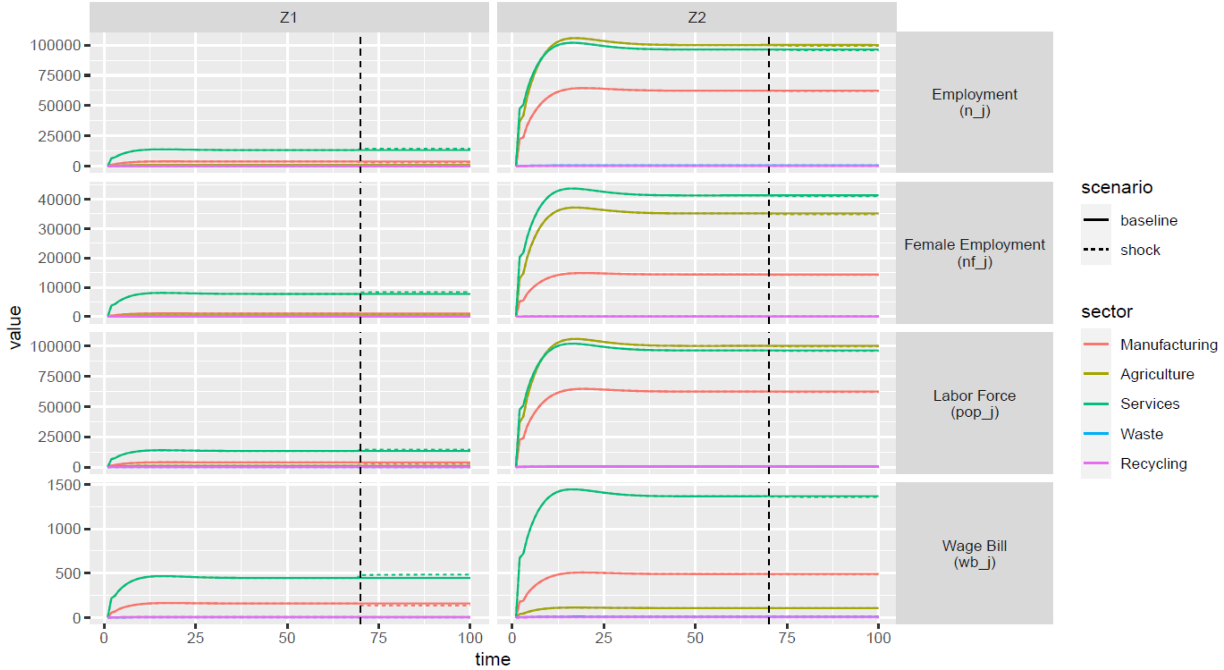



Shock 1: Reduction in Consumption Level
Aggregate Ecological Indicators. Vertical dashed line indicates shock time
Annual CO2 Emissions (emis)
CO2 Concentration (co2_cum)
Energy Required for Production (en)
Extraction of Matter (mat)
Non−Renewable Energy (nen)
Recycled Matter (rec)
Renewable Energy (ren)
Socio−Economic Stock (kh)
Waste (wa)
value
time
area
Z1
Z2
scenario
baseline
shock

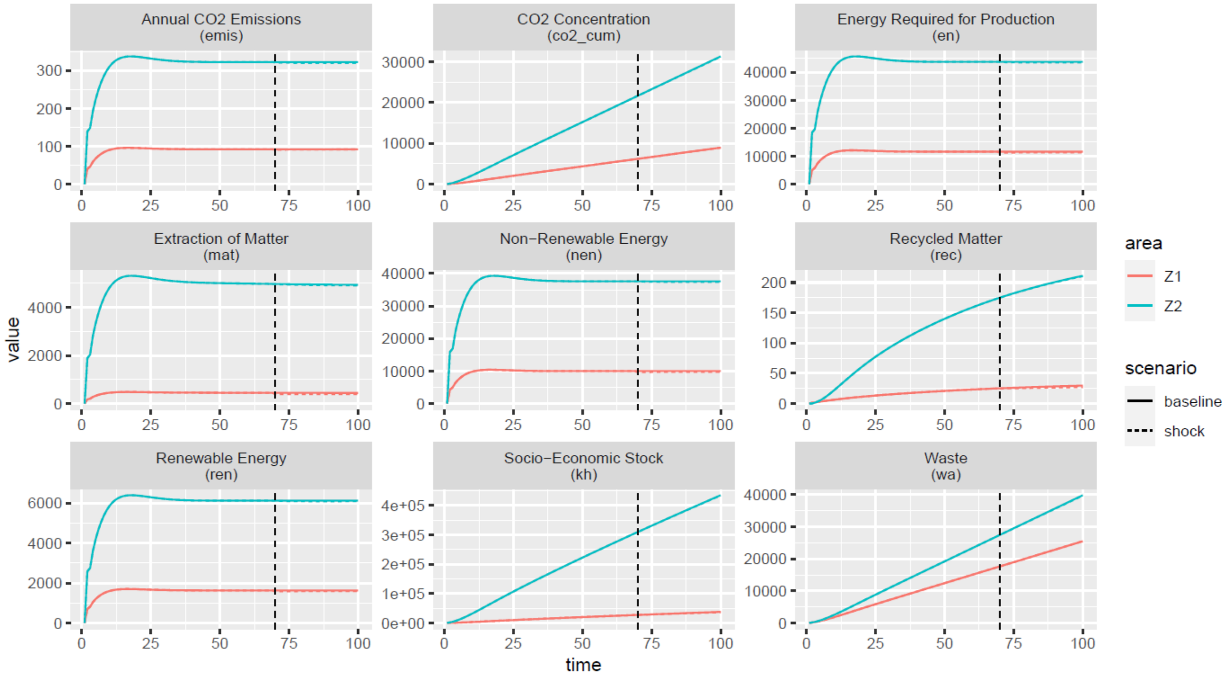
[C.2] Shock 1.2


Shock 2: Change in Consumption Composition towards Services
Selected Aggregate Macroeconomic Indicators. Vertical dashed line indicates shock time
Current Account Balance (cab)
Employment (n)
Female Employment (nf)
Functional Inequality (ineq)
Government Deficit (gdef)
Gross Output (go)
Total Real Consumption (c)
Trade Balance (tb)
Value Added (va)
value
time
area
Z1
Z2
scenario
baseline
shock

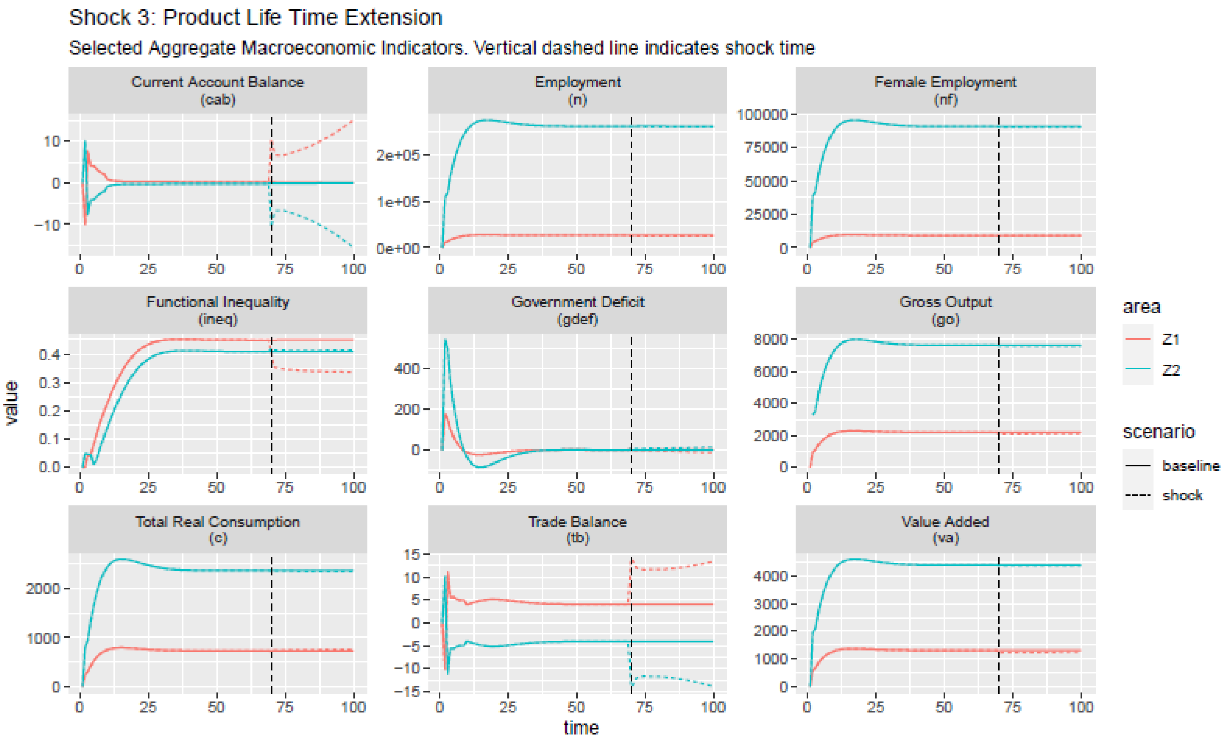
Shock 2: Change in Consumption Composition towards Services
Industry−level Labour Market Indicators. Vertical dashed line indicates shock time

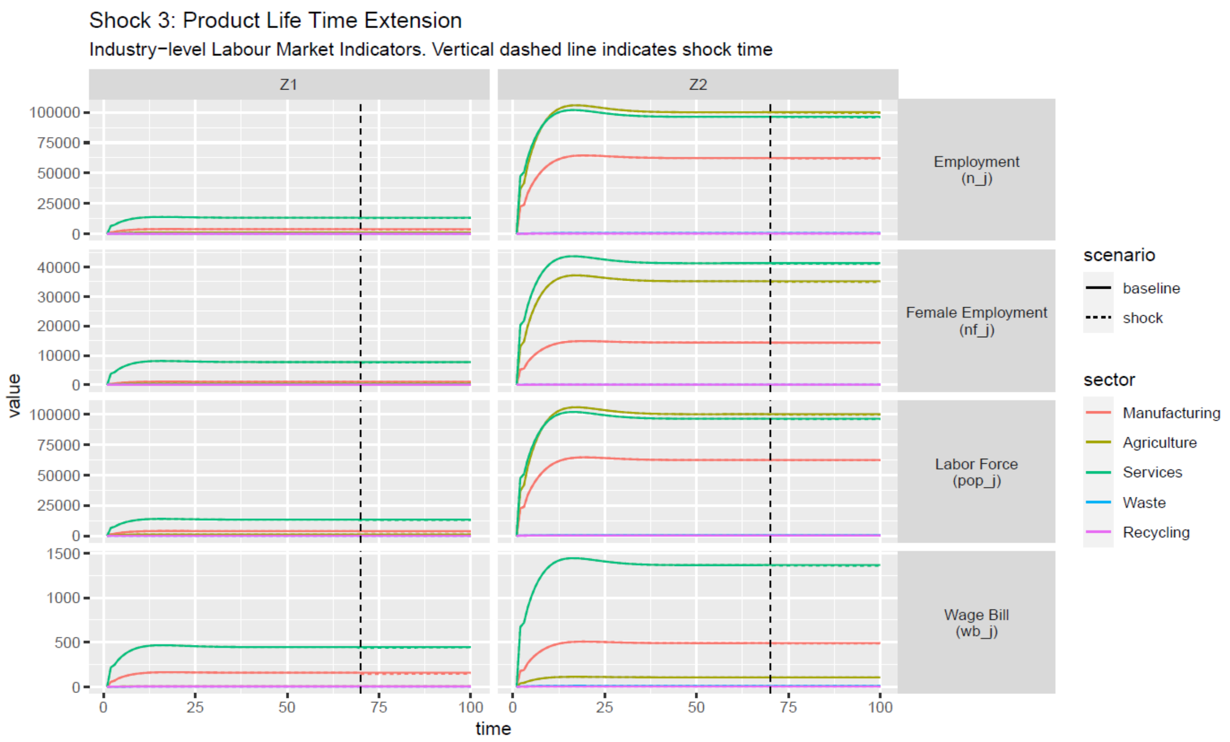


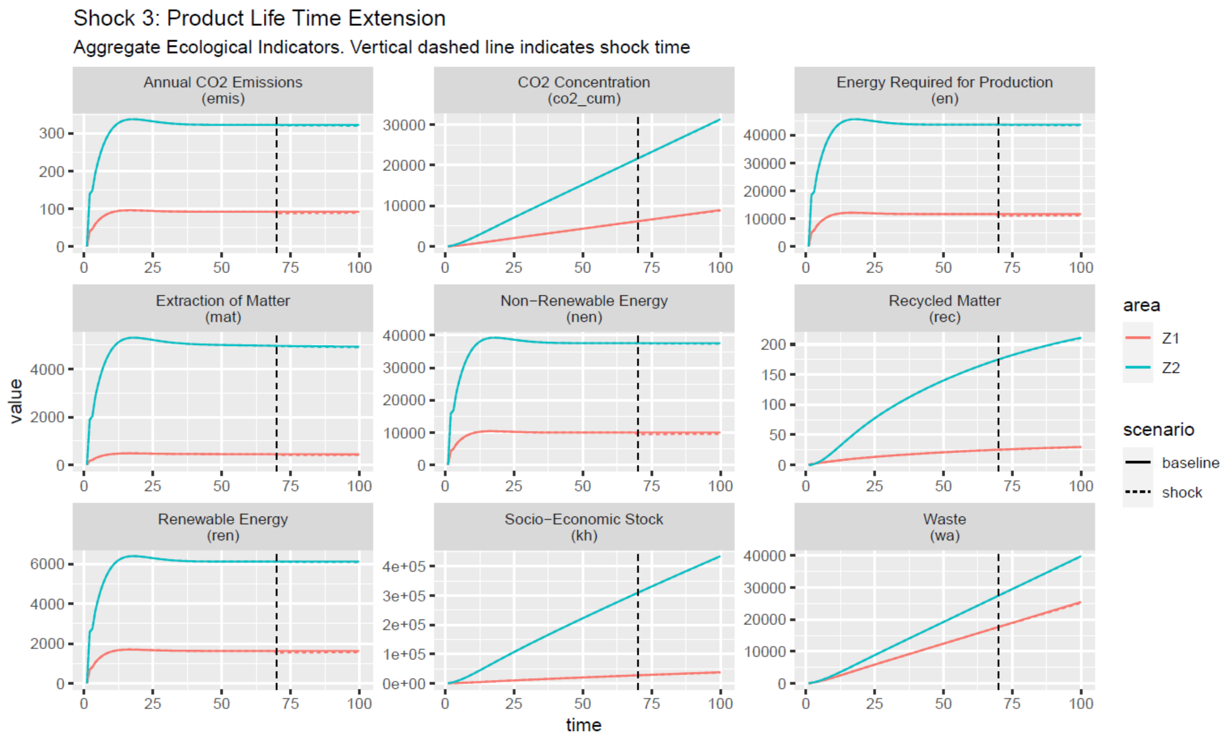
Shock 2: Change in Consumption Composition towards Services
Aggregate Ecological Indicators. Vertical dashed line indicates shock time



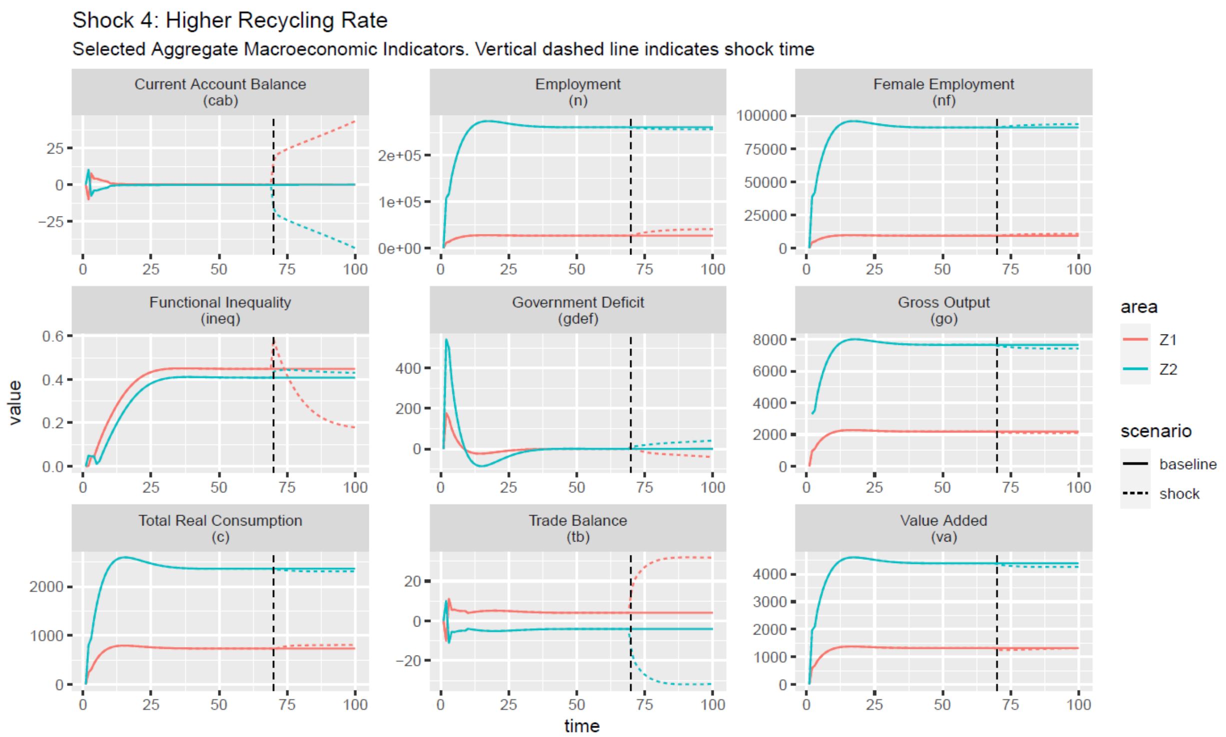
[C.2] Shock 1.3


Shock 3: Product Life Time Extension
Selected Aggregate Macroeconomic Indicators. Vertical dashed line indicates shock time
Current Account Balance (cab)
Employment (n)
Female Employment (nf)
Functional Inequality (ineq)
Government Deficit (gdef)
Gross Output (go)
Total Real Consumption (c)
Trade Balance (tb)
Value Added (va)
value
time
area
Z1
Z2
scenario
baseline
shock


Shock 3: Product Life Time Extension
Industry−level Labour Market Indicators. Vertical dashed line indicates shock time
Z1
Z2
Employment (n_j)
Female Employment (nf_j)
Labor Force (pop_j)
Wage Bill (wb_j)
value
time
scenario
baseline
shock
sector
Manufacturing
Agriculture
Services
Waste
Recycling

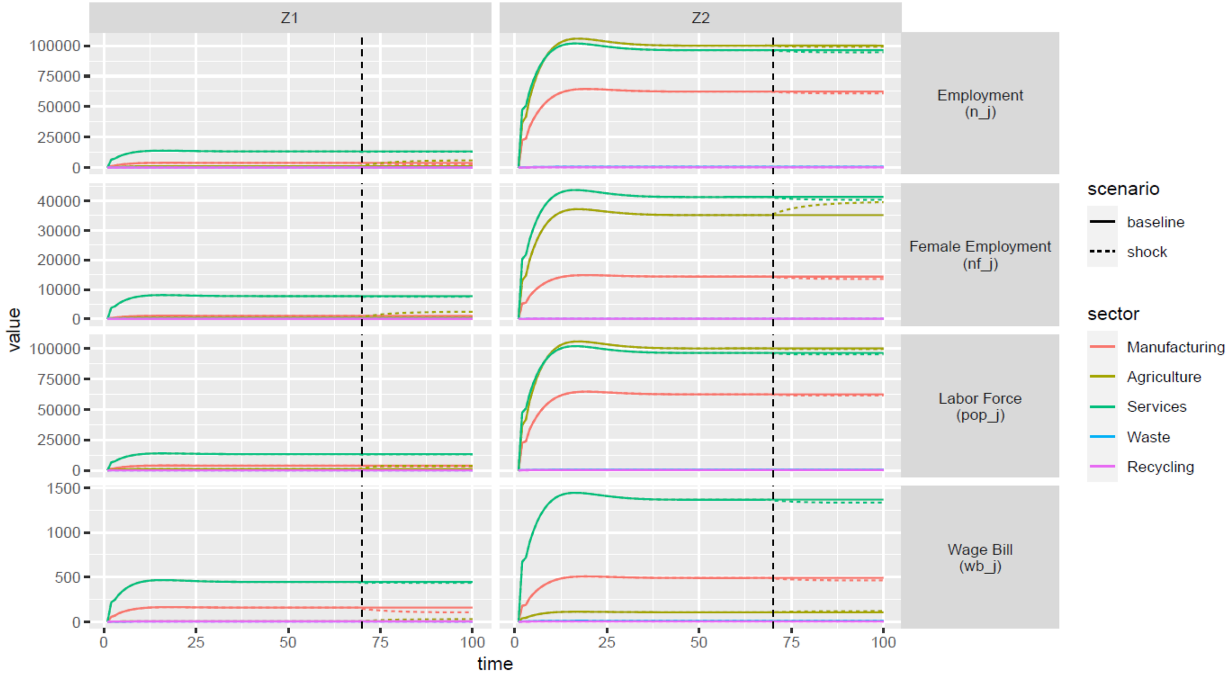

Shock 3: Product Life Time Extension
Aggregate Ecological Indicators. Vertical dashed line indicates shock time
Annual CO2 Emissions (emis)
CO2 Concentration (co2_cum)
Energy Required for Production (en)
Extraction of Matter (mat)
Non−Renewable Energy (nen)
Recycled Matter (rec)
Renewable Energy (ren)
Socio−Economic Stock (kh)
Waste (wa)
value
time
area
Z1
Z2
scenario
baseline
shock

[C.4] Shock 1.4


Shock 4: Higher Recycling Rate
Selected Aggregate Macroeconomic Indicators. Vertical dashed line indicates shock time
Current Account Balance (cab)
Employment (n)
Female Employment (nf)
Functional Inequality (ineq)
Government Deficit (gdef)
Gross Output (go)
Total Real Consumption (c)
Trade Balance (tb)
Value Added (va)
value
time
area
Z1
Z2
scenario
baseline
shock

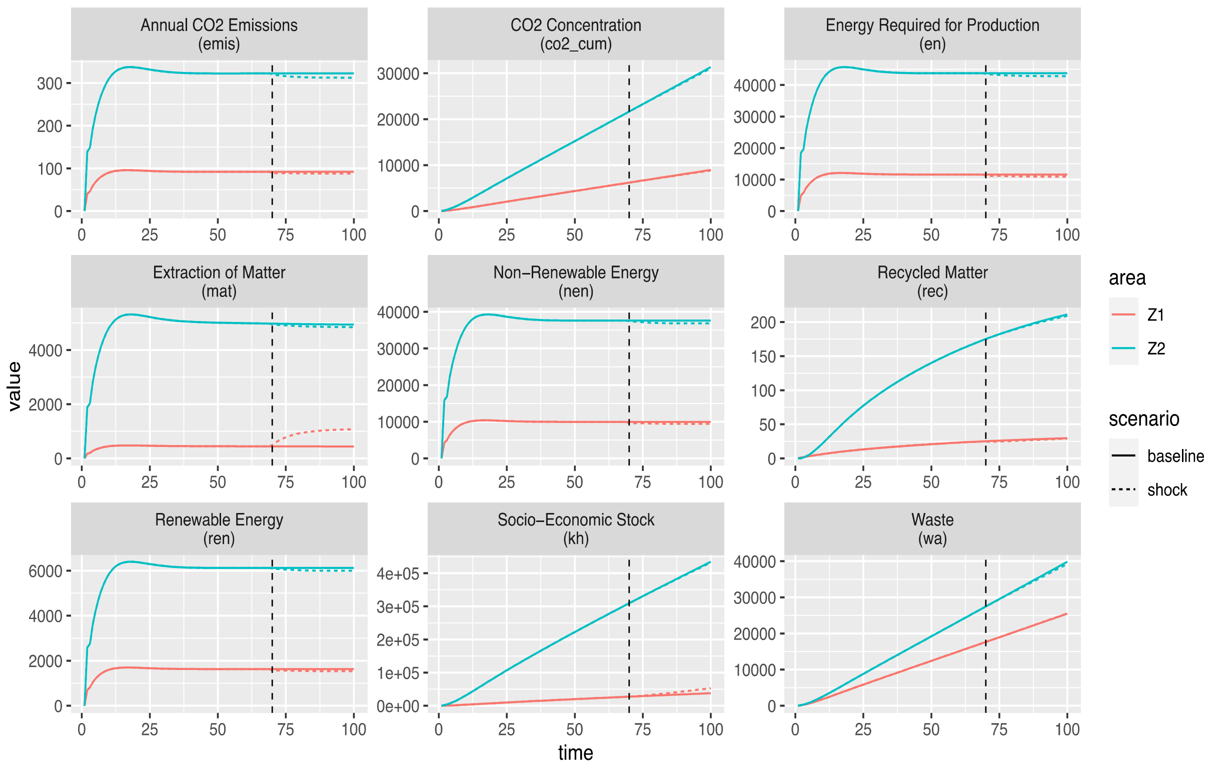
Shock 4: Higher Recycling Rate

Industry−level Labour Market Indicators. Vertical dashed line indicates shock time

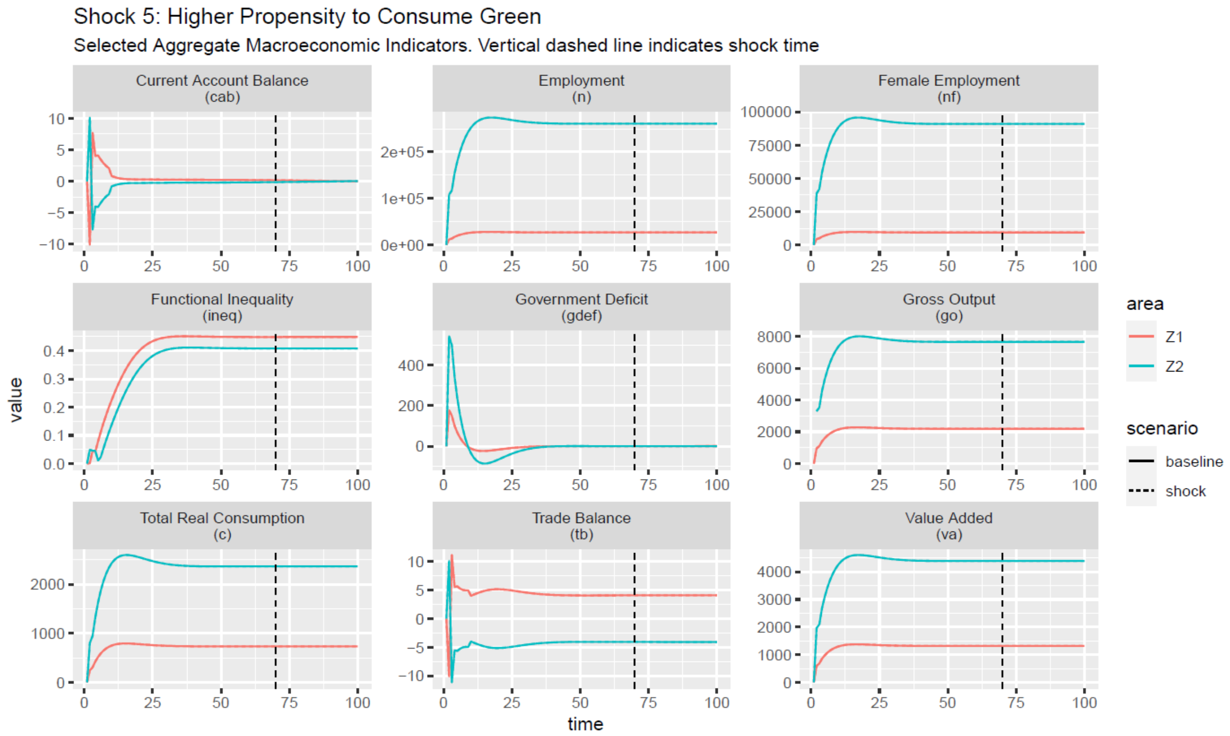


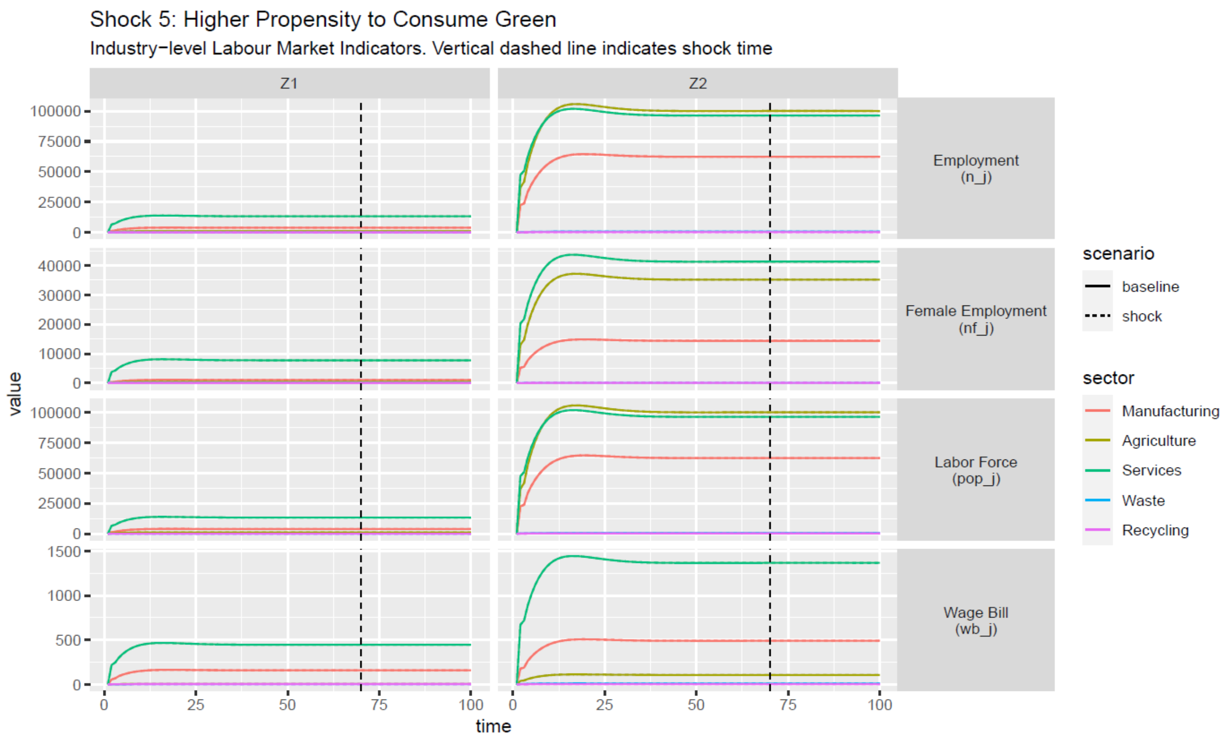
Shock 4: Higher Recycling Rate

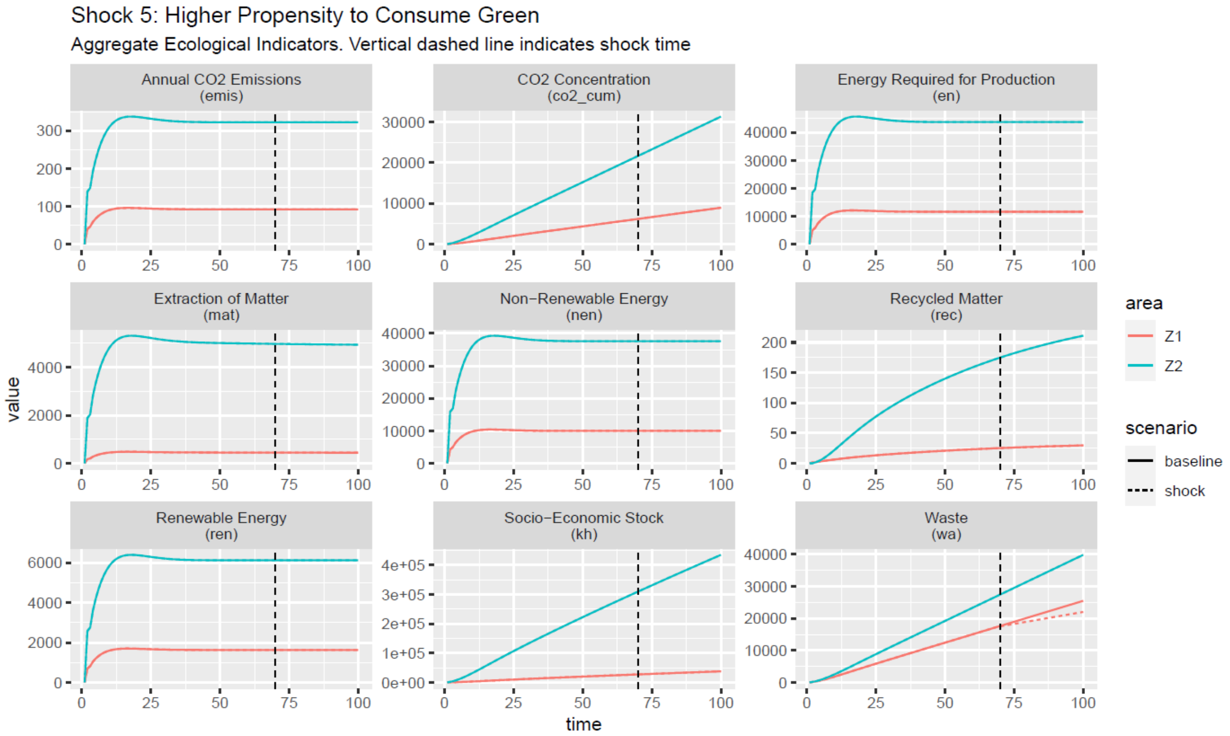
Aggregate Ecological Indicators. Vertical dashed line indicates shock time



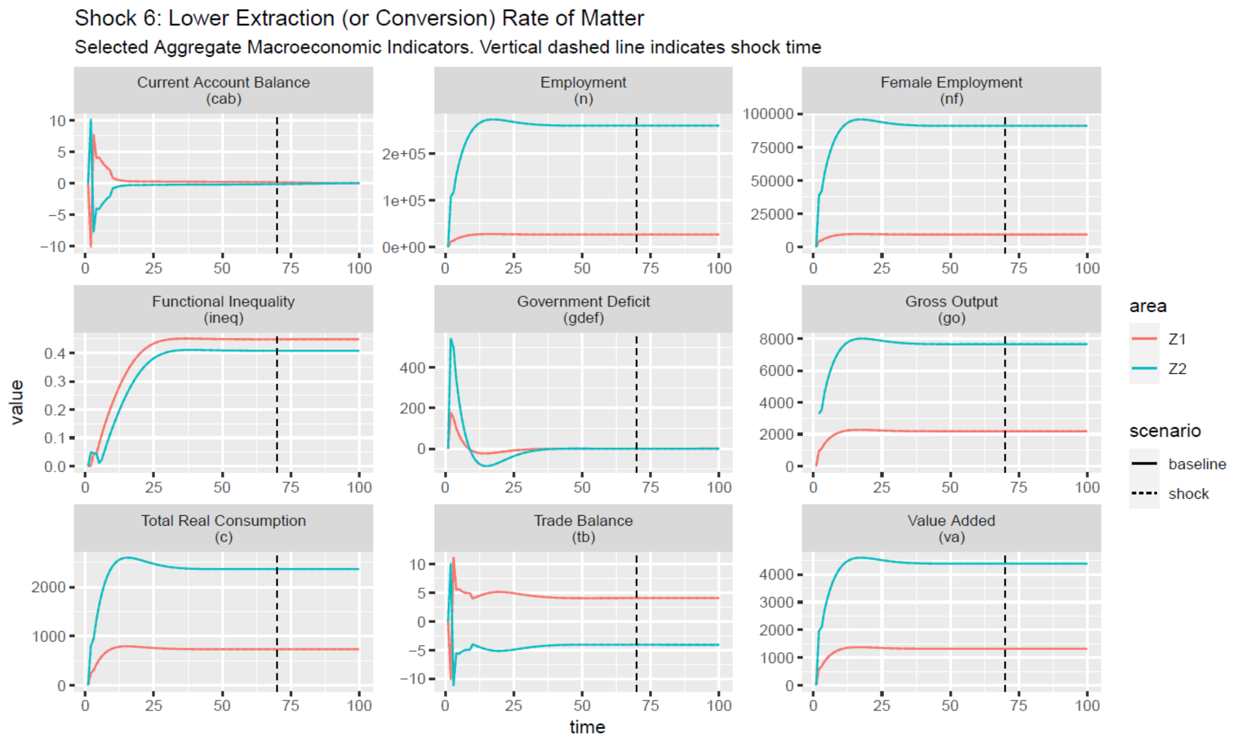
[C.5] Shock 1.5


Shock 5: Higher Propensity to Consume Green
Selected Aggregate Macroeconomic Indicators. Vertical dashed line indicates shock time
Current Account Balance
(cab)
Employment
(n)
Female Employment
(nf)
Functional Inequality
(ineq)
Government Deficit
(gdef)
Gross Output
(go)
Total Real Consumption
(c)
Trade Balance
(tb)
Value Added
(va)
value
time
area
Z1
Z2
scenario
baseline
shock

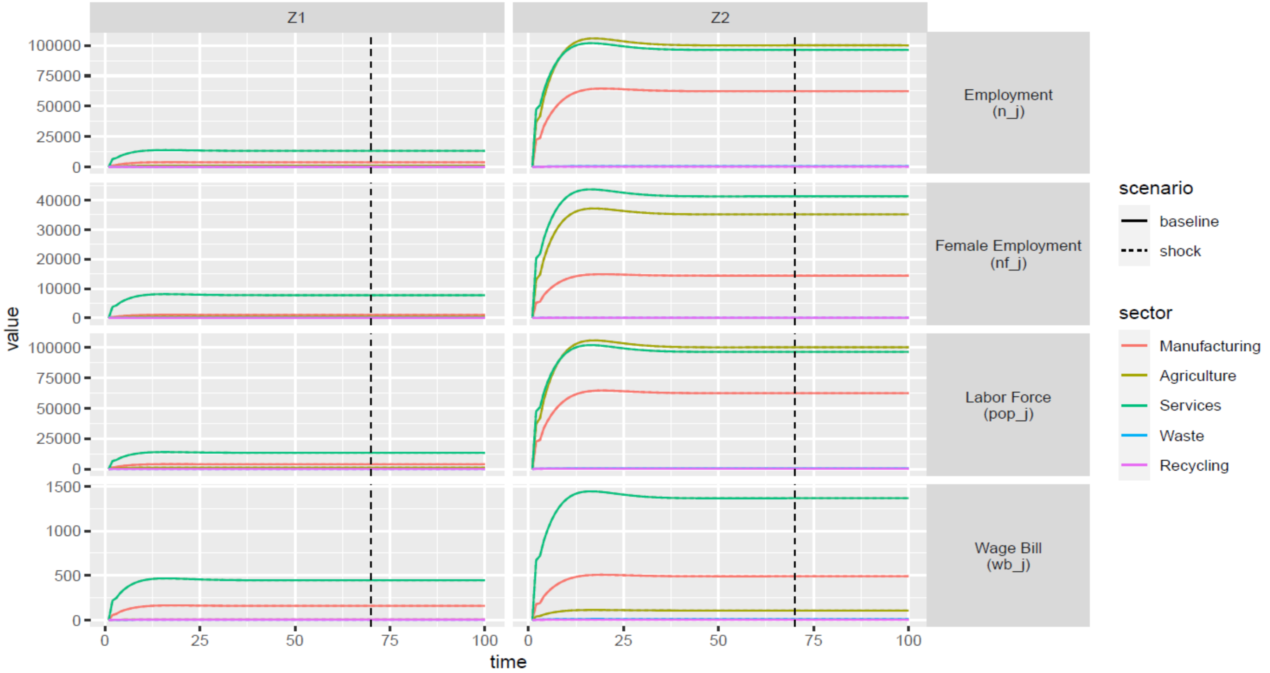

Shock 5: Higher Propensity to Consume Green
Industry−level Labour Market Indicators. Vertical dashed line indicates shock time
Z1
Z2
Employment
(n_j)
Female Employment
(nf_j)
Labor Force
(pop_j)
Wage Bill
(wb_j)
value
time
scenario
baseline
shock
sector
Manufacturing
Agriculture
Services
Waste
Recycling


Shock 5: Higher Propensity to Consume Green
Aggregate Ecological Indicators. Vertical dashed line indicates shock time
Annual CO2 Emissions (emis)
CO2 Concentration (co2_cum)
Energy Required for Production (en)
Extraction of Matter (mat)
Non−Renewable Energy (nen)
Recycled Matter (rec)
Renewable Energy (ren)
Socio−Economic Stock (kh)
Waste (wa)
value
time
area
Z1
Z2
scenario
baseline
shock

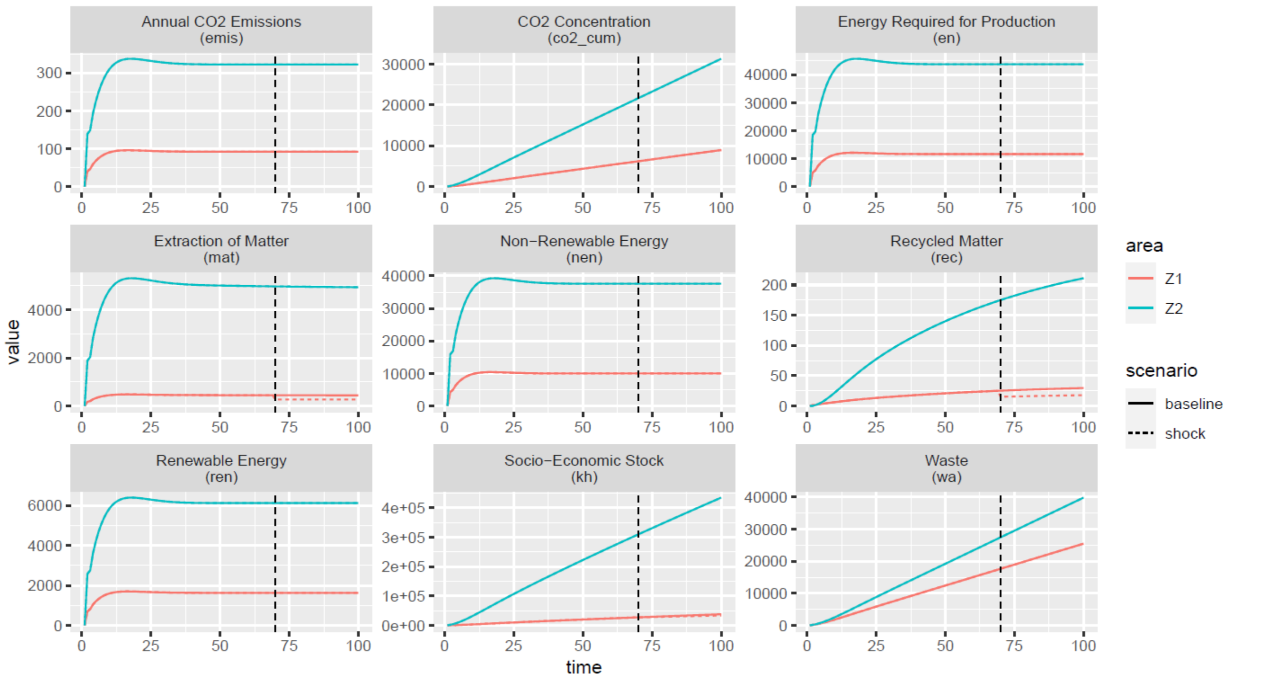
[C.6] Shock 1.6


Shock 6: Lower Extraction (or Conversion) Rate of Matter
Selected Aggregate Macroeconomic Indicators. Vertical dashed line indicates shock time
Current Account Balance (cab)
Employment (n)
Female Employment (nf)
Functional Inequality (ineq)
Government Deficit (gdef)
Gross Output (go)
Total Real Consumption (c)
Trade Balance (tb)
Value Added (va)
value
time
area
Z1
Z2
scenario
baseline
shock

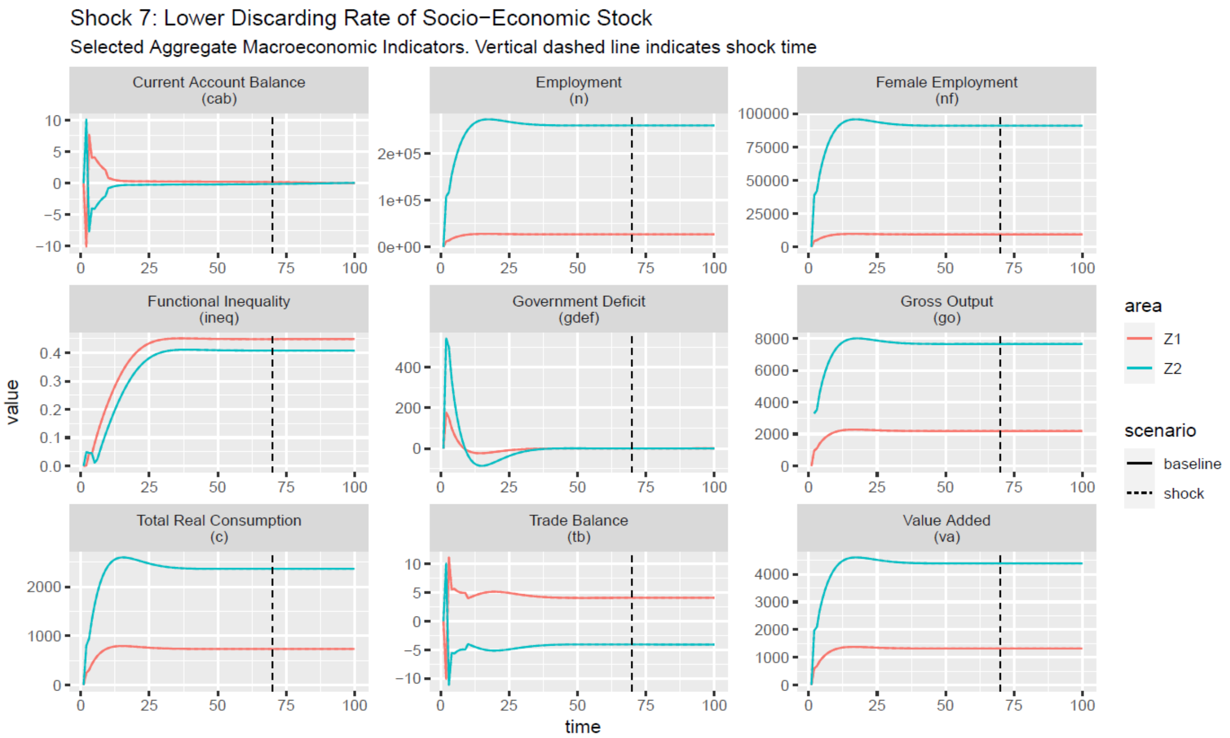
Shock 6: Lower Extraction (or Conversion) Rate of Matter
Industry−level Labour Market Indicators. Vertical dashed line indicates shock time

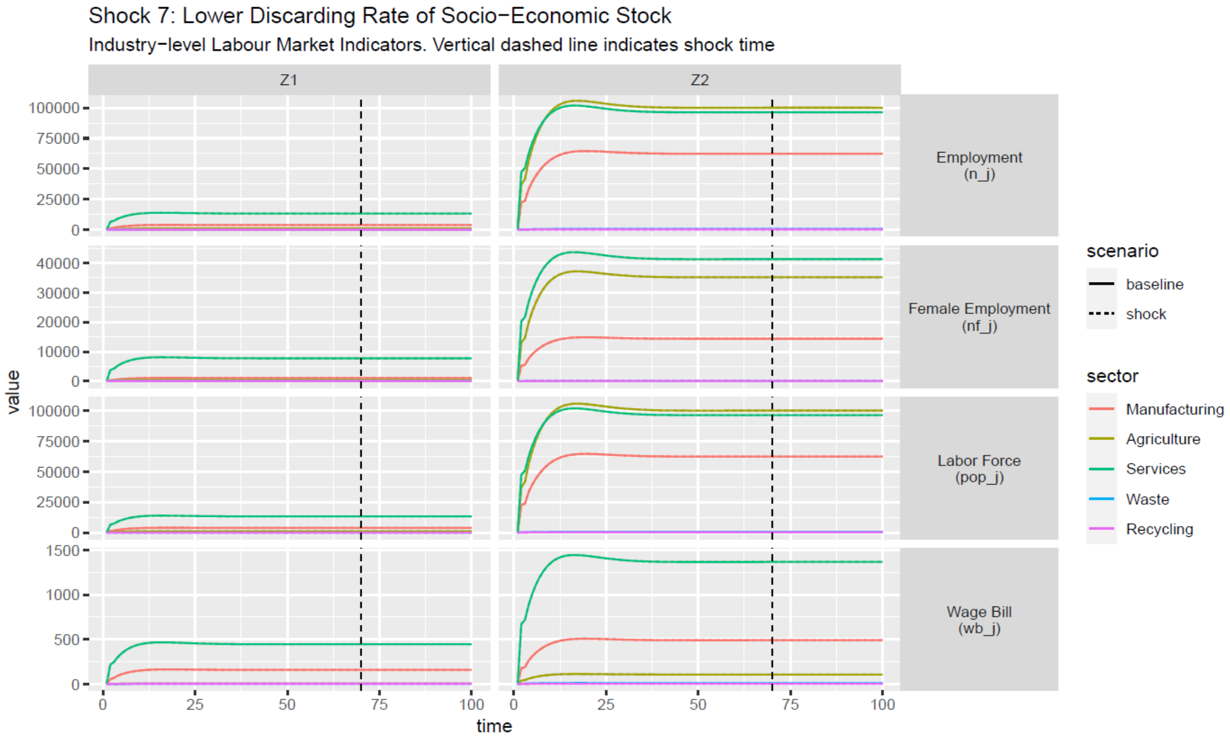


Shock 6: Lower Extraction (or Conversion) Rate of Matter
Aggregate Ecological Indicators. Vertical dashed line indicates shock time



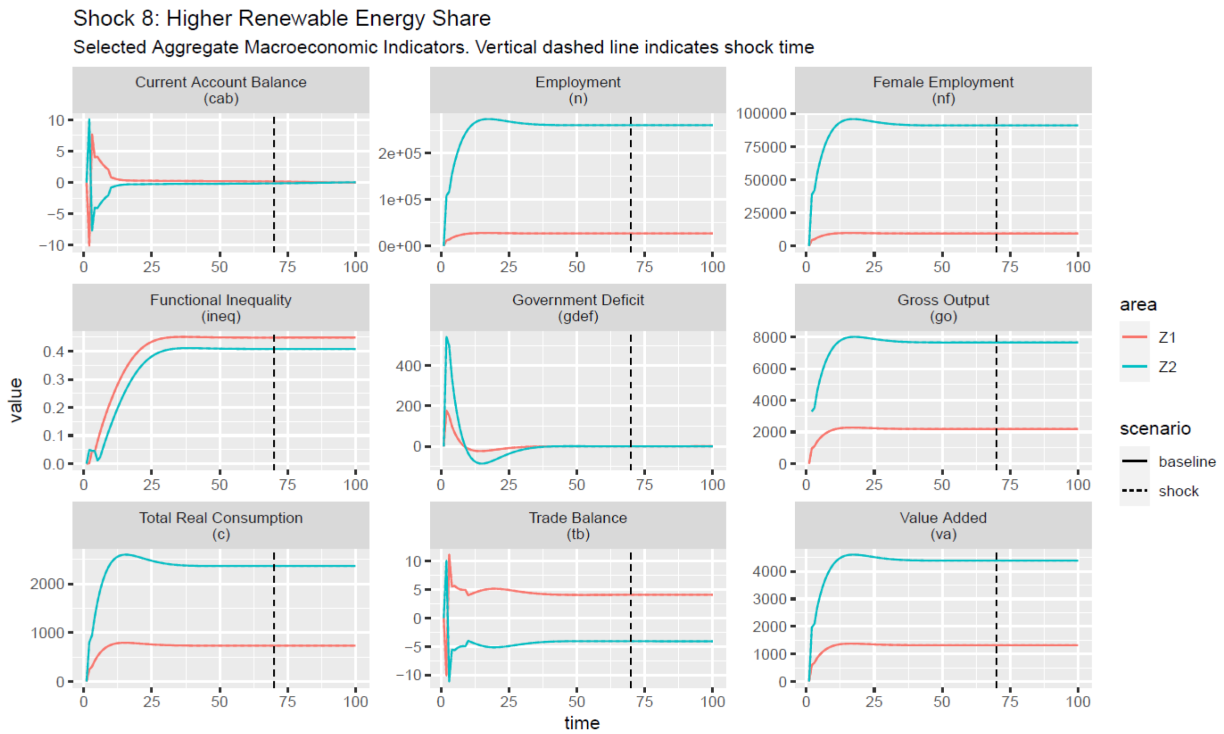
[C.7] Shock 1.7

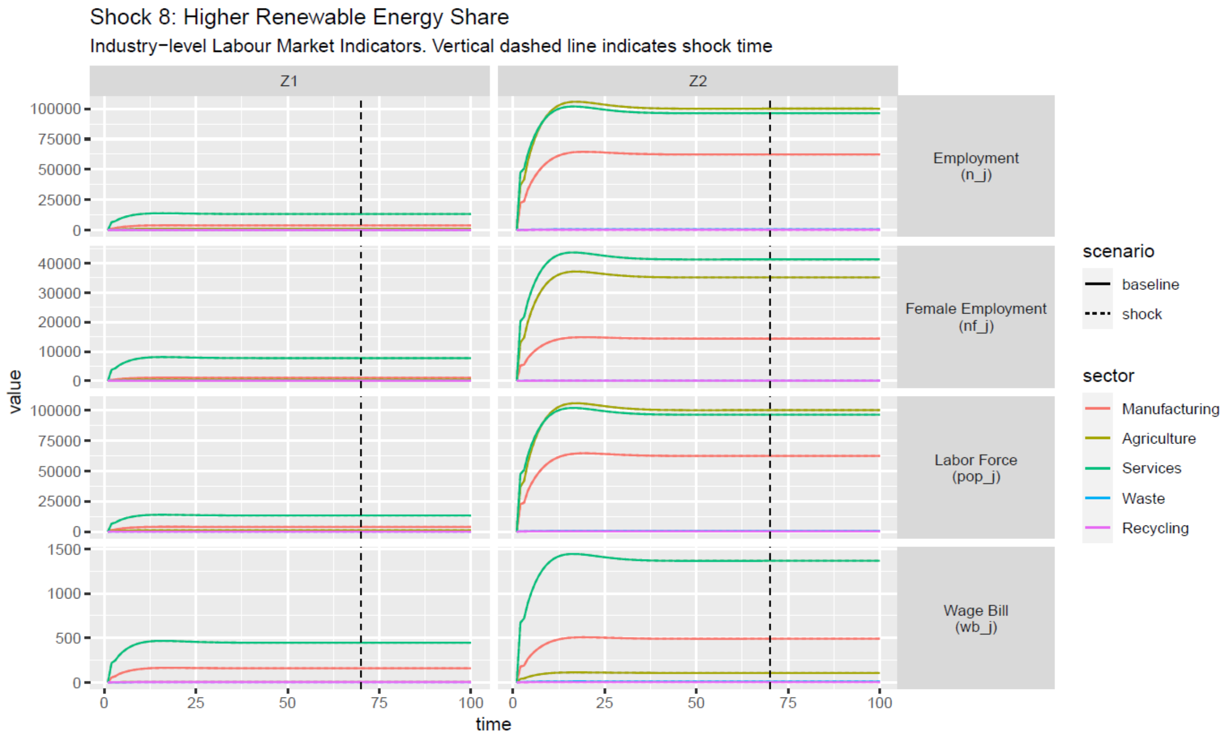

Shock 7: Lower Discarding Rate of Socio−Economic Stock
Selected Aggregate Macroeconomic Indicators. Vertical dashed line indicates shock time
Current Account Balance (cab)
Employment (n)
Female Employment (nf)
Functional Inequality (ineq)
Government Deficit (gdef)
Gross Output (go)
Total Real Consumption (c)
Trade Balance (tb)
Value Added (va)
value
time
area
Z1
Z2
scenario
baseline
shock

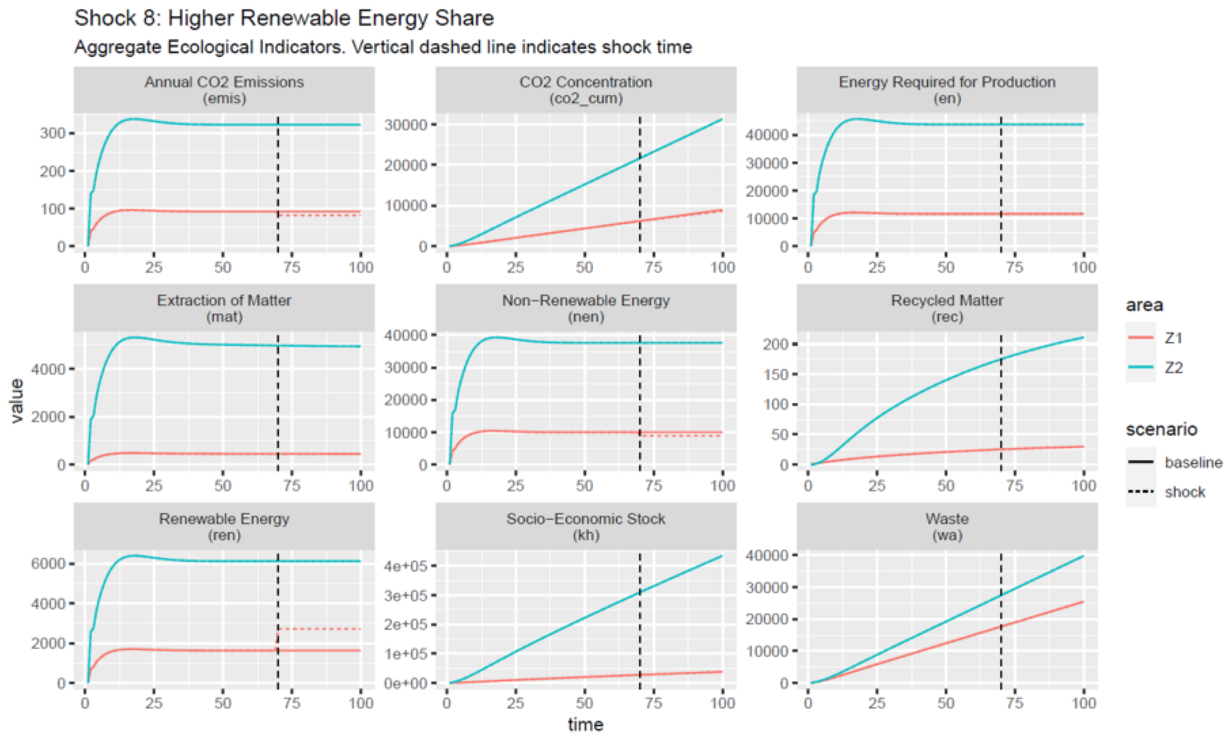

Shock 7: Lower Discarding Rate of Socio−Economic Stock
Industry−level Labour Market Indicators. Vertical dashed line indicates shock time
Z1
Z2
Employment (n_j)
Female Employment (nf_j)
Labor Force (pop_j)
Wage Bill (wb_j)
value
time
scenario
baseline
shock
sector
Manufacturing
Agriculture
Services
Waste
Recycling


Shock 7: Lower Discarding Rate of Socio−Economic Stock
Aggregate Ecological Indicators. Vertical dashed line indicates shock time
Annual CO2 Emissions (emis)
CO2 Concentration (co2_cum)
Energy Required for Production (en)
Extraction of Matter (mat)
Non−Renewable Energy (nen)
Recycled Matter (rec)
Renewable Energy (ren)
Socio−Economic Stock (kh)
Waste (wa)
value
time
area
Z1
Z2
scenario
baseline
shock

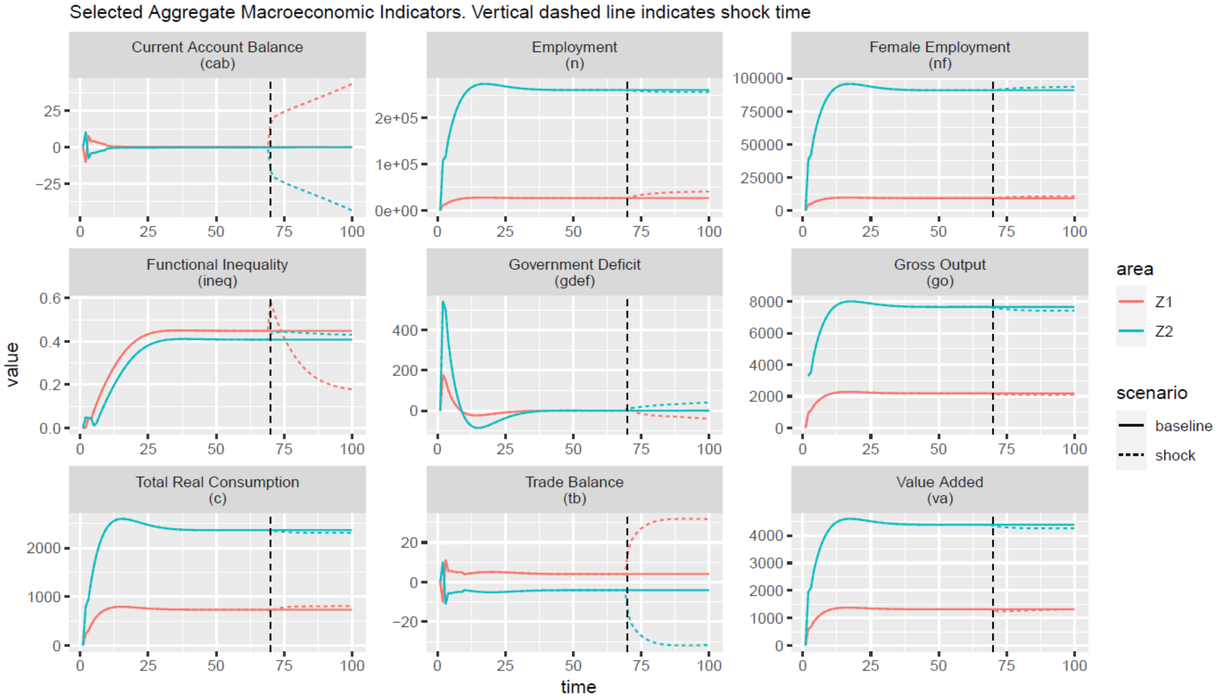
[C.8] Shock 1.8

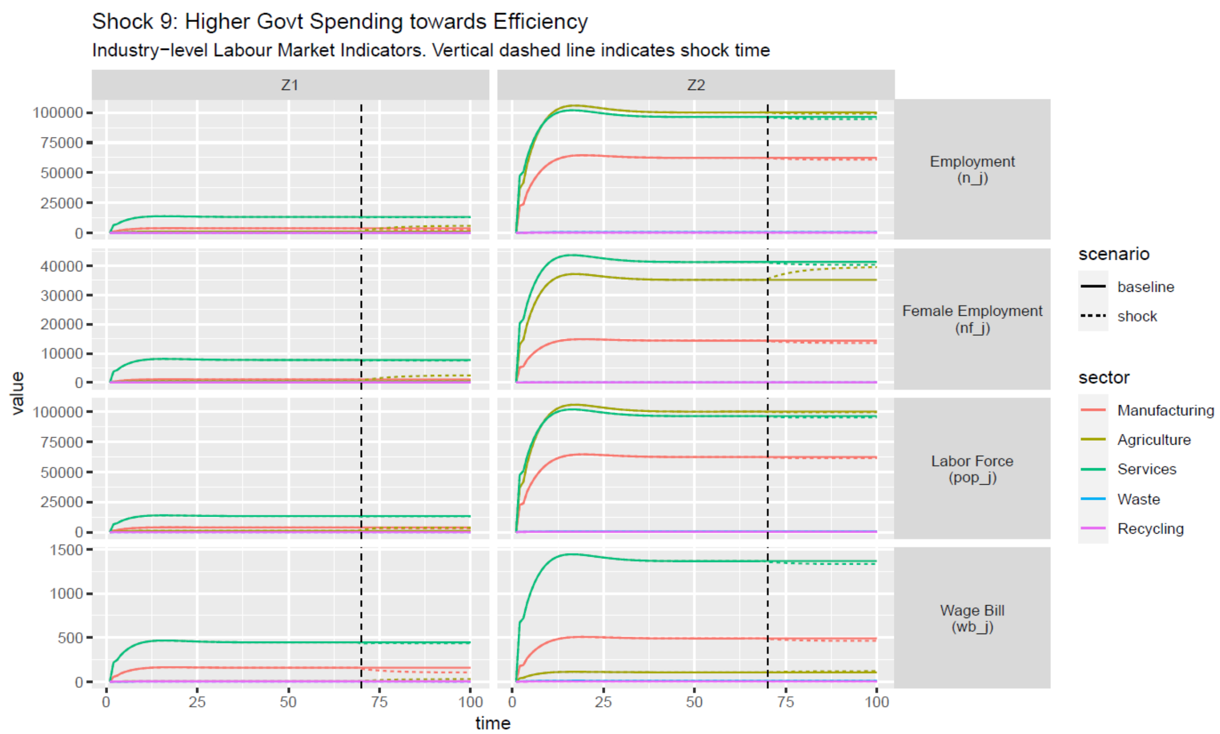

Shock 8: Higher Renewable Energy Share
Selected Aggregate Macroeconomic Indicators. Vertical dashed line indicates shock time
Current Account Balance (cab)
Employment (n)
Female Employment (nf)
Functional Inequality (ineq)
Government Deficit (gdef)
Gross Output (go)
Total Real Consumption (c)
Trade Balance (tb)
Value Added (va)
value
time
area
Z1
Z2
scenario
baseline
shock


Shock 8: Higher Renewable Energy Share
Industry−level Labour Market Indicators. Vertical dashed line indicates shock time
Z1
Z2
Employment (n_j)
Female Employment (nf_j)
Labor Force (pop_j)
Wage Bill (wb_j)
value
time
scenario
baseline
shock
sector
Manufacturing
Agriculture
Services
Waste
Recycling


Shock 8: Higher Renewable Energy Share
Aggregate Ecological Indicators. Vertical dashed line indicates shock time
Annual CO2 Emissions (emis)
CO2 Concentration (co2_cum)
Energy Required for Production (en)
Extraction of Matter (mat)
Non−Renewable Energy (nen)
Recycled Matter (rec)
Renewable Energy (ren)
Socio−Economic Stock (kh)
Waste (wa)
value
time
area
Z1
Z2
scenario
baseline
shock

[C.9] Shock 2.1- Higher Government spending towards Efficiency





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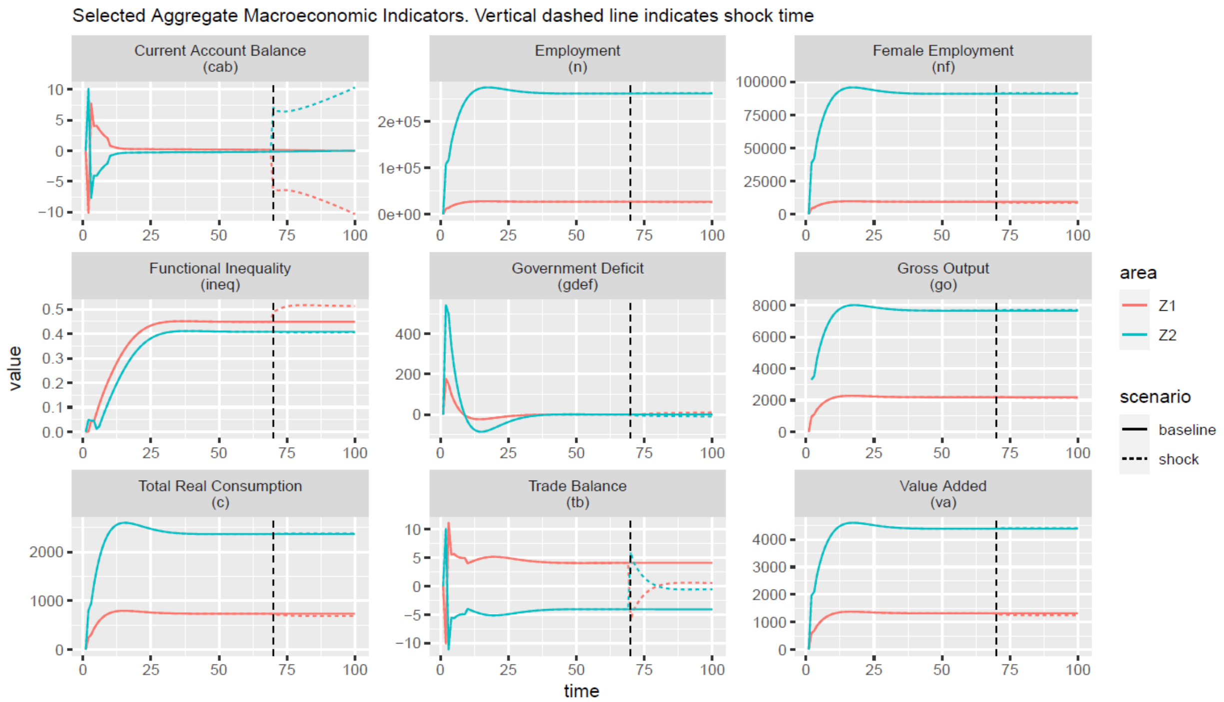
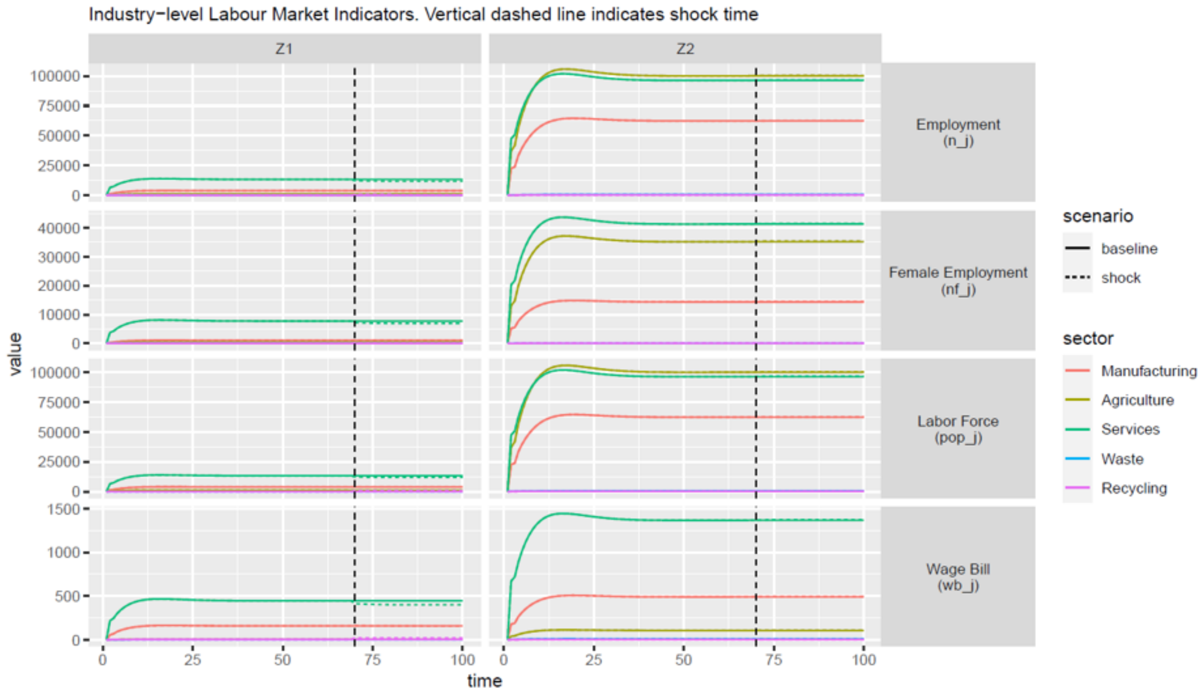
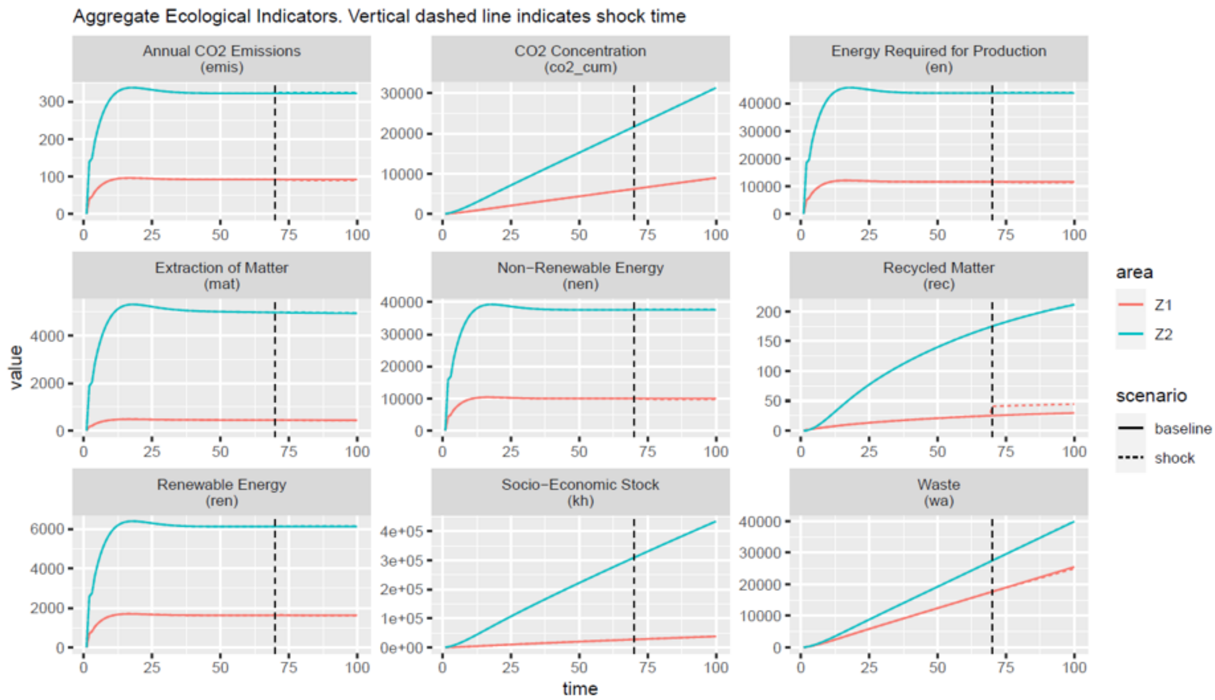
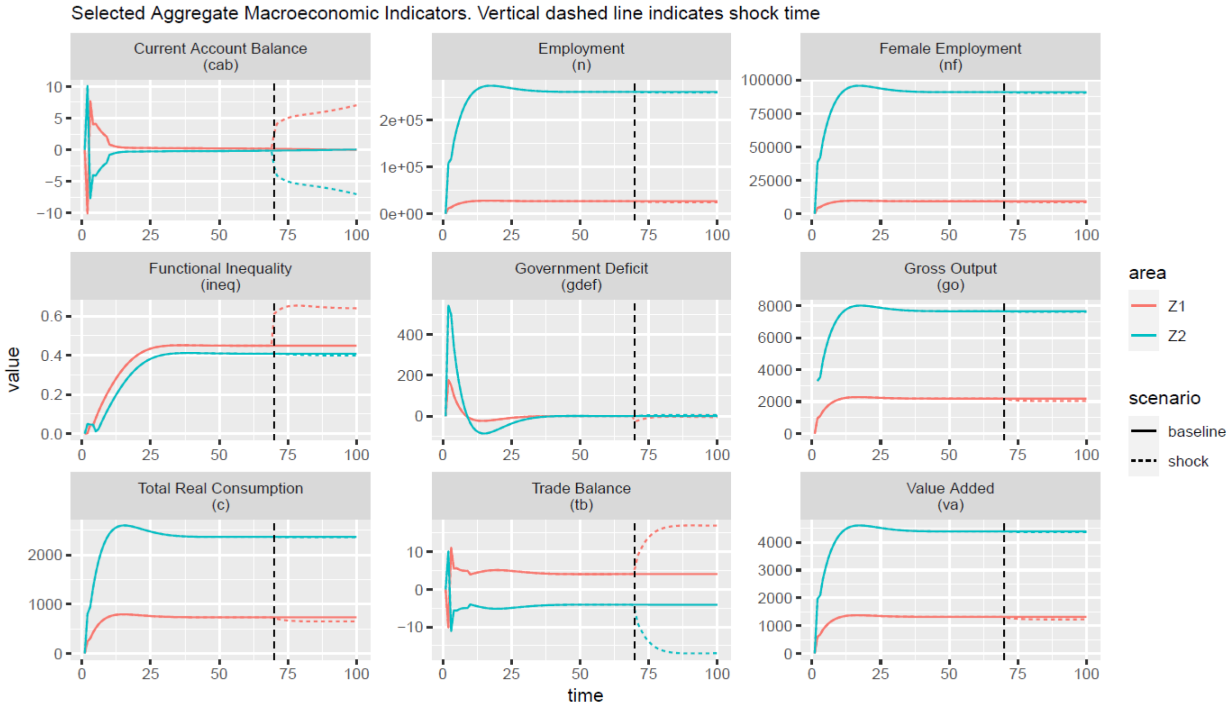
[C.10] Shock 2.2- More Selective government expenditure

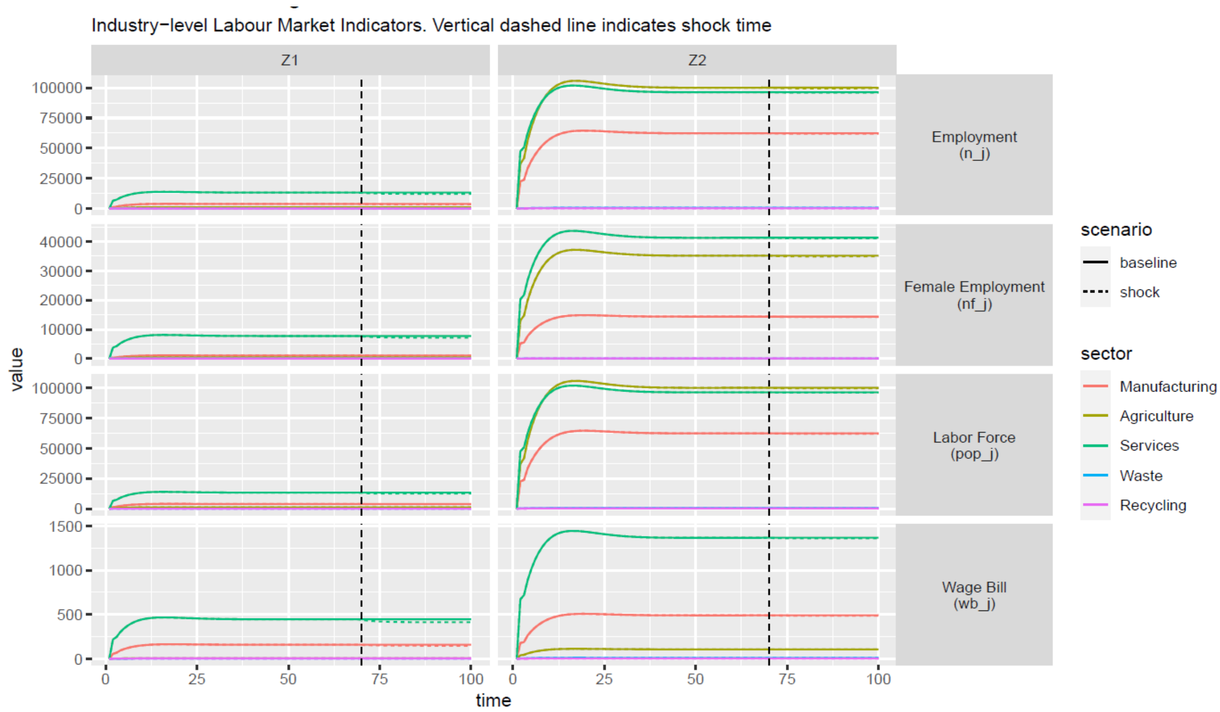



Industry−level Labour Market Indicators. Vertical dashed line indicates shock time
Z1
Z2
Employment (n_j)
Female Employment (nf_j)
Labor Force (pop_j)
Wage Bill (wb_j)
value
time
scenario
baseline
shock
sector
Manufacturing
Agriculture
Services
Waste
Recycling

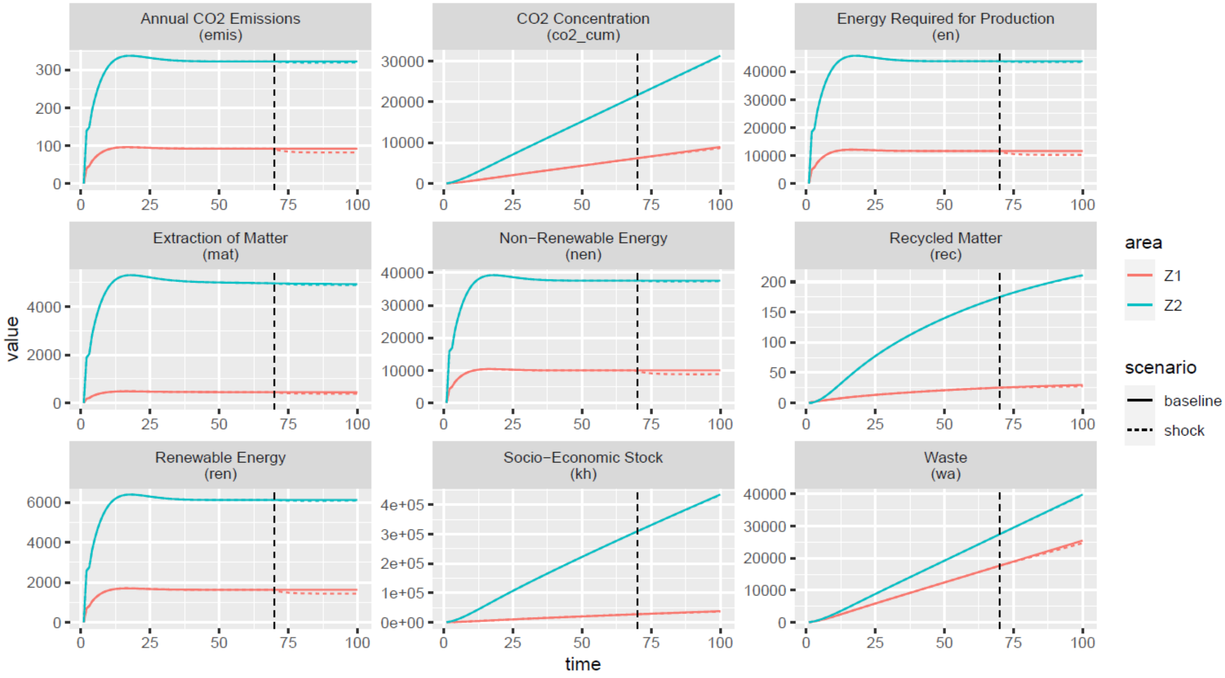

Aggregate Ecological Indicators. Vertical dashed line indicates shock time
Annual CO2 Emissions (emis)
CO2 Concentration (co2_cum)
Energy Required for Production (en)
Extraction of Matter (mat)
Non−Renewable Energy (nen)
Recycled Matter (rec)
Renewable Energy (ren)
Socio−Economic Stock (kh)
Waste (wa)
value
time
area
Z1
Z2
scenario
baseline
shock

[C.11] Shock 3.1- More progressive





Aggregate Ecological Indicators. Vertical dashed line indicates shock time



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