Resource scarcity, circular economy and the energy rebound: a macro-evolutionary Input-Output model

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Abstract

In this paper, we propose an Agent-Based Stock-Flow Consistent model combined with a reduced Input-Output (IO) structure of production. In the model, heterogeneous firms interact in the energy, material, capital and consumption markets. Materials for production of consumer goods can be manufactured using non-renewable or recycled resources. We examine the conditions under which the circular economy emerges through market mechanisms, as well as it can be a source of the rebound effect. An important novelty of our approach is that recycling and mining sectors employ different types of capital for production. Capital goods (machinery) are produced by capital firms, which constantly engage in innovations to improve their technological features, such as: energy intensity, the capital-to-output ratio, or the capital-to-labor ratio. This way we endogenize changes in technological coefficients of the Input-Output tables and we include time-consuming and long-term factor substitutability. We show that sectoral interdependencies along the value chain can render the energy rebound effect due to the circular economy (CE) even if energy intensity of the recycling process is lower compared to mining. For instance, if the recycling sector is characterised by the higher capital-to-output ratio than the mining sector, the CE transition can increase total production and energy intensity in the economy. Finally, we assess the role of different macroeconomic policies, namely mission-oriented innovation policies (MOIPs) and environmental taxation in fostering the CE transition, while mitigating the rebound effect. We find that the combination of MOIPs and active fiscal policy is the most effective in promoting the circular economy, preserving employment and ensuring a sustainable growth path.

Keywords: Circular economy; Rebound effect; Agent based – Stock Flow consistent models; Input-Output models.

1. Introduction

The global industry is highly dependent on non-renewable natural resources for both energy and material production. Over the next decades, the demand for metals and minerals is expected to double to satisfy the needs of the fast-growing population and the transition to a low-carbon economy (Dominish et al. 2019; UNEP, 2020). The scarcity of natural non-renewable resources imposes constraints not only on economic growth but also on the feasibility of such a transition. This relates to the fact that production of renewable energy is mineral- and metal-intensive. For instance, a photovoltaic system uses 11-40 times more copper than fossil fuel generation, while wind power plants use 6-14 times more iron (Hertwich et al., 2014). Moreover, resource extraction and the disposal of waste are important sources of greenhouse gas emissions, pollution and biodiversity loss (SPI, 2021). For instance, the mining industry consumes approximately 3.5% of energy consumption globally (Word Bank, 2020). Tackling these problems requires urgent attention.

To address them, the Circular Economy (CE) has been proposed as the solution that ensures a sustainable and long-lasting growth, while simultaneously reducing global emissions (Nansai et al. 2014; Allwood, 2014; McKinsey & Company, 2014; Morgan and Mitchell, 2015; Pansera et al. 2021). The CE relies on reusing, refurbishing and recycling products for as long as possible instead of extracting virgin materials. The transition to the circular economy would require the transformation of productive capacity, including dismissing the current capital stocks and investing in new technologies and plants. Similar large-scale transitions happened only few times in the past (i.e. from wood to coal). They typically relied on market mechanisms and took many decades to occur (Fouquet, 2010; Smil, 2010, Jackson et al. 2021). Currently, many recycled materials cost more than virgin ones (UNDP, 2020). This creates a barrier for the CE and requires public policy interventions to support its scaling. Moreover, even if recycling becomes cost-competitive, the circular economy may render the rebound effect by promoting the diffusion of cheaper products made of recycled materials, increasing their demand. The rebound effect describes the phenomenon that policies aimed at promoting resource efficiency may fail to accomplish a proportional reduction in energy or raw material use, or even increase it (Sorrel and Dimitripoulos, 2008). To understand these challenges and guide the choice of public policies to support the CE, new macroeconomic models are urgently needed that account for feedback loops in production as well as material and energy flows.

To address this gap, in this paper, we propose an Agent-Based Stock-Flow Consistent model (AB-SFC) to study the economic and environmental impacts of scaling up of the recycling sector. The model is Stock-Flow Consistent, which implies that each financial stock is associated with its own flow (Goodley and Lavoie, 2007; Passarella and Fontana, 2016). It includes five markets, namely: energy, capital goods, consumption goods, recycled and virgin raw material sectors. An important novelty of our approach is that the recycling and mining sectors employ different types of capital for production. In-use stocks of manufactured capital have been shown to limit possibilities for the circular economy, but this effect has achieved only limited attention in the literature (Krausmann et al. 2017; Mayer et al., 2019). In our model, capital firms constantly engage in innovations so as to minimize the unit cost of production of their clients, by improving technological features of capital goods, such as: their energy intensity, the capital-to-output, or capital-to-labor ratios. This way we endogenize changes in technological coefficients of the Input-Output tables. We show that sectoral interdependencies along the value chain can render the energy rebound effect due to the CE even if energy intensity of the recycling process is lower compared to mining. For instance, the rebound effect can emerge if the recycling sector uses capital characterised by the higher capital-to-output ratio than the mining sector. In this case, the transition towards the CE would result in capital expansion, increasing total production and energy use in the economy.

Our paper relates to the recent literature on modelling the circular economy. Typically, studies use Computable General Equilibrium (CGE) models (Schumacher and Sands, 2007; Yamazaki, 2011) or dynamic Input-Output simulations to study this topic (Si Li, 2012; Meyer et al. 2015; Palotto and Halog 2016; Nakamura and Kondo, 2018; Donati et al. 2020). In the CGE models, substitution between factors of production depends on relative prices of different inputs. This ignores that factor substitution typically requires investments in new capital that take time and require replacing productive capacity, which we consider in our model. On the other hand, IO studies do not account for the feedback loop that goes from inputs of production to final demand. They typically assume fixed coefficients of production and zero-factor substitution. In our model, demand is endogenous, i.e., an increase in final demand may trigger a feedback loop between consumption, capital investments and the GDP, while technological coefficients evolve as a result of R&D investments by capital firms. This allows us to study the rebound effect due to changes in: (1) the inter-sectoral multipliers (technical channel); and (2) the level of output (macroeconomic channel). Both channels affect total material and energy intensities of the economy.

Our study relates also to the literature on climate policy assessment. Typically, climate policies are studied using the General Equilibrium and Integrated Assessment Models (IAMs) (e.g. Nordhaus, 2017). Such models rely on the assumptions of aggregate equations, market equilibrium and rationality of representative agents. The approach has been increasingly criticized for not being equipped for dealing with uncertainty, technological change, and distributional issues while assuming ad-hoc damage functions (Falmer et al., 2015; Stern and Stiglitz, 2021). Such models disregard key elements driving outcomes in real-work markets (Colander et al., 2009; Kirman, 2010; Haldane and Turrell, 2018; Stiglitz, 2018; Blanchard, 2018; Lavoie, 2014; Barker, 2011). For instance, they ignore the monetary nature of the production process (Borio and Disyatat, 2011; Roger, 2019), while assuming simultaneous exchange of inputs and outputs (Gaffeo et al. 2007, Gallegati et al. 2015). In addition, many IAMs ignore the multi-sectoral relationships of the economic system (see exceptions in Bouakez et al.; Petrella and Santoro; 2011). Amid this criticism, macro-economic ABMs have been increasingly applied to study the economic impacts of climate change and energy policies (Dosi et al. 2019; Lamperti et al., 2018, Ponta et al. 2018; Safarzynska and van den Bergh 2017a,b). ABMs are considered to be better equipped to handle out-of-equilibrium dynamics, tipping points and large transitions in socio-economic systems than traditional macro-economic models (see e.g. Tesfatsion and Judd, 2006; Balbi and Giupponi, 2010; Kelly et al., 2013; Smajgl et al., 2011; Farmer et al., 2015; Stern, 2016; Mercure et al., 2016; Battiston et al., 2016a). The key features of the agent-based macroeconomic models are: (a) macro-level regularities emerge from decentralized interactions across heterogeneous agents; b) interactions are characterised by path-dependencies, learning effects and deep uncertainty (Hafner et al. 2020); c) agents are boundedly rational, instead of constantly optimizing their choices; d) trade of goods occurs at the micro level instead of through a centralized mechanism (Lengnick, 2013). Many of the agent-based macroeconomic models are integrated within a stock-flow consistent framework, paying special attention to the role of bank, money and credit (Naqvi; 2015; Jackson and Victor, 2015; Fontana and Sawyer, 2016; Dafermos et al., 2016). Examples of macro agent-based models are: the Schumpeter meeting Keynes (K+S) model by Dosi et al. (2010, 2016a), CATS (Delli Gatti et al., 2005, 2011) or EURACE (Cincotti et al., 2010; Teglio et al., 2012). Agent-based models for integrated assessment include the ENGAGE model (Gerst et al. 2013a,b) and Lagom RegiO (Wolf et al. 2013).

Recently, macro ABMs have been increasingly applied to study climate and energy policies (Balint et al., 2017; Hofner et al., 2020). For instance, Lamperti et al. (2019) extend a K+S model by Dosi et al. (2010, 2013, 2016) with the climate cycle. In their model, economic activity affects greenhouse gas emissions, which, in turn, increases the likelihood of climatic shocks destroying the capital stock of individual firms. In Safarzynska and van den Bergh (2022), climate damages reduce budgets of heterogenous consumers. The authors employ the model to study the distributional impacts of the social cost of carbon. As another example, Ponta et al. (2018) include the energy sector in the EURACE model to study the fiscal costs of financing energy policies (Cincotti et al., 2010, 2012a,b; Raberto et al., 2012, 2014; Teglio et al. 2012). Most macro-ABMs do not consider sectoral interdependencies (see exceptions in Lorentz and Savona, 2008; Poledna, 2018). Typically, they assume a linear system of production, where consumer goods are produced by the means of labour and capital, while capital goods are produced using only a single input, namely labour. An important exception is Poledna et al. (2018), who develop a macro agent-based model of the Austrian Economy calibrating it on the national input-output table. Our model offers another example of a macro agent-based model that accounts for sectoral interdependencies as it includes basic commodities (energy and capital). Basic commodities are those commodities that enter directly or indirectly into the production of all commodities produced in the economic system (Leontief, 1937; Von Neumann, 1937; Sraffa, 1960). Moreover, we consider the circularity of production, as in our model, materials are recovered from discarded consumer goods and subsequently recycled.

We assess the role of macroeconomic policies, such as: mission-oriented innovation policies (MOIPs), active fiscal policies (AFPs) and environmental taxation, in fostering the CE transition and achieving a sustainable growth path. Our results show that MOIPs are the most effective in promoting the circular economy. However, the policy can undermine aggregate demand, causing a reduction in GDP and employment. This effect can be prevented if MOIPs are combined with fiscal policies that keep the level of output close to full employment.

The remainder of the paper is as follows: Section 2 presents an overview of our model and discusses different channels that can render the rebound effect in the CE. In Section 3, we present the results from model simulations, while in Section 4, we discuss policies to promote the CE. Section 5 concludes.

2. Model Setup

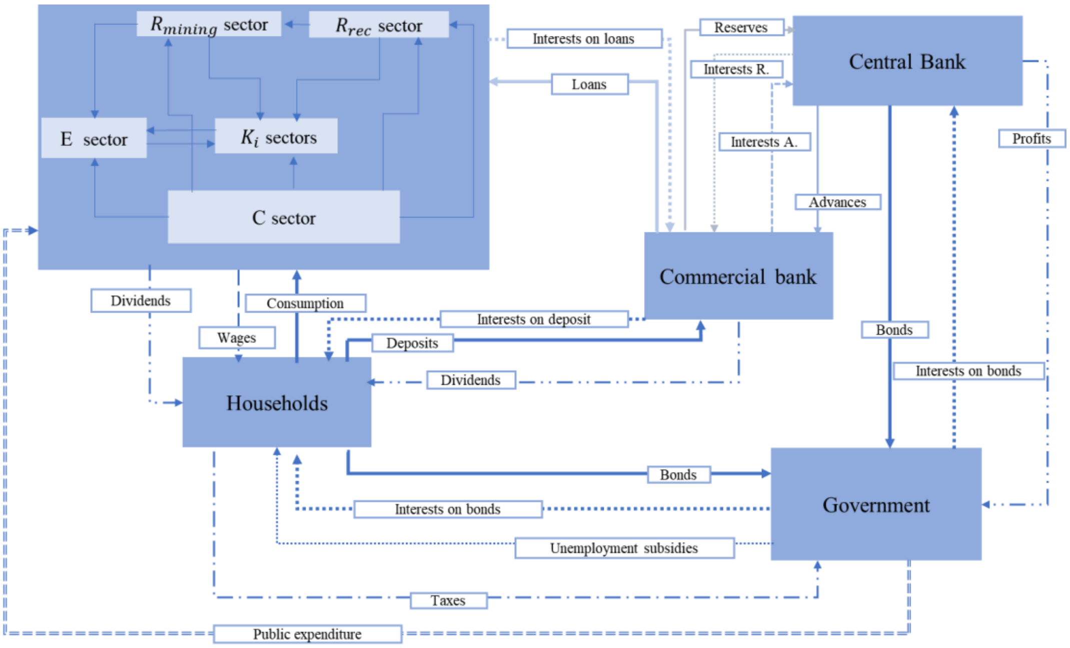
In this section, we present the model setup. Firms interact in six markets: energy, material, capital, consumption, labour and credit markets. The economy is composed by a firm producing energy (E), n_r firms producing raw materials in the mining sector (R^V); n_{r_s} firms producing material goods by recycling the consumption good (R^R); four K-sectors producing capital goods; n_c firms producing the consumption good (C); n_h households (H); Government (G); Central Bank (CB); and a commercial bank (B). Figures 1(a) and (b) illustrate the model structure: inter-sectoral monetary and material flows, respectively. Appendix A lists the sequence of events in our model.

In the model, outputs in different sectors are simultaneously inputs of production in others. Table 1 summarizes the matrix of inter-industry coefficients (IO table). The material market consists of firms selling/mining virgin raw materials and firms producing recycled materials: R^V-firms produce raw virgin materials using the natural stock of resources, while R^R-firms recycle materials embedded in goods discarded by consumers. These are perfect substitutes in the production of consumer products. In each period, the available quantity of scrap input (waste) depends on the production level in C-sector and consumers' decisions regarding waste disposal.

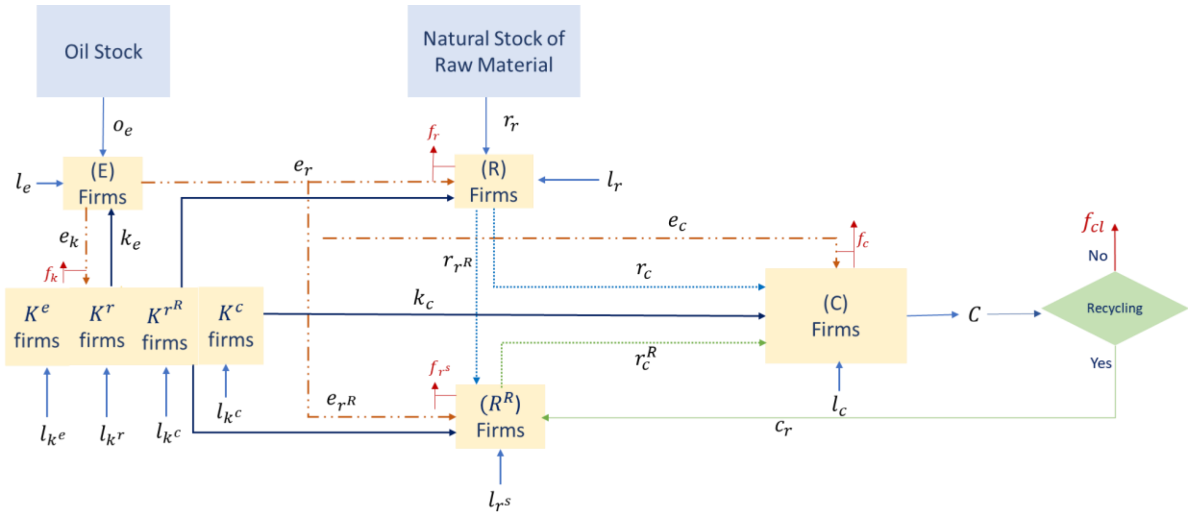
Each K-sector consists of heterogenous firms producing capital goods. Each type of sector $K_1 - K_4$ sells its product to different customers, namely: energy, virgin raw material, recycled material and final good producers, respectively. Capital goods can be thought of as machinery and define input productivities of firms in different sectors. K-firms invest in R&D activities so as to improve the technological features of their goods, namely: the capital-to-output, capital-to-labour, energy-to-output ratios so as to minimize the unit costs of their clients per unit of R&D expenditure. This constitutes a novelty of our approach, as in existing macro-evolutionary models, innovation typically focuses only on improving a single feature of capital, namely the capital-to-labor ratio (Dosi et. al, 2010, 2014, 2017; Ciarli et al., 2019; Roventini et al., 2019, 2021) or the energy/output ratio (Raberto et al, 2019).

C-firms set the desired production based on the expected demand; they pay wages in advance, buy inputs for production and purchase capital goods (machinery) if needed. Producers finance their costs through a mix of self-financing (retained profits) and loans. Production of firms in R, K and E sectors depends on orders from their customers. The total number of firms in each sector is fixed, while their size varies endogenously depending on demand and its distribution across firms. A firm that is unable to repay debts goes bankrupt, while a newcomer replaces it.

The household sector consists of workers and entrepreneurs. In each period, households consume a fraction of their income. Workers offer labour to firms and receive wages in exchange. Entrepreneurs are owners of firms and receive dividends. They hold their savings in the form of deposits and public bonds, workers only in the form of deposits. Households choose which products to buy based on prices. The price of each good depends on the cost of inputs and a markup. Mark-ups evolve over time reflecting the market power of firms, which in turn depends on the attractiveness of their products to consumers. Finally, the commercial bank provides credit to firms, collects deposits from households, and buys public bonds. The interest rate depends on the rate set by the monetary authority. The Government issues government bonds to finance the public deficit as well as purchases products from consumer firms. Primary public spending, i.e., on goods and services, is distributed among C-firms proportionally to their productive capacity.



(a) Monetary flows



(b) Material flows

Figure 1. Structure of the model

Note: In Figure 1(b), l_j are working hours required to produce one unit of commodity j; c_r is the fraction of the raw material embedded in the consumer good that can be restored by recycling firm; f_j is pollution per unit of j; e_j is the amount of energy required to produce one unit of j; r_c and r_c^R are the amounts of raw and recycled materials required to produce one unit of consumer good, respectively; k_j is the amount of capital required to produce one unit of j.

Table 1. Matrix of inter-industry coefficients

From/To	Energy	$\boldsymbol{K_e}$- good	$\boldsymbol{K_{r_v}}$- good	$\boldsymbol{K_{r_s}}$- good	$\boldsymbol{K_c}$- good	Virgin raw material	Recycled material	Consumer good
Energy	0	e_k	e_k	e_k	e_k	e_r	e_{r^R}	e_c
$\boldsymbol{K_e}$- good	v_e	0	0	0	0	0	0	v_c
$\boldsymbol{K_{r_v}}$- good	0	0	0	0	0	v_{r^V}	0	0
$\boldsymbol{K_{r_r}}$- good	0	0	0	0	0	0	v_{r^R}	0
$\boldsymbol{K_c}$ - good	0	0	0	0	0	0	0	v_c
Raw Material	0	r_k	0	0	0	0	r_{r^R}	r_c
Recycled material	0	r_{k_s}	0	0	0	0	0	r_c^R
Consumer good	0	0	0	0	0	0	c_r	0

2.1 Consumer sector

C-firms produce final consumer goods using labour $L_{t,i}$, capital goods $k_{t,i}$, energy $E_{t,i}$ and materials $R_{t,i}$. The production is described by a Leontief technology:

$$y_{t,i} = \min\left(\frac{L_{t,i}h^m}{l_{t,i}}; \frac{k_{t,i}}{v_{t,i}^*}; \frac{E_{t,i}}{e_{t,i}}; \frac{R_{t,i}}{r_{t,i}}\right), \tag{1}$$

Where $L_{t,i}$ is the number of workers, $l_{i,t}$ is the number of working hours required to produce one unit of output, h^m is the maximum number of hours that each employee can work per unit of time; $v_{t,i}^*$ is the capital-to-output ratio at full utilization of productive capacity; $e_{t,i}$ and $r_{t,i}$are the production coefficients of energy and material as reported in Table 1.

Firms set current production ($y_{t,i}^d$) based on expected demand ($q_{t,i}^e$). This is determined through adaptive expectations depending on sales realized in previous periods:

$$q_{t,i}^e = q_{t-1,i}^e + \gamma\left(q_{t-1,i}^r - q_{t-1,i}^e\right), \tag{2}$$

where β is the expectation parameter.

In addition, firms consider a buffer of inventories to address the discrepancies between expected demand and realized one. The planned production $y_{t,i}^d$ is defined as:

$$y_{t,i}^d = \max\left\{0, q_{t,i}^e(1+\sigma^T) - inv_{t-1,i}\right\}, \tag{3}$$

where σ^T is the desired ratio of inventory on sales and $inv_{t-1,i}$ is the amount of inventories from the previous period. The planned degree of capacity utilization in line with the desired production is equal to:

$$\omega_{t,i}^e = \min\left\{1, \frac{y_{t,i}^d v_{t,i}^*}{k_{t,i}}\right\}. \tag{4}$$

Given the amount of capital needed to produce $y_{t,i}^d$ and the capital-to-labor ratio ($\alpha_{t,i}$), it is possible to derive the labour demand as:

$$L_{t,i}^d = \frac{\omega_{t,i}^e k_{t,i}}{\alpha_{t,i}\, v_{t,i}^*\, h^m} = y_{t,i}^d l_{t,i}, \tag{5}$$

where $k_{i,t}$ is the amount of fixed capital and $\alpha_{t,i}$ is the capital-to-labor ratio

The virgin raw material demand is given by:

$${R_{t,i}^V}^d = \frac{\omega_{t,i}^e k_{t,i}}{v_{t,i}^*} r_{t,i}^v. \tag{6}$$

In case C-firm decides to use recycled materials as an input, which depends on relative price of both types of materials, the demand for recycled material is equal to:

$$R^{R}{}_{t,i}^{d} = \frac{\omega_{t,i}^e k_{t,i}}{v_{t,i}^*} r_{t,i}^R, \tag{7}$$

Finally, energy demand is equal to:

$$E_{t,i}^d = \frac{\omega_{t,i}^e k_{t,i}}{v_{t,i}^*} e_{t,i}. \tag{8}$$

C-firm aims at adjusting productive capacity to satisfy expected demand with a normal (desired) degree of capacity utilization in the period in which the capital will be available. In particular, the capital good ordered in period t is installed in period $t + dk$, where dk is the number of periods needed to produce the capital good. The investment function is defined as:

$$I_{t,i} = \max\{0; q_{t+dk,i}^e (1 + \sigma^T) v_{t,i}^n - k_{t+dk,i}\}, \tag{9}$$

where $v_{t,i}^n$ is the capital-to-output ratio in correspondence with the normal degree of utilization; $k_{t+dk,i}$ is the residual capital that firm would have in dk periods if no investments are carried out in period t; $g_{t+1,i}^e$ is the expected growth rate of demand in $t + 1$, calculated using an adaptive expectation function.

The unit cost is calculated using the historical normal-cost methodology (Garbert, 2006), i.e. at the normal (or desired) degree of capacity utilization:

$$c_{t,i} = p_{e_{t,i}} e_{t,i} + p_{r_{t,i}} r_{t,i} + \frac{\overline{w}_{t,i} * L_{n_{t,i}}}{y_{t,i}^n} + \frac{am_{t,i}}{y_{t,i}^n} , \tag{10}$$

where amortization $am_{t,i}$ is computed assuming that productive capacity is made of capital goods with different ages, using the opportunity-cost approach (see Appendix A for derivations):

$$am_{t,i} = \frac{\frac{1}{a\,z} \sum_{j=t-z+1}^{t} p_{k_j} K_j^{ins} (1 + r_j b l_j)(j + z - t)}{\frac{u_n}{v_{t,i}^*} \sum_{j=t-z+1}^{t} K_j^{ins} \left(\frac{j+z-t}{z}\right)}. \tag{11}$$

In eqns. (10-11), $L_{n_{t,i}}$ is the number of working hours corresponding to the normal degree of capacity utilization; $y_{n_{t,i}}$ is the normal production, i.e. the production realized at the normal degree of capacity utilization; $\overline{w}_{t,i}$ is the nominal wage; K_j^{ins} is the amount of installed capital in period j; p_{k_j} is the price; u_n is the normal degree of capacity utlilization; r_j is the interest rate in period j; parameters $a = \sum_{i=1}^{z} \frac{i}{z}$ and $b = \frac{1}{a\,z} \sum_{i=1}^{z} \frac{i^2+i}{2}$ are the multiplying factors for the computation, respectively, of the interest payment on the debt incurred in a given period and of the cumulated normal production over the useful life of the capital good. If p_{k_j}, r_j and l_j are constant over time and $l_j = 1$, eq. (10) simplifies to:

$$c_{t,i} = p_{e_{t,i}} e_{t,i} + p_{r_{t,i}} r_{t,i} + \bar{w}_t l_{t,i} + \frac{v_{t,i}^* p_k}{a\omega^n}(1 + rb). \tag{12}$$

2.2 Mining and recycling sectors

A mining firm R^V produces the virgin raw material by means of labour, capital good and energy. Recycling R^R firms produce recycled materials by means of labour, energy, capital, virgin raw material as well as using scrap recovered from consumers' discarded products. Both sectors produce on-spot based on the orders received by sector C. Labour and energy demand are determined in the same way as in the consumer sector. The feasible production in R^R sector is:

$$y_{t,i} = \min\left(\frac{L_{i,t} h^m}{l_{t,i}}; \frac{k_{i,t}}{v_{t,i}^*}; \frac{E_{t,i}}{e_{t,i}}\right). \tag{13}$$

R^R sector demand for R^V goods is:

$$R_{t,i}^{V\ d} = \frac{\omega_{t,i}^e k_{t,i}}{v_{t,i}^*} r_{t,i}. \tag{14}$$

The demand for C-goods needed to recover/recycle raw materials from discarded consumer products in R^R sector is equal to:

$$C_{R_{t,i}^R}^d = yd_{t,i} c_r, \tag{15}$$

Finally, the production in R^R sector is:

$$y_{t,i} = \min\left(\frac{L_{i,t} h^m}{l_{t,i}}; \frac{k_{i,t}}{v_{t,i}^*}; \frac{E_{t,i}}{e_{t,i}}, \frac{R_{t,i}}{r_{t,i}}, \frac{S_{c_t} \mu_{t,i}}{c_{r_{t,i}}}\right), \tag{16}$$

where $S_{c_t} = S_{c_{t-1}} + C_{t-1} f_{t-1}$ is the available stock of wastes (consumer goods); $\mu_{t,i}$ is the share of total wastes at the disposal of firm i and $c_{r_{t,i}}$ is the amount of waste needed to produce one unit of recycled material. As in the C-sector, R-firms attempt to adjust their productive capacities to match the expected demand at the normal degree of capacity utilization. The computation of existing capital stock and amortization is the same as in the C-sector. The unit cost of R^V-firms is:

$$c_{t,i}^{R^V} = p_{e_{t,i}} e_{t,i} + \bar{w}_{t,i} l_{t,i} + \frac{am_{t,i}}{y_{t,i}^n}, \tag{17}$$

and the unit cost of R^R-firms is:

$$c_{t,i}^{R^R} = p_{e_{t,i}} e_{t,i} + p_{r_{t,i}} r_{r_{t,i}} + \bar{w}_{t,i} l_{t,i} + \frac{am_{t,i}}{y_{t,i}^n}. \tag{18}$$

2.3 Energy sector

There is one E-firm in the E-sector, which produces energy using capital and labour and a non-renewable energy source, which can be thought of as oil. Each period, the firms try to adjust its productive capacity to be able to match the expected demand for energy from other sectors. Because of simultaneity between K- and E-sectors, the demand for energy cannot be known ex-ante, thus E-firm uses expectations of demand from K-firms at time *t*:

$$q_{t,i}^{e,K} = q_{t-1,i}^{e,K} + \alpha(q_{t-1,i}^{r,K} - q_{t-1,i}^{e,K}), \tag{19}$$

On the other side, K-firms know demand for capital of R- and C-sectors. The expected demand is described by the following equation:

$$q_{t+dk,i}^{e} = q_{t,i}^{e}(1 + g_{t,i}^{e}), \tag{20}$$

where:

$$q_{t,i}^{e} = q_{t,i}^{e,K} + q_{t,i}^{R} + q_{t,i}^{C}. \tag{21}$$

Once the demand for capital goods is determined, the E sector sets its desired production as:

$$yd_{t,i} = E_{t,i}^{d,K} + E_{t,i}^{d,C} + E_{t,i}^{d,R+R^R}, \tag{22}$$

Which is the sum of demand of energy by firms in different sectors (K, C,R^V, R^R). The labour demand is computed in the same way as in the C sector. The feasible production in the current period is equal to:

$$y_{t,i} = \min\left(\frac{L_{i,t}h^m}{l_{t,i}}; \frac{k_{i,t}}{v_{t,i}^*}\right). \tag{23}$$

The unit cost of energy is equal to:

$$c_{t,i}^{e} = \overline{w}_{t,i}l_{t,i} + \frac{am_{t,i}}{y_{t,i}^{n}}. \tag{24}$$

2.4 Capital sector

K-firms use labour and energy as inputs in the production of capital goods. We assume that the number of periods required to produce one capital good (dk) is higher than one. The quantity, which firm *i* would like to produce at time *t*, is equal to:

$$y_{t,i}^{d} = \sum_{j=t-dk}^{t} \frac{orders_{j,i}}{dk}, \tag{26}$$

where the sum corresponds to the number of capital goods ordered by firms *i* from previous dk periods to period t. In each period share $\frac{1}{dk}$ of each order is produced. Given $yd_{t,i}$, it is possible to determine the labour and energy demand:

$$L_{t,i}^{d} = \frac{yd_{t,i}l_k}{h^m}, \tag{27}$$

$$E_{t,i}^{d} = yd_{t,i}e_k. \tag{28}$$

2.5 Price setting

In setting their final prices, firms apply a markup over unit-cost of production. C-firms increase their markups ($\varphi_{t,i}^{uc}$) if two conditions are fulfilled: (1) the ratio between inventories and sales has been lower for several consecutive periods ($\rho^{lim,inc}$) than the target level (s^T); and (2) the realized degree of capacity utilization has been above the normal one during this period (see Caiani et al., 2016). Firms reduce markups in case the target ratio has been higher than the target level for $\rho^{lim,dec}$ consecutive periods and the weighted average of the degree of capacity utilization has been lower than the normal one. In all other cases, C-firms keep markups constant. These conditions can be formalized as follows:

$$\varphi_{t,i}^{uc} = \begin{cases} \varphi_{t-1,i}^{uc}(1 - FN) \quad if \ \left(\bar{u}_{t-1,\dots,t-s}^{r} < u_n \wedge \rho_{t-1,i}^{r,dec} > \rho^{lim,dec} \right) \\ \varphi_{t-1,i}^{uc}(1 + FN) \ \ if \left(\ \bar{u}_{t-1,\dots,t-s}^{r} > u_n \ \wedge \ \rho_{t-1,i}^{r,inc} > \rho^{lim,inc} \right) \\ \qquad \varphi_{t-1,i}^{uc} \ otherwise \end{cases} \tag{29}$$

where FN is the markup drawn from a Folded Normal Distribution with parameters $(\mu_{FN}, \sigma_{FN}^2)$; $\rho_{t-1,i}^{r,dec}$ is the number of consecutive periods during which the sales/inventory ratio has been lower than target; $\rho_{t-1,i}^{r,inc}$ is the number of consecutive periods during which the ratio has been higher than target; $\bar{u}_{t-1,\dots,t-s}^{r}$ is the weighted average with decreasing weight over time of the realized degree of capacity utilization.

R^V-, R^R-, E- and K- firms set their markups based on market shares. Firms in these sectors increase/decrease their markups if their market shares ($m_{t,i}$) are higher/lower for several consecutive periods ($\rho^{lim,inc}$) than the target one (m^T):

$$\varphi_{t,i}^{uc} = \begin{cases} \varphi_{t-1,i}^{uc}(1 - FN) \ \ if \ \rho_{t-1,i}^{r,dec} > \rho^{lim,dec} \\ \varphi_{t-1,i}^{uc}(1 + FN) \quad if \ \rho_{t-1,i}^{r,inc} > \rho^{lim,inc} \\ \qquad \varphi_{t-1,i}^{uc} \ otherwise \end{cases}, \tag{30}$$

2.6 Supplier selection

In the baseline, households choose goods exclusively based on the price. As a consequence, C-firms aim to purchase the cheapest material input available on the market among outputs of R^V- and R^R- firms, which we assume to be perfect substitutes. Initially, C-firms are matched randomly with material suppliers. In each period, the probability that the firm would change its supplier depends on the price differential between the previous supplier and the cheapest supplier in period t: e:

$$Pr_{t,i} = \begin{cases} 1 - e^{\frac{\epsilon\left(p_{t,indexC} - p_{t,indexC_{t-1}}\right)}{p_{t,indexC}}} & if \quad p_{t,indexC} < p_{t,indexC_{t-1}}, \\ \quad 0 & otherwise \end{cases} \tag{31}$$

where ϵ is the elasticity for the price differential, $p_{t,indexC}$ is the price of the firm selected at time t and $p_{t,indexC_{t-1}}$ is the price offered by the supplier of the previous period. The larger value of parameter ϵ increases the probability that a firm would change its supplier. The same mechanism applies to other markets, including households choosing which product to buy. In the capital market, firms select the supplier that ensures the lowest unit cost of production.

2.7 Labour market

We model a simple labor market with aggregate bargaining and homogeneous wages. Dynamics of nominal wage are described by:

$$w_t = w_{t-1}\left(1 + \varsigma \frac{E_{t-1}}{E}\right) \tag{32}$$

where E_{t-1} is the employment rate in the previous period and E is the full employment rate. According to eq. (32), the nominal wage increases depending on the difference between the actual and full employment rate.

2.8 R&D activity in capital sectors

Following the well-established evolutionary tradition, we model firms' research activities as a two-step stochastic process (Nelson and Winter, 1977b,a, 1982; Winter, 1984; Andersen, 1996; Dosi et al., 2010; Caiani, 2012; Vitali et al., 2013). In the first stage, a Bernoulli draw determines if a firm will engage in R&D activities. If successful, in the second stage, a K-firm draws the productivity gain from a beta-distribution. The probability of success ${pr_{t,i}}^{inn}$ in the first stage depends on the cumulated working hours $h_{t,i}$ in research activities:

$${pr_{t,i}}^{inn} = 1 - e^{-\beta h_{t,i}}, \tag{33}$$

where β is the parameter describing the impact of working hours on the likelihood of innovation.

Firms spend fraction ε of their profits on R&D activities:

$$w_{t.i} h_{t,i} = \varepsilon\, \pi_{t-1,i}, \tag{34}$$

where $h_{t,i}$ is the total number of working hours in the R&D sector.

Before investing in R&D, a firm has to decide on the direction of such investments, namely which technological feature of capital goods to improve: the capital-to-output ratio, the capital-to-labor ratio or energy efficiency. K-firms choose the feature that ensure the highest unit-cost minimization for their customer per unit of R&D spending. To this end, K-firm i estimate the expected unit cost of its customer (*indexj*). The expected unit cost of j-firm is defined as follows:

$$c^e_{t,indexj} = p_{e_{t,}}\, e_{t,indexj} + p_{r_t} r_{c_{t,iindexj}} + \overline{w}_t \frac{v^*_{t,indexj}}{\alpha_{t,indexj}} + \frac{c^e_{t,i}(1+\varphi)v^*_{t,indexj}}{a\omega^n}(1+rb), \tag{35}$$

In eq. (36), $c^e_{t,i}$ is the expected unit cost of production of the capital good after successful innovation, which is equal to:

$$c^e_{t,i} = \overline{w}_t l_{t,i} + \frac{Ctot^{e,R\&D}_{t,i}}{q^e_{t,i}\,\overline{T}}, \tag{36}$$

where $q^e_{t,i}$ is the expected quantity to sell in each of the next $\overline{T}$ periods; $\overline{T}$ captures how long a firm intends to produce the capital good embedding the new technology before the next innovation arrives (see Appendix A for derivations); $Ctot^{e,R\&D}_{t,i}$ is the expected R&D expenditure. The K-firm keeps investing a fraction of their profits in R&D ($\varepsilon\,\pi_{t-1,i}$) for the next $\bar{T}$ periods. As a result, the total expenditure in R&D becomes equal to:

$$Ctot_{t,i}^{e,R\&D} = \sum_{i=t}^{t+\bar{T}} \varepsilon\,\pi_{t-1,i} = \bar{T}\,\varepsilon\,\pi_{t-1}. \tag{37}$$

K-firm chooses which technological feature to improve based on the following conditions:

$$\frac{\partial c_{t,i}^{e}}{\partial e_{t,indexj}} = p_{e_{t,indexj}},$$

$$\frac{\partial c_{t,i}^{e}}{\partial v_{t,indexj}^{*}} = \frac{\bar{w}_t}{\alpha_{t,indexj}} + \frac{(\bar{w}_t l_{t,i} + \frac{\bar{T}\,\varepsilon\,\pi_{t-1}}{q_{t,i}^{e}\,\bar{T}})(1+\varphi)(1+rb)}{a\omega^{n}}\ , \tag{38}$$

$$\frac{\partial c_{t,i}^{e}}{\partial \alpha_{t,indexj}} = -\frac{\bar{w}_{t,i} v_{t,indexj}^{*}}{\alpha_{t,indexj}}.$$

In particular, the firm chooses the feature which yields the highest value among partial derivatives above. This ensures the highest unit-cost minimization per-unit of R&D spending. Once the firm had chosen the technological feature to improve, it keeps investing in it until the innovation process is successful. Firms that fail to innovate can imitate technologies of their more successful competitors. New technologies become available to everyone after some period of time following their invention, pushing forward the technological frontier.

2.9 Households

The household sector is composed of workers and entrepreneurs; each entrepreneur is an owner of one firm. Consumption demand of households depends on income and wealth stock. The consumption function of workers is defined as follows:

$$c_{i,t}^{D,w} = YD_{t,i}c_{1,w} + M_{t-1,i}c_{2,w}\min(\quad), \tag{39}$$

where $M_{t-1,i}$ is worker's deposit, while $YD_{t,i}$ is total income at t equal to:

$$YD_{t,i} = \begin{cases} (w_{t,i}h_{t,i}^{work} + M_{t-1}r_{t-1}^{m})(1-\tau^{work})\ if\ employed \\ (w_{gov} + M_{t-1}r_{t-1}^{m})(1-\tau^{work})\ \ otherwise \end{cases}, \tag{40}$$

where w_{gov} is the unemployment benefit and τ^{work} is the tax rate on workers' income.

The consumption function of entrepreneurs is equal to:

$$c_{i,t}^{D,\pi} = \min\left(YD_{t-1,i}c_{1,\pi} + V_{t-1,i}c_{2,\pi}, YD_{t-1,i} + M_{t-1,i}\right). \tag{41}$$

Entrepreneurs receive income in form of dividends distributed by firms and banks, and the interest accrued on deposits and public bonds:

$$YD_{t-1,i} = \left(Div_{t-1,i} + M_{t-1,i}r_{t-1}^{m} + B_{t,i}^{h}r_{t-1}^{b}\right)(1-\tau^{\pi}). \tag{42}$$

where $Div_{t-1,i}$ are dividends and τ^{π} is the tax rate on capitalists' income.

The wealth of entrepreneurs consists of deposits $M_{t,i}$ and government bonds $B_{t,i}^{h}$:

$$V_{t,i} = M_{t,i} + B_{t,i}^{h}. \tag{43}$$

It changes over time according to:

$$V_{t,i} = V_{t-1,i} + YD_{t-1,i} - C_{t,i}. \tag{44}$$

The demand for government bonds is a function of the stock of wealth $V_{t,i}$, disposable income $YD_{t,i}$and the interest rate r_t^b:

$$B_{t,i}^d = (\lambda_0 + \lambda_1 r_t^b)V_{t,i} + \lambda_2\big(YD_{t,i}\big), \tag{45}$$

where λ_0 , λ_1 and λ_2 are the elasticities of bond demand with respect to the stock of wealth, the interest rate and disposable income, respectively.

2.10 Government

The government collects taxes and pays unemployment benefits, which are equal to a fraction of the wage in the private sector. Each period, the government purchases goods from the consumer sector. The growth rate of this component of government spending is kept constant. Unemployment benefits and debt service are anticyclical. In Appendix C, we discuss the role of public spending in economic growth in greater detail.

2.11 Central Bank and Commercial bank

We consider one commercial bank, which sets the interest rate on loans and deposits, depending on the markup set by the Central Bank. The interest rate on loans is always higher than on deposits. Money in the economy is created through two channels: the Government overdraft at the CB to finance public expenditure and loans granted to firms. The balance sheet and the transaction matrix describing the economy are reported in Appendix A.

Profits of the Central Bank depend on interests earned on public bonds (B_{t-1}^{cb}), advances *(A_{t-1})* and from interests paid on reserves (H_{t-1}^{cb}):

$$\pi_t^{cb} = B_{t-1}^{cb} r_{t-1}^b - H_{t-1}^{cb} r_{t-1}^{riserve} + A_{t-1} r_{t-1}^a. \tag{46}$$

In the public bonds market, the Central Bank acts as the lender of last resort:

$$B_t^{cb} = B_t - \sum_i^{ncap} B_{t,i}^d, \tag{47}$$

where $\sum_i^{ncap} B_{t,i}^d$ is the amount of bonds held by entrepreneurs.

The redundant equation checking the stock-flow consistency of the model is:

$$M_t = L_t + B_{cb,t} + NPL_t + A_t \tag{48}$$

where $M_t$is total deposits; L_t bank loans; A_t are advances from CB to the commercial bank; NPL_t non-performing loans and $B_{cb,t}$ public bonds held by CB.

2.12 Economic and environmental impacts of the circular economy

In this section, we discuss general mechanisms operating in our model. We assume homogenous coefficients of production among firms in each industry, which allows us to derive some theoretical predictions regarding the economic feasibility of the circular economy in Section 2.12.1 and its environmental consequences in Section 2.12.2.

2.12.1 Economic feasibility of the circular economy

In the baseline model, there is no recycling sector initially. The sector emerges only if recycled materials are cheaper than virgin materials. This is because firms producing final consumers' goods choose between raw materials and recycled inputs only based on prices, i.e., they are perfect substitutes. To derive the conditions under which the recycling sector is cost-competitive with the mining sector, we solve the system of price equations:

$$\boldsymbol{pA}(1+m) + \boldsymbol{b_n} w(1+m) = \boldsymbol{p}, \tag{49}$$

where **A** is the matrix of production coefficients described in Table 1, $\boldsymbol{p}$ is the vector of prices, $\boldsymbol{b_n}$ is the vector of labour productivity, m is the markup and w is the nominal wage. This leads to the vector of prices[1]:

$$\boldsymbol{p} = \begin{pmatrix} p_k \\ p_e \\ p_r \\ p_{r_r} \\ p_c \end{pmatrix} = \begin{pmatrix} \mu \\ \varepsilon \\ [\mu e_r + wl_r + \frac{v_r^* \varepsilon}{a\omega^n}(1+rb)](1+m) \\ [\mu e_{r^s} + wl_{r^s} + p_r r_{r^s} + wl_{r^s} + \frac{v_{r^s}^* \varepsilon}{a\omega^n}(1+rb)](1+m) \\ [\mu e_c + p_r r_c + wl_c + \frac{v_c^* \varepsilon}{a\omega^n}(1+rb)](1+m) \end{pmatrix}, \tag{50}$$

where $\mu = w(1+m)\left(\frac{al_e + v_e^n l_k(1+rb)(1+m)}{a - v_e^n e_k(1+rb)(1+m)^2}\right)$ and $\varepsilon = aw(1+m)\left(\frac{l_k + e_k(1+m)l_e}{a - v_e^n e_k(1+rb)(1+m)^2}\right)$ are the prices of basic commodities (energy and capital); $\vartheta = \frac{v_e^*}{a\omega^n}(1+rb)$, $\beta = \frac{v_r^*}{a\omega^n}(1+rb)$, $\gamma = \frac{v_{r^s}^*}{a\omega^n}(1+rb)$, $\omega = \frac{v_{r^s}^*}{a\omega^n}(1+rb)$ capture the amortization of capital.

The condition for the recycled material to be cost-competitive is as follows:

$$\left[\mu e_r + wl_r + \frac{v_r^* \varepsilon}{a\omega^n}(1+rb)\right](1+m) > \left[\mu e_{r^s} + wl_{r^s} + p_r r_{r^s} + wl_{r^s} + \frac{v_{r^s}^* \varepsilon}{a\omega^n}(1+rb)\right](1+m) \tag{51}$$

Eq. (51) implies that the relative price of recycling compared to mining depends on technical coefficients, relative inputs prices and markups in both sectors. It is important to note that changes in technical coefficients can have a nonlinear impact on the relative prices of mining and recycling. For instance, an increase in the energy price does not automatically imply that the relative price of the more energy-intensive sector becomes cheaper. This is because the energy price affects simultaneously the relative costs of capital goods used in both sectors, as energy is an input of production in the capital sector. As a result, it is not possible to identify any general and deterministic relation between changes in production coefficients or distributive variables (markups and interest rate) and the direction of the change in commodity prices (Sraffa, 1960).

[1] Since capital goods have the same production coefficients and homogenous markups, there is just one price for capital in the price vector.

2.12.2 The environmental impacts of the circular economy

The CE transition implies a structural change, where the recycling sector replaces the mining sector. This affects the total energy and material use in the economy by: (1) changing the total production level, and (2) material and energy intensities according to intersectoral multipliers of IO tables. We will refer to the former channel as the 'macroeconomic' channel, and to the latter as the 'technical IO' channel (Figure 2).

According to the 'macroeconomic' channel, changes in intersectoral multipliers affect the total capital intensity[2] of the economy. This is likely to result in capital expansion, boosting aggregate demand and the GDP. As a result of the interaction between the 'capital accelerator' and 'consumption multiplier', the GDP would permanently increase, raising also energy and material use in the economy (Serrano and Freitas, 2017; Pariboni and Girardi, 2016, Deleidi and Mazzuccato, 2021).

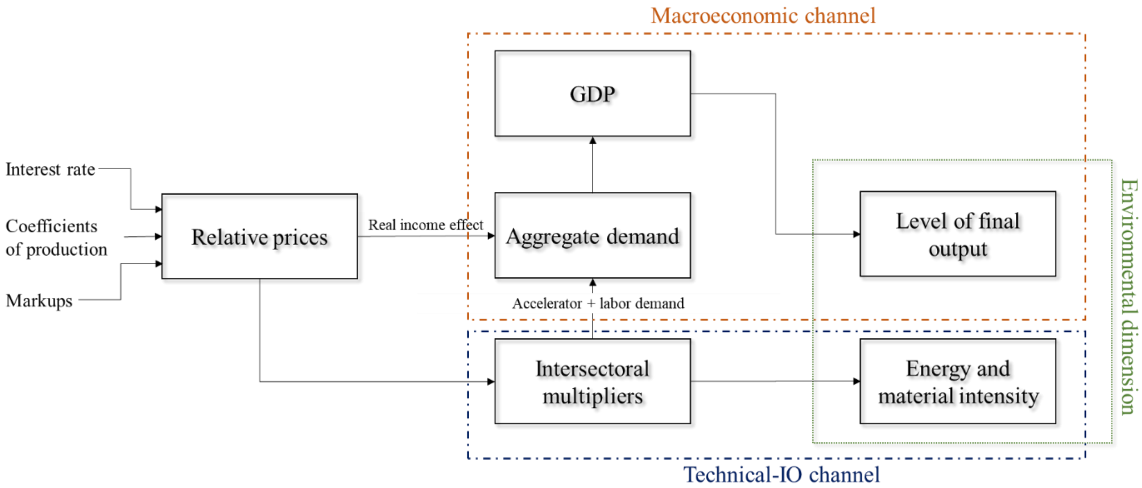


Figure 2. An overview of mechanisms behind the economy-wide impacts of the transitions to the CE

According to the 'technical-IO' channel, a change in intersectoral multipliers modifies total energy and material intensities of the economy. These intensities are defined as the total energy use and the total material use divided by the GDP. In particular, assuming homogeneous coefficients of productions across firms in the same sector, the energy and material intensities m_e and m_r in the non-CE can be computed using the Leontief Inverse matrix (see Appendix A for derivations) as:

$$m_e = \frac{\mathrm{e_c} + \mathrm{e_r r_c} + \mathrm{e_k}\sigma_c + \mathrm{e_k r}_c\sigma_r}{1 - \mathrm{e_k}\sigma_e} \tag{52}$$

$$m_r = r_c \tag{53}$$

The energy and material intensity in the CE is equal to (see Appendix A):

$$m_{eCE} = \frac{(1-r_c)(1+(1+\beta)e_k+e_r)+2e_c+e_{r}s(1+r_c)+e_k(2\omega+\gamma+\gamma r_c)+r_{r}s(\beta e_k+e_r)(1+r_c)}{\sigma} \tag{54}$$

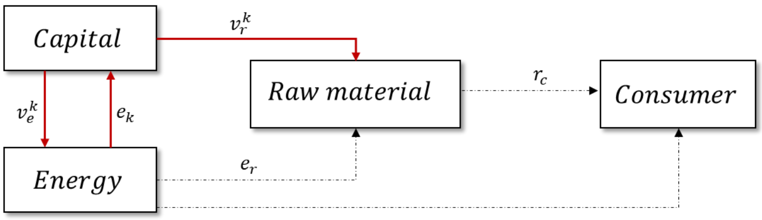
[2] Appendix B explains the measure of capital intensity and its relationship with GDP.

$$m_{rCE} = \frac{\sigma + r_r s(1-\vartheta e_k)(1+r_c)}{\sigma} \tag{55}$$

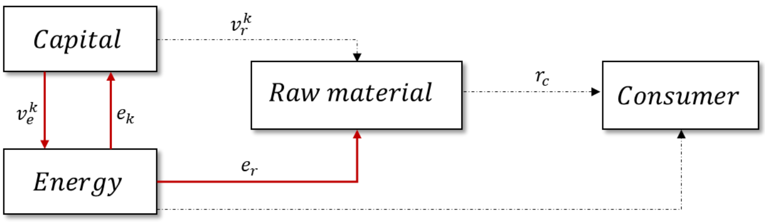
Comparing eqns. (52) and (54) (or 53 and 55) allows for deriving the conditions under which the substitution of virgin raw materials by recycled materials would increase the total energy/material intensity.

It is important to emphasize that to study the economy-wide impacts of recycling, it is not enough to look at input use of a single sector, but it requires considering energy and materials embedded in all inputs, i.e., along the value chain. Figure 3 illustrates feedback loops between basic commodities, namely: capital and energy that affect the total capital and energy use of the economy. Figure 3(a) depicts the 'capital-energy' channel, according to which changes in capital intensity of the recycling sector affect the total energy intensity of the economy. For instance, in case the recycling sector is characterised by a higher capital-to-output ratio than mining, the transition to the CE economy would increase the amount of capital needed to produce one unit of material output. This would increase energy used in the production of capital goods, and in turn capital required to produce one unit of energy, increasing the total energy intensity (Figure 3(a)). Simultaneously, an increase in the total capital intensity would boost total output through the interaction of the 'consumption multiplier' and 'capita accelerator'.

Figure 3(b) illustrates the 'energy-capital' channel, according to which changes in the energy efficiency of the recycling sector affect the total capital intensity of the economy. For instance, if more energy is needed to produce recycled than raw materials, the transition to the CE would increase the amount of capital needed to produce one unit of material goods through the energy-capital channel. This, in turn, would increase the total energy intensity as well as the level of production in the economy.



(a) The capital-energy channel



(b) The energy-capital channel

Figure 3. The feedback loop between basic commodities

The analysis presented above has been based on the model with homogenous coefficients of production across firms of the same sector.[3] Since our model is complex and involves stochastic innovations, we examine the effects of different mechanisms using an agent-based model in Section 3.

3. Baseline model simulations

In this section, we present the results from the baseline model simulations, using agent-based modelling with heterogeneous firms. We discuss the impact of different types of innovations in the K-sector on the economy. We calibrate the baseline model so that the recycling sector is not cost-competitive with mining, and thus absent from the market. In Section 3.1, we study the transition to the CE due to a one-time shock to the energy intensity in the recycling sector, which makes the recycling sector cost-competitive with mining. We compare model dynamics for different capital-to-output ratios in the recycling sector as well as for different shock sizes to energy efficiency. The reader may think of shocks to energy efficiency as an outcome of public R&D activities. In Section 3.1, we do not consider endogenous innovations, to make the impact of mechanisms operating in our model transparent. In Section 4, we present the results from model simulations of the baseline model with endogenous innovations, where we examine the impact of public policies that provide support for the recycling sector.

Each model simulation lasts for 800 periods, of which each step corresponds to one month. Supplementary Table C1 summarizes the baseline parameter values. As our model includes stochastic factors, we conduct a Monte Carlo analysis, where we report the average results from 50 simulations for the same initial conditions.

Figure 4 illustrates the long-run evolution of real GDP, energy intensity, energy per-person employed, material depletion and sectoral employment in the baseline model simulations with endogenous innovation and no recycling.[4] Material depletion corresponds to the amount of extracted raw material in each period. The figure illustrates that the baseline model generates a stable growth of the GDP characterized by persistent fluctuations and rare crises. The GDP growth is fueled by an increasing rate of public spending (see for discussion Appendix C). On the other hand, the growth rate of the GDP per person employed is driven by different types of innovations in the capital sector. Such innovations increase total labour productivity. Finally, the baseline model generates a decline in energy intensity accompanied by an increase in energy use, following empirical facts (Sun, 2003; Goldemberg and Prado, 2013; Baksi and Green, 2007).

Figure 5 presents the impact of K-firms innovations on the evolution of technological coefficients of different firms in each sector (capital productivity, energy efficiency and the capital-to-labor ratio). Although firms are characterized by different technical coefficients, their evolution over time exhibits the same increasing trend due to market competition and imitation in K-sectors. In the baseline, there is no

[3] A similar analysis could be conducted using the weighted average of coefficients of production in each sector.
[4] Real GDP is the deflated value of sum of investments and consumption goods.

demand for recycled materials. As a result, firms in K-sector producing capital goods for mining firms benefit from growing profits and keep innovating for the mining sector. This increases the technological gap between the mining and recycling sector, enhancing a lock-in to recycled raw materials

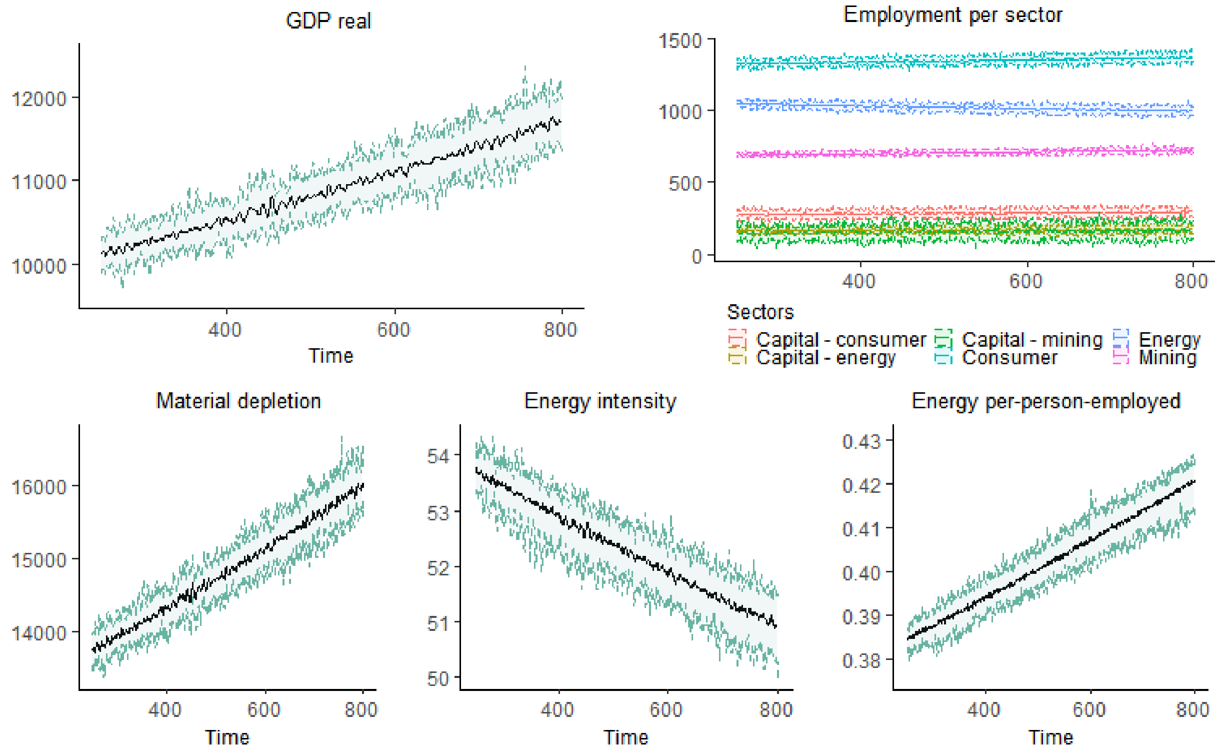


Figure 4. Main macroeconomic and environmental variables in the baseline scenario.
Note: Black lines correspond to the averages of 50 Monte Carlo runs; colourful bands correspond to minimum and maximum bounds. Energy intensity is the amount of energy embedded in the production of one unit of consumer good.

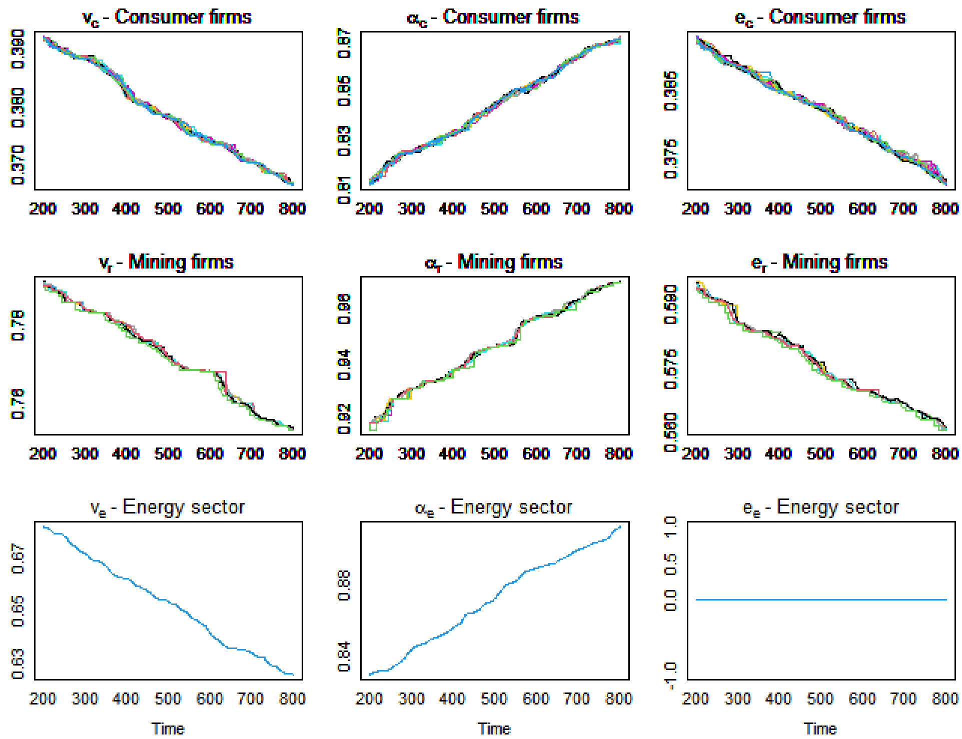


Figure 5. Changes in capital productivity (panels on the left); in capital-to-labor ratio (middle panels) and in energy efficiency (panels on the right) in three sectors: the energy, mining and consumer sector. Each firm is represented by a different color.

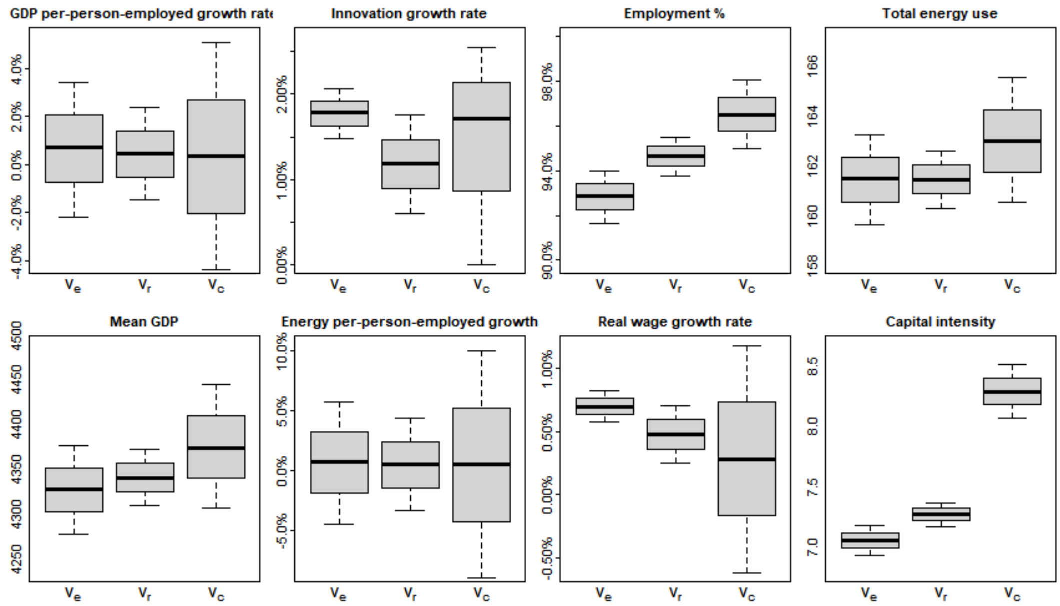
Note: Capital productivity ($1/v$), capital labour ratios (α) and energy consumption (e).

Figures 4 and 5 present the results from the model with endogenous innovations in different sectors. Here, K-firms decide which features of their capital goods to improve, depending on the cost structure of their clients. Such improvements can have sometimes opposing impacts on macroeconomic variables. To isolate the effect of each type of innovation on the economy, below we discuss the impact of firms in the K-sector performing only one type of innovation for only one sector at a time. In particular, Figure 6(a) shows the impact of innovations aimed at improving the capital-to-output ratio (K/Y) ratio in each sector separately; Figure 6(b) does the same for improvements in the capital-to-labour ratio (K/L), while Figure 6(c) illustrates the impact of improvements in energy efficiency. For the sake of results comparability, we keep the unemployment benefits equal to zero in these simulations.

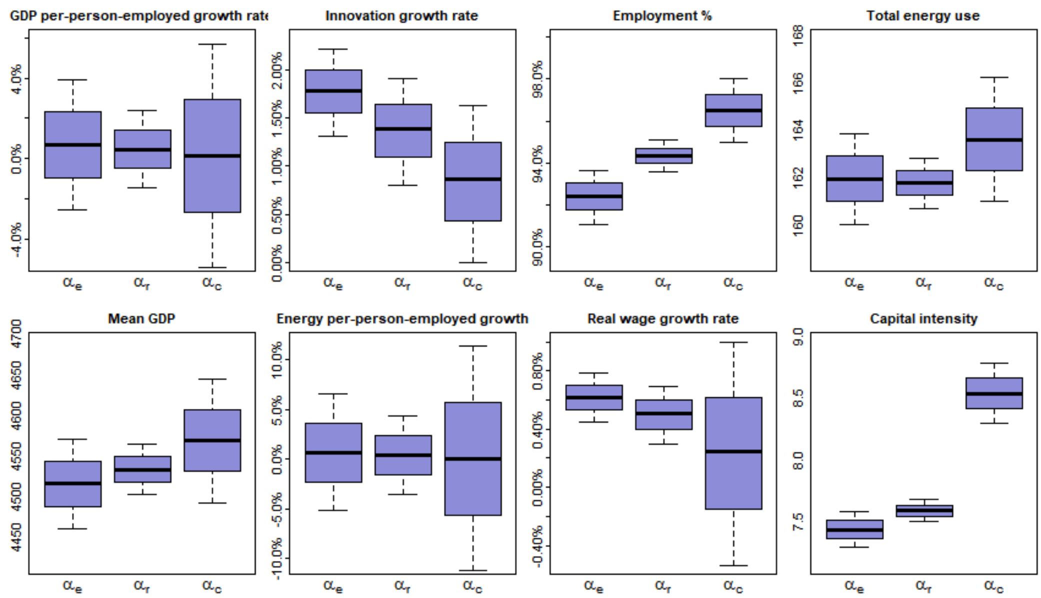
The key finding from these model simulations can be summarized as follows. Innovations in the capital-to-output ratio in the energy sector have the greatest impact on the growth rate of GDP per-person-employed but result simultaneously in the lowest total GDP level compared to such innovations in other sectors (Figure 6(a)). This is due to the feedback mechanisms caused by basic commodities. Innovations in the capital-to-output ratio in the energy sector strongly reduce the capital and energy intensity of the economy. As a result of this, the GDP and energy use is lower compared to other sectoral innovations.

Innovations in the capital-to-labour ratio in the energy sector have the greatest impact on the growth of GDP per person employed (Figure 6(b)). The impacts of such innovations on the GDP do not differ between sectors, as innovations in the capital-to-labour ratio do not affect the capital intensity of the economy, but only reduce employment. On the one hand, an increase in the labor productivity affects the real wage and profits, increasing consumption demand. On the other hand, labor-saving innovations reduce employment and consumption. These effects offset each other. Finally, improvements in energy efficiency increase the growth rate of GDP per-person-employed but cause a decline in the GDP level (Figure 6(c)). Such innovations reduce the total capital intensity of the economy and energy use due to the 'capital-energy' channel.

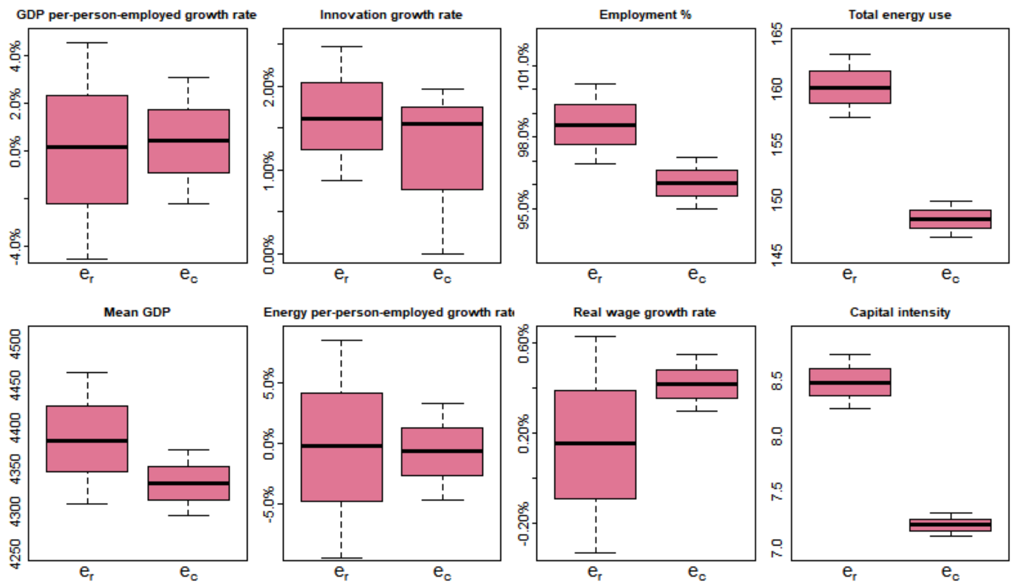
All in all, the results show that innovations in sectors producing basic commodities have a greater impact on the growth rate of GDP per-person-employed and capital intensity of the economy compared to other sectors. This relates to the fact that basic commodities enter directly and indirectly in the production of all other goods. As a result, changes in their technical coefficients affect all prices in the economy and have the greatest impact on aggregate demand.



(a) Innovations in the capital-to-output (K/Y) ratio of the energy sector (v_e); mining sector (v_r); and consumer-good sector (v_c)



(b) Innovations in the capital-to-labour (K/L) ratio of the energy sector (α_e); mining sector (α_r); and consumer-good sector (α_c)



(c) Innovations in the energy efficiency of the mining (e_r) and consumer-good sector (e_c)

Figure 6. The impact of different types of innovations conducted in one sector at the time on macroeconomic variables

Note: The figure presents the results from 50 Monte Carlo runs

3.1 An exogenous shock triggering the transition to the circular economy

In the baseline model simulations, there is no recycling sector due to the high cost of recycling compared to mining. Below, we present the results from model simulations where we introduce an exogenous one-time shock to the energy efficiency in the recycling sector in period 350, which makes recycling cost-competitive. We consider no endogenous innovations.

Figure 7(a) presents the results from scenario A, where we examine the impact of the one-time shock to energy efficiency in the recycling sector on the GDP and energy use for different values of the capital-to-output ratio in the recycling sector. In particular, we consider scenarios A.1, A.2 and A.3, where the capital-to-output ratio in the recycling sector is equal to 0.4, 0.5 and 0.6 respectively, which is higher than in the mining sector (0.3). A shock to energy efficiency in the recycling sector is calibrated in a way that recycled materials become cheaper than virgin raw materials. As a result, new firms start to enter the recycling sector. Newcomers first order capital that takes time to be produced and installed. During the transition phase, firms in the mining sector continue to invest in capital replacement, as they still receive orders, while firms in the recycling sector built their production capacity. This results in a ‘doubling’ of capital investments and a surge in the GDP between periods 400-500. New capital formation for the CE temporarily increases total energy use.

In Figure 7(b), we compare the impact of a one-time shock to energy efficiency in the recycling sector, as in scenario A. However, in scenario B, we consider three shock sizes, which change the energy efficiency of the recycling sector from 0.28 in the baseline to 0.22, 0.19 and 0.16 in Scenarios B1, B2 and

B3, respectively. In these scenarios, the capital-to-output ratio of the recycling sector is equal to the same value as in the mining sector. Table 2 summarizes parameter values in all scenarios. Below Figures 7(a) and (b), we decompose changes in the total energy use into the GDP effect and the 'intersectoral multiplier' effect. The GDP effect measures the percentage change in total energy use compared to the baseline scenario, which is caused by the change in the level of output. The 'intersectoral multiplier' effect expresses the percentage change in energy use as a result of a change in the total energy intensity of the economy.

Figure 7(a) illustrates that the effect of scaling-up of the recycling sector depends on the value of the capital-to-output ratio. On the one hand, the higher value of the capital-to-output ratio boosts aggregate demand and the GDP level by increasing the total capital intensity, and through the 'capital-energy' channel also the total energy intensity. On the other hand, the shock to energy efficiency affects the total energy intensity by directly reducing energy use in the recycling sector and, indirectly, through the 'energy-capital' channel. The latter reduces also the total capital intensity of the economy, undermining aggregate demand and the GDP.

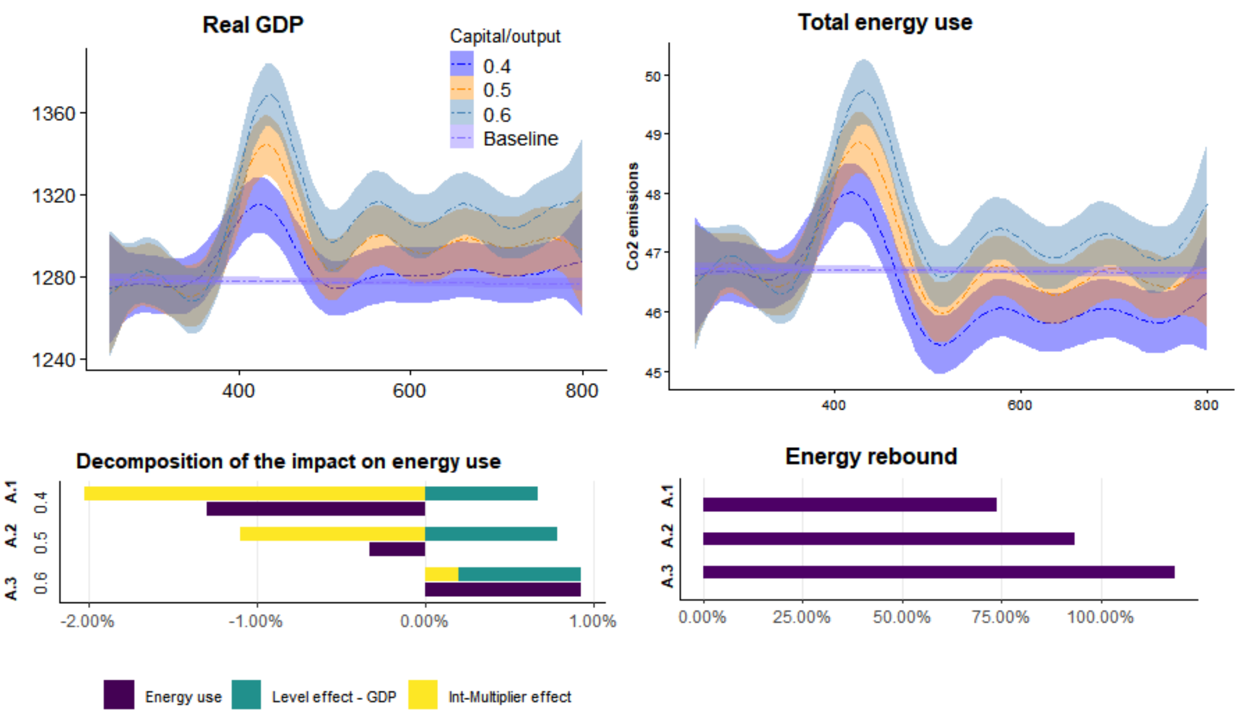
The net effect of these two mechanisms depends on the precise value of the capital-to-output ratio in the recycling sector. For the capital intensity equal to 0.4 or 0.5, total energy use is reduced as the 'intersectoral multiplier' effect dominates the GDP effect (Scenarios A.1 and A.2). For the capital intensity equal to 0.6 (or higher), energy savings due to recycling being less energy-intensive than mining are offset by an increase in the GDP level as well as in the total energy intensity due to the feedback loop between the production of capital and energy (Scenario A.3). The higher capital-to-output ratio in the recycling sector implies that more energy is needed to produce one unit of raw material, via the 'capital-energy' channel, which leads to a higher total capital intensity of the economy. These two mechanisms affect the total energy use by increasing the total energy intensity and the level of output.

Finally, Figure 7(b) shows that the scaling up of the recycling sector, characterized by a lower energy intensity than the mining sector, reduces both GDP levels and energy use. This is explained by the fact that improving energy efficiency in the recycling sector reduces both total energy intensity of the economy and the GDP level due to changes in the total capital intensity.

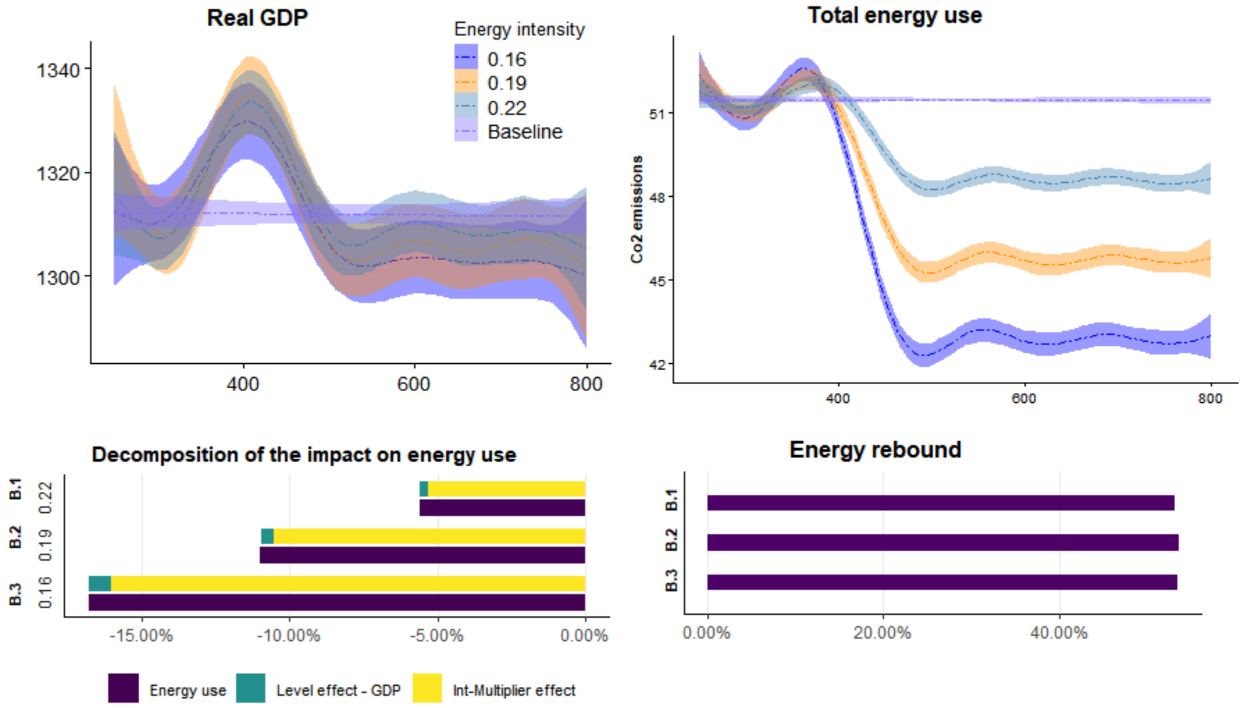
Table 2. Values of the parameters in Scenario A and B

Description	Sub-scenarios	Capital intensity of the recycling (v_{r_s})	Pre-shock/ post shock Energy intensity in recycling (e_{r_s})	Energy rebound	Material rebound
Scenario A	A.1	0.4	0.26/0.18	72 %	1.8 %
	A.2	0.5		86 %	2.3 %
	A.3	0.6		123 %	3.1 %
Scenario B	B.1	0.3	0.28/0.22	59.1%	0.5 %
	B.2		0.19	59.8%	-0.4 %
	B.3		0.16	60.2%	-0.7%

Note: In all scenarios the capital-to-output and the energy intensity of the mining sector are, respectively, 0.3 ad 0.26.



(a) Changes in the capital-to-output ratio – Scenario A



(b) Changes in the energy efficiency – Scenario B

Figure 7. The impact of exogenous changes in energy and capital-to-output ratio in the recycling sector

Note: Bottom panels show the percentage change in total energy use in different scenarios compared to the baseline model *('energy use')*, which we decompose into the change in energy use due to a change in the GDP level (*'level effect'*) and a change in total energy intensity (*'Int-multipliers' effect*).

In Table 2, we report the energy rebound effect corresponding to each scenario. Following Saunders (2000, 2008), the rebound is computed as:

$$re_e = \frac{E^e - E^a}{E^a}, \tag{56}$$

where E^a is the percentage change in energy use in a given scenario compared to the baseline; while E^e is the expected change in energy use. The latter is defined as the percentage change in energy efficiency in the R-sector due to recycling firms replacing mining firms ($E^e = \frac{e_{r_S} - e_r}{e_r}$). The material rebound effect is computed in an analogous way as:

$$re_m = \frac{M^e - M^a}{M^a}, \tag{57}$$

where M^a and M^e are the actual and expected percentage change in the use of the raw virgin material compared to the baseline. The expected change in material use (M^e) is equal to 100% as the recycling materials are expected to fully replace virgin materials. This is conditional on the assumption that materials embodied in consumer products can be recycled infinitely and virgin and recycled materials are full substitutes.

The results in Table 2 indicate that in all discussed scenarios, the reduction in energy use is lower than improvements in energy efficiency of the recycling sector. In fact, the rebound effect is always present in our model. This follows from the fact that the percentage change in the total energy intensity as a result of improvements in energy efficiency in the recycling sector is always less than 1, which implies the rebound effect. This can be shown by looking at the ratio between the partial derivative of the 'energy intensity' of the CE economy (eq. 58) with respect to the energy efficiency of the recycling sector (e_r) relative to the energy intensity (for $e_r = 1$):

$$\frac{\frac{\partial m_{eCE}}{\partial e_r}(e_r = 1)}{m_{eCE}(e_r = 1)} = \frac{\mathrm{r_c}}{e_c + r_c + e_k\sigma_c + e_k r_c \sigma_v}, \tag{58}$$

Eq. (58) describes the percentage change in the total energy intensity as a result of improvements in energy efficiency in the recycling sector. For the rebound effect to be absent, eq. (58) would need to be equal to 1, which is satisfied only if the material intensity r_c is equal to $r_c = \frac{-e_c - e_k\sigma_c}{e_k\sigma_v}$. This would result in an implausible (negative) value of the material intensity.

The results from Scenarios B.1-B.3 in Table 2 indicate that the size of the shock to energy efficiency in the recycling sector has a negligible impact on the energy rebound effect. On the contrary to this, increasing the value of the capital-to-output ratio in Scenarios A1-A3 translates into a larger rebound effect, by increasing the GDP, and total energy and capital intensities.

Our study highlights the importance of modelling explicitly capital investments and sectoral relationships for the assessment of the rebound effect. It has been shown that different types of production functions can determine the size of the rebound effect. For instance, the Leontief function is always fuel conserving, while other functions, such as: Cobb-Douglass or Generalised Leontief, are never fuel-conserving and generate the rebound effect (Saunders 2000, 2008). In our study, the rebound effect emerges due to changes in aggregate demand, capital and energy intensities as a result of technological change, even though we employ the Leontief production functions.

4. Policy experiments

In this section, we evaluate the role of Mission-Oriented Innovation Policies (MOIPs) in fostering the CE transition. In particular, we introduce a National Research Laboratory (NLR) that works on radical innovations to enlarge the set of technological opportunities available in the economy (see Dosi et al. 2021 for a similar experiment). At each time step, the NRL receives public funding from the government to perform its research efforts. The discovery of a radical innovation by the NRL depends on its own cumulative search efforts, as well as on those performed by capital-good firms. If NRL discovers a radical innovation, it becomes publicly available knowledge. Firms adopt it if it offers improvements over the technology that they are currently using. Since improvements in resource efficiency reduce aggregate demand via the 'capital accelerator' effect, MOIPs are combined with fiscal policies to prevent economic decline.

We consider the following policy scenarios:

1. The MOIP - e_{r_s} scenario, where we study the impact of the NRL undertaking R&D activities so as to improve energy efficiency of the recycling process (e_{r_s}). In this scenario, the government aims at keeping the economy at full employment, so it adjusts fiscal spending to maximize the growth rate of the economy goes to mitigate the negative effect of innovations on total output.
2. In the MOIP – $e_{r_s} + r_c$ scenario, the NRL focuses on improving the energy efficiency of the recycling process (e_{r_s}), just as in *MOIPS* - e_{r_s}, but also the material efficiency of the consumer sector (r_c). Here, the Government adjusts fiscal spending to achieve a 'sustainable' growth path, where the growth rate of the GDP level is consistent with the growth rate of material efficiency. Otherwise, the growth rate of the economy would exceed the growth of material efficiency, which would cause a constant decline in the stock of natural resources.
3. Finally, in the tax scenario, the Government introduces a tax on the mining sector to reduce cost disadvantage of the recycling sector. The value of the tax changes over time to make the price of mining 10% more expensive than the recycled material.

Table 3 summarizes the results from policy simulations. We report the mean results from the last 500 rounds of model simulations (unless stated otherwise). The results indicate that the baseline scenario is characterized by the lowest GDP growth. There is a negative feedback loop between improvements in the capital-to-output ratio or/and energy efficiency and aggregate demand. As R&D activities depend on the market size, the lower aggregate demand and GDP growth slow down technological progress, known in the literature as the Kaldron-Verdoon law (Verdoon, 1949; Mamgain, 1999; Deledi et al. 2018). This relates to the fact that firms' spending on innovation depends on their profits, and thus on total demand. In addition, each type of innovation increases the total labor productivity and reduces employment (either directly or indirectly). The combination of these effects undermines growth but still results in high levels of material depletion and energy use.

Both MOIPs scenarios reduce the depletion rate of the natural resource and ensure 100% recycling rate. There are important differences between them. The *MOIP* - e_{r_s} scenario results in the higher growth of the economy compared to the baseline scenario, and thus higher energy use and material depletion. Here, public spending, which aims at keeping the economy at the full employment rate acts as a fiscal stimulus, increasing the GDP growth. On the other hand, in the *MOIPs* - $e_r + r_c$ scenario, the Government provides funding for improvements in the material efficiency in C-sector, while at the same time aligns the GDP growth rate with growth in material efficiency. This results in the higher level of employment and energy use compared to the baseline. As a result, the lower growth rate in aggregate demand slows down technological progress. In the long run, the energy intensity in this scenario is higher than in MOIPs (e_r).

Both MOIPs lead to a change in the composition of private R&D expenditures in favour of the recycling sector. As long as the production cost of recycling drops and the demand for recycled materials goes up, the expansion in capital demand in the recycling sector leads to more R&D expenditures in the K_3 sector, fostering the CE transition. As a consequence, the share of R&D expenditures of firms producing capital goods for the mining sector decreases, which leads to a polarization of R&D activities towards the recycling sector.

MOIPs have a twofold impact on employment and aggregate demand. On the one hand, they increase aggregate demand due to spending on R&D activities. This effect is relatively small. On the other hand, MOIPs cause a reduction in employment and aggregate demand because of productivity improvements resulting from innovations. Active fiscal policies (AFP) can offset this effect. A combination of both policies allows transforming gains from improvements in output-per-employee due to MOIPs into a positive GDP growth rate while keeping the unemployment rate close to the frictional unemployment rate. In addition, the policy has a positive impact on private R&D activities. It is important to note that unless MOIPs are accompanied by AFPs, their effectiveness in fostering the growth rate of input productivities is undermined. This is due to the negative effect of MOIPS on aggregate demand which has a relatively low crowding-in effect on private R&D activities.

Finally, the environmental tax shifts innovation activities from the mining sector to recycling. This increases substantially the recycling rate compared to the baseline, but it also boosts energy use. The tax makes the recycled material cheaper than the raw material, capital investments and production in the recycling sector. This leads to the concentration of the R&D activities in the K-sector producing capital goods for recycling firms, increasing the technological gap between recycling and mining in favour of recycled materials. However, the economy suffers from lower growth and employment, similarly to the baseline scenario, creating a downward spiral between technological progress and lower demand. The share of the recycling sector in material production reaches 92%, below its 100% target. This can be explained by the fact that firms in the mining sector reduce mark-ups in response to the tax to make their products cost competitive with recycled materials, and this way they are still able to capture a share of the market (<10%).

Table 3. The summary statistics on selected variables under different policy scenarios

	Baseline	**MOIP-** $\boldsymbol{e_{r_s}}$	**MOIP-** $\boldsymbol{e_{r_s} + r_c}$	**Tax**
Growth of material intensity	-0.09	-0.34	-1.05	-0.07
Growth of energy intensity	-0.31	-2.5	-1.32	-0.29
Volatility of $\boldsymbol{R_s}$ demand	0.987	0.123	0.138	0.231
% recycling – 500 periods	12.4 %	100 %	100%	92.3 %
A % change in energy use compared to the baseline	B	4.7 %	-2.1 %	1.9 %
Mean decline in the stock of natural resources	-28.2 %	-6 %	-0.74 %	-1.23 %
Growth rate of the economy	0.06 %	3.3%	0.96 %	-0.02 %
Material rebound	-	12.3%	9 %	22.3 %
Energy rebound	-	48.3%	33.3%	8.1 %
Unemployment rate	15.3 %	3.2%	6.7 %	14.3 %
Public debt-to-GDP ratio	134.6 %	100.2 %	113.5 %	128.5%

5. Conclusions

In this paper, we present an agent-based stock-flow consistent model of the macro economy that accounts for the inter-sectoral relationships and material/energy flows. We pay special attention to the feedback loop mechanisms behind prices, aggregate demand, as well as total energy, material and capital intensities of the economy. The important novelty of our model is that the mining and recycling sectors use different types of capital goods to produce materials. As a result, technological change in the circular (CE) economy occurs due to investments in new capital in the recycling sector. We employ the model to study the economic feasibility of, and the rebound effect related to, the CE transition. In the baseline scenario, we assume that recycling is not cost-competitive with mining. The recycling sector emerges as a result of exogenous changes in the technological coefficients of the recycling sector, which affect all prices in the economy, or due to public policies, which make recycling goods cost-competitive with virgin materials.

Our results show that the impact of the CE transition depends on changes in the intersectoral multipliers due to the scaling-up of the recycling sector. Such changes modify the total material/energy intensities of the economy and the level of production and may render the rebound effect. For instance, if changes in the intersectoral multipliers increase the total capital intensity of the economy, this boosts aggregate demand and total output through the interaction between the 'capital accelerator' and 'consumption multiplier' effect, increasing total energy use. Simultaneously, this would result in higher total energy intensity, through the 'capital-energy' channel. The rebound effect can occur even if the recycling sector is characterized by a higher energy efficiency than the mining sector. This relates to the fact that in our model, there is simultaneity in the production of energy and capital, which constitute inputs of production for each other. As a result, a change in demand for one of these inputs affects the production of the other sector.

The main finding from our policy exercises can be summarized as follows: Mission-Oriented Innovation Policies (MOIPs) together with fiscal policies can help increase recycling rates, and prevent the rebound effect without reducing employment. By promoting resource efficiency improvements, MOIPS reduce total output and employment. On the one hand, improvements in energy efficiency or capital productivity reduce the GDP and employment via the capital accelerator effect. On the other hand, labour-saving technologies reduce employment directly without affecting aggregate demand. Both effects can be offset by expansionary fiscal policies. The combination of MOIPs and fiscal policies causes a crowding-in effect of private R&D activities. This leads to the polarization of the R&D activities in the recycling sector.

Our research shows a negative side of the Government setting the goal of achieving material neutrality, by aligning the growth rate of the GDP with the growth rate of material efficiency. In this case, fiscal adjustment cannot compensate for the loss in aggregate demand and employment induced by technical progress. This reduces spending on R&D activities by firms and the innovation potential of the economy. As a result, the employment rate and the GDP growth rate are lower compared to the scenario where the Government targets full employment and full recycling. Yet, the policy aimed at achieving material neutrality achieves the greatest reduction in energy use and depletion of natural resources.

Our research opens venues for future research. In the future, it is important to calibrate macro-evolutionary models with the input-output structure on existing I/O databases. Such empirically calibrated models could provide new insights into the assessment of the economic-wide impacts of the scenarios proposed in the EU's Energy Roadmap 2050 (ER2050), including the effect of energy transitions on the demand for rare minerals. Moreover, future macro-evolutionary models combined with input-output analysis can help unravel conditions under which decoupling between energy consumption and GDP growth is possible.

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Appendix A Computation of unit cost of production

The stock of capital in period t is composed of the residuals of capital goods installed in the z + 1 previous periods (vintage capital goods), with z representing the life span of the capital good:

$$k_{t,i} = \sum_{j=t-z+1}^{t} k_{j,i}^{ins} \left(\frac{j+z-t}{z}\right)$$

where $k_{j,i}^{ins} = I_{t-dk,i}$ is the amount of capital installed in period j and corresponds to the gross investments from dk previous periods. The total deterioration in each period is composed of the sum of the deterioration of capital goods installed in the previous z periods (including the current one):

$$deterioration_{t,i} = \sum_{j=t-z+1}^{t} \frac{k_{j,i}^{ins}}{z}.$$

Amortization computed using the realized *leverage* is equal to:

$$amortization_{t,i} = \frac{1}{a\,z} \sum_{j=t-z+1}^{t} p_{i,indexK} k_j^{ins} (1 + r_j b l_j)(j + z - t),$$

where r_j e l_j are the interest rate in the period when the debt was created and the *leverage* realized in purchasing the capital good, respectively. $K_{j,i}^{ins}$ is the installed capital in period j from firm i and $p_{i,indexK}$ is its price (because z is the useful life of the capital, it goes back up to a maximum of z periods in the depreciation calculation). Parameters $a = \sum_{i=1}^{z} \frac{i}{z}$ and $b = \frac{1}{a\,z} \sum_{i=1}^{z} \frac{i^2+i}{2}$ are the multiplying factors for the computation, respectively, of the interest payment on the debt incurred in a given period and of the normal cumulative production over the useful life of capital good. Because the capital good has a finite useful life, a constant absolute depreciation of installed capital is assumed. As a result, the related depreciation rate is increasing. In each period, the residual capital stock is a composite of the residual capital goods installed in the previous periods.

Because of innovation dynamics, each newly installed capital embodies different technology. Thus, production coefficients are a weighted average of the coefficients related to each installed capital good forming the existing productive capacity. The (normal) capital-to-output ratio is:

$$v_{t,i}^{n} = \frac{\sum_{j=t-z+1}^{t} k_{j,i}^{ins} \left(\frac{j+z-t}{z}\right) {v^n}_{j,i}}{\sum_{j=t-z+1}^{t} k_{j,i}^{ins} \left(\frac{j+z-t}{z}\right)}$$

The normal capital-to-labor ratio is:

$$\alpha_{t,i}^{n} = \frac{\sum_{j=t-z+1}^{t} k_{j,i}^{ins} \left(\frac{j+z-t}{z}\right) \alpha_{j,i}^{n}}{\sum_{j=t-z+1}^{t} k_{j,i}^{ins} \left(\frac{j+z-t}{z}\right)}$$

The energy/output ratio is:

$$e_{t,i} = \frac{\sum_{j=t-z+1}^{t} k_{j,i}^{ins} \left(\frac{j+z-t}{z}\right) e_{j,i}}{\sum_{j=t-z+1}^{t} k_{j,i}^{ins} \left(\frac{j+z-t}{z}\right)}$$

Markups evolution

$$\rho_{t,i}^{r,inc}, \rho_{t-1,i}^{r,dec} = \begin{cases} if\, \dfrac{inv_{t,i}}{rs_{t,i}} < s^T: \quad \rho_{t,i}^{r,inc} = \rho_{t-1,i}^{r,inc} + 1\,; \;\; \rho_{t,i}^{r,dec} = 0 \\ \quad otherwise\; \rho_{t,i}^{r,inc} = 0\,; \;\; \rho_{t-1,i}^{r,dec} = \rho_{t-1,i}^{r,dec} + 1 \end{cases}$$

Financing, debt service and bankruptcy

The loan demand is defined as:

$$\begin{cases} if\; cash_{t.i} \geq WB_{t,i} + K_{t,i}^{df}(1 - l^T): \;\; L_{t,i}^{d,long} = K_{t,i}^{df}\, l^T;\; l_{t,i}^{w} = 0;\; l_{t,i}^{k} = l^T \\ else\; if\; cash_{t.i} \geq WB_{t,i}: \;\; L_{t,i}^{d,long} = K_{t,i}^{df}\, l_{t,i}^{k};\; l_{t,i}^{w} = 0;\; l_{t,i}^{k} = \frac{K_{t,i}^{df} - cash_{t,i} + WB_{t,i}}{K_{t,i}^{df}} \\ else\; L_{t,i}^{d,short} = WB_{t,i} l_{t,i}^{w};\; L_{t,i}^{d,long} = K_{t,i}^{df}\, l_{t,i}^{k};\; l_{t,i}^{w} = \frac{WB_{t,i} - cash_{t,i}}{WB_{t,i}};\; l_{t,i}^{k} = 1 \end{cases}$$

where $L_{t,i}^{d,long}$ is the long-term loan to finance the purchasing of the capital good, l^T is the leverage target, $l_{t,i}^{k}$ is the realized leverage to finance the purchasing of capital good, $L_{t,i}^{d,short}$ is the short-term loan to finance the wage bill and $l_{t,i}^{w}$ is the relative realized leverage. Since the interest rate may vary across the periods in which the debt was incurred, the interest rate payments are calculated using the historical composition of the residual debt stock. The evolution of each debt installment (related to the purchase of the capital good) is decreasing, consistently with the evolution of capital amortization. Total debt service includes debt installments of short-term and long-term loans and *Ponzi* loans, including the respective interest rates:

$$servicedebt_{tot_{t,i}} = servicedebt_{capital_{t,i}} + servicedebt_{short_{t,i}} + servicedebt_{ponzi_{t,i}},$$

and it is equal to:

$$\begin{aligned} servicedebt_{tot_{t,i}} &= \\ &= \frac{1}{a\,z} \sum_{j=t-z}^{t-1} l_{i,j} K_{i,j}^{d}\left(1 + b^{long} r_j\right)(j + z - t) \\ &+ \frac{1}{z^{short}} \sum_{j=t-z^{short}}^{t-1} l_j WB_{j,i}\left(1 + a^{short} r_j\right)(j + z^{short} - t) \\ &+ \frac{1}{z^{ponzi}} \sum_{j=t-z^{ponzi}-1}^{t-2} L_{j,i}^{ponzi}\left(1 + a^{ponzi} r_j\right)(j + z^{ponzi} - t), \end{aligned}$$

The financial resources of firms C at the end of the period are:

$$\begin{aligned} cashF_{t,i} = cashF_{t-1,i} + revenues_{t,i} + L_{t,i}^{d,short} + L_{t,i}^{d,long} + L_{t-1,i}^{ponzi} - WB_{t,i} - \sum p_{indexk,t} k_{i,t}^{D} \\ - SD_{tot_{t,i}} \end{aligned}$$

where $cashF_{t,i}$ it is the cash available to the firm, , $L_{j,i}^{ponzi}$ is the loan granted to payback the outstanding debt, $WB_{t,i}$is the wage bill, $\sum p_{indexk,t} k_{i,t}^{D}$ is the expenditure to acquire the capital good and $SD_{tot_{t,i}}$ is the total debt service including financial charges.

In case the cash net of the debt service is negative, a firm can ask for an additional loan to pay the outstanding debt. This possibility is granted by the bank for a maximum number of periods lim^{ponzi} (within the same window of the debt repayment issuing another debt,). If the net wealth is positive or the number of periods of (over) indebtedness is less than lim^{ponzi} the firm is granted a further loan; otherwise, it goes bankrupt. If capitalist deposits (relating to the bankrupt firm) are at least equal to the residual value of physical capital and inventories, the firm is "recapitalized" for that value and, therefore, the non-performing loan corresponds to the debt stock of firm net of residual value. If the deposits are lower, the Non-performing loan registered by the bank is equal to the difference between the firm debt stock and the deposits of the capitalist (owner of the firm). In case firm does not have enough liquidity to pay the service debt, the following expression defines the condition under which the *ponzi* loan is granted and the updating of financial variables in case of bankruptcy:

$$\begin{cases} L_{j,i}^{ponzi} = -cashF_{t,i} \,;\; n_{t,i}^{ponzi} = n_{t-1,i}^{ponzi} + 1 \;\; if\; NW_{t,i} > 0 \,\vee\, n_{t,i}^{ponzi} < l^{ponzi}: \\ bankrupcy_{t,i} = 1 \; and \begin{cases} if\,(M_{t,cap_i} \geq Rv_{t,i}:\; NPV_{t,i} = D_{t,i} - Pdr_{t,i} - Rv_{t,i} \\ else:\;\; NPV_{t,i} = D_{t,i} - Pdr_{t,i} - M_{t,cap_i} \end{cases} \quad otherwise \end{cases},$$

where $NW_{t,i}$ is firm net wealth, $n_{t,i}^{ponzi}$ is the number of periods the firm has been granted with a *ponzi* loan, M_{t,cap_i} is the deposit amount of the owner of the bankrupted firm, $D_{t,i}$ is the outstanding debt, $NPV_{t,i}$ is the non-performing loan and $Pdr_{t,i}$ is the fraction of the current stock of debt paid back by the bankrupted firm:

$$Pdr_{t,i} = cashF_{t-1,i} + revenues_{t,i} + L_{t,i}^{d,short} L_{t,i}^{d,long} + Ponzidebt_{t-1,i} - WB_{t,i} - \sum p_{indexk,t} k_{i,t}^{D}.$$

The net wealth of firms is equal to:

$$NW_{t,i} = am_{t,i}^{residual} + \left(cashF_{t,i} + serviceDebtTot_{t,i}\right) - D_{t,i} + inv_{t,i} uc_{t,i}^{h}$$

$$Rv_{t,i} = ResidualValue_{t,i} = am_{t,i}^{residual} + inv_{t,i} uc_{t,i}^{h}$$

The realized and expected unit-cost of production covering R&D expenditures

To compute the units cost of production associated with R&D, K-firms spread the total expenditure over the total production generable during $\bar{T}$ periods, where $\bar{T}$ captures how long a firm intends to produce the capital good embedding the new technology, i.e., before the next innovation arrives. This is not known a priori. As a result, the firm uses expectations of $\bar{T}$. The value of $\bar{T}$ is determined by the probability of innovating and the level of expenditure in R&D in each period. It is expressed as follows:

$$E = p + 2p(1-p) + 3p(1-p)^2 + 4p(1-p)^3 + \cdots + np(1-p)^{n-1}.$$

Under the assumption that firms invest in R&D a constant fraction of their profits, the probability of innovation p is equal to:

$$p = 1 - e^{-\beta\varepsilon\frac{\pi_{t-1,i}}{w_{t.i}}}.$$

The previous series converges to the average time needed for innovation to emerge:

$$\bar{T} = \frac{1}{p} = \frac{1}{1 - e^{-\beta\varepsilon\frac{\pi_{t-1,i}}{w_{t.i}}}}$$

As a result, the unit cost of production associated with R&D expenditure is equal to:

$$c_{t,i}^{R\&D} = \frac{Ctot_{t,i}^{R\&D}}{\sum_{j=1}^{\bar{T}} q_{j,i}^{e}} = \frac{\sum_{j=t-s}^{t} \varepsilon\, \pi_{j-1,i}}{q_{j,i}^{e}\, \bar{T}},$$

where $Ctot_{t,i}^{R\&D}$ is the realized total cost of innovation:

$$Ctot_{t,i}^{R\&D} = \sum_{j=t-s}^{t} C_{j,i}^{R\&D} = \sum_{j=t-s}^{t} \varepsilon\, \pi_{j-1,i},$$

and s is the period in which the previous innovation has been realized.

Table A1. Balance sheet and transaction matrix

	Workers	Entrepreneurs	Firms E	Firms R	Firms $\mathbf{R^s}$	Firms K	Firms C	Bank	Government	CB	Σ
Check deposit	$+M1_w$	$+M1_{cap}$	$+M1_{\mathrm{e}}$	$+M1_{\mathrm{r}}$	$+M1_{\mathrm{r}^s}$	$+M1_k$	$+M1_c$	$-M1$			
Time deposit	$+M2_w$	$+M2_{cap}$						$-M2$			
Reserves								$+H_b$		$-H$	
Advances BC								$-A$		$+A$	
Loans			$-L_E$	$-L_R$	$-L_{R^s}$		$-L_c$	$+L$			
NPL			$+NL_E$	$+NL_R$	$+NL_{R^s}$		$+NL_c$	$-NL_c$			
Fixed Capital			$+K_E$	$+K_R$	$+K_{R^s}$		$+K_f$				$+K_f$
Inventories							$+INV_f$				$+INV_f$
Public bonds		$+B_{\mathrm{h},cap}$							$-B$	$+B_{cb}$	
Net wealth	$-V_{\mathrm{h},w}$	$-V_{\mathrm{h},cap}$	$-V_{\mathrm{e}}$	$-V_r$	$-V_{r^s}$	$-V_k$	$-V_c$	0	$+Deb$	0	$-K_f$
Σ	0	0	0	0	0	0	0	0	0	0	

	Workers	Entrepreneurs	Firms E	Firms R	Firms $\boldsymbol{R^s}$	Firms K*	Firms C	Government	Banks		Central Bank		Σ
									Current	Capital	Current	Capital	
Consumption	$-C_w$	$-C_{cap}$					$+C$						0
Investments				$-I_{\mathrm{r}}$	$-I_{\mathrm{r}^s}$	$+I_k$	$-I_c$						0
Input (energy)			$+E$	$-E_r$	$-E_{r^s}$	$-E_k$	$-E_c$						0
Input (Raw)				$+R_c$	$+R_c^s$		$-R_c$						0
Intra-Input (Raw)				$+R_r$	$-R_r^s$								0
Public expenditure							$+G$	$-G$					0
MOIPs	$+G_m$							$-G_m$					0
Un. subsidies	$+U$							$-U$					0
Wages	$+W$		$-W_{\mathrm{e}}$	$-W_r$	$-W_{r^s}$	$-W_k$	$-W_c$						0
Tax	$-T_w$	$-T_{cap}$						$+T$					0
Profits		$+Div_F$	$-Div_{\mathrm{e}}$	$-Div_r$	$-Div_{r^s}$	$-Div_k$	$-Div_c$						0
Profits Banks		$+Div_B$							$-Div_B$				0
Profits BC								$+F_{cb}$			$-F_{cb}$		0
Recapitalization		$-K_r$	$+K_{r_E}$	$+K_{r_R}$	$+K_{r_{R^s}}$		$+K_{r_c}$						0
Int. On deposits	$+r_m M2_{w,t-1}$	$+r_m M2_{c,t-1}$							$-r_m M2_{t-1}$				0
Int. On loans			$-r_l L_{E,t-1}$	$-r_l L_{R,t-1}$	$-r_l L_{R^s,t-1}$		$-r_l L_{c,t-1}$		$+r_l L_{t-1}$				0
Int. on Bonds		$+i_{t-1} B_{\mathrm{h},t-1}$						$-i_{t-1} B_{t-1}$			$+i_r B_{bc,t-1}$		0
Int. On Reserves									$+r_{r-1} H_{t-1}$		$-r_{r-1} H_{t-1}$		0
Int. On Advances									$-r_{a,t-1} A_{t-1}$		$+r_{a,t-1} A_{t-1}$		0
ΔDepositi time	$-\Delta M2_w$	$-\Delta M2_{cap}$								$+\Delta M2$			0
Δ Depositi check	$-\Delta M1_w$	$-\Delta M1_w$	$-\Delta M1_E$	$-\Delta M1_R$	$-\Delta M1_{R^S}$		$-\Delta M1_c$			$+\Delta M1$			0
Δ Loans			$+\Delta L_E$	$+\Delta L_R$	$+\Delta L_{R^s}$		$+\Delta L_c$			$-\Delta L$			0
Δ Bond		$-\Delta B_{\mathrm{h}}$						$+\Delta B$				$-\Delta B_{bc}$	0
Δ Non-performing L.	$-\Delta NL_c$									$+\Delta NL_c$			0
Δ Reserves										$-\Delta H$		$+\Delta H$	0
Δ Advances										$+\Delta A$		$-\Delta A$	0
Σ	0	0	0	0	0	0	0	0	0	0	0	0	0

A2. Sequence of events

1. Updating of the stock of capital goods
2. Computation of unit costs and setting of markups in each sectors;
3. C-Firms determine the quantity to produce and the demand of raw materials, energy and capital goods;
4. Matching in raw material market;
5. Firms in the recycling and mining sectors determine the desired production, and capital and energy demand;
6. Capital good firms determine the desired production and energy demand;
7. Energy sector determines the capital goods demand;
8. K_1-firms fix desired production and energy demand;

8.1 K-firms fix R&D expenditure, and the output of the innovation process is generated;

9. Sector E fixes the desired production and labor demand;
10. Labor market matching: E-Sector;
11. Sector $K_{1,2,3}$ determine the labor demand;
12. Labor market matching: K-Sectors;
13. Raw material producers fix labor demand;
14. Labor market matching: mining and recycling sector;
15. C-firms determine labor demand;
16. Labor market matching: C-Sector;
17. Firms start the production phase:

    K-sectors:

$$\begin{cases} y_{t,i} = y_{t,i}^{d}\,;\;\; h_{t,i}^{work} = \dfrac{L_{t,i}^{d}}{h^{m}} \; if \; L_{t,i}^{d} = employees_{t,i} \\ y_{t,i} = \dfrac{employees_{t,i}\; h^{m}}{l_r}\;;\;\; h_{t,i}^{work} = h^{m} \; otherwise \end{cases}$$

    If firms have satisfied their labor demand, working hours are distributed among the respective employees in such a way as to produce exactly the desired quantity. In the case that labor demand has remained unsatisfied, workers will work full time (h^m).

    C, E, R_v and R^S Sectors:

$$\begin{cases} y_{t,i} = \min\left(y_{t,i}^{d}; \dfrac{k_{t,i}}{v_{t,i}}\right);\;\; h_{t,i}^{work} = \dfrac{Ld_{t,i}}{h^{m}} \; if \; Ld_{t,i} = employees_{t,i} \\ u_{t,i}^{l} = \dfrac{employees_{t,i}\; h^{m}\; \alpha_{t,i}}{k_{t,i}};\; y_{t,i} = \min\left(u_{t,i}^{l}\dfrac{k_{t,i}}{v_{t,i}}; \dfrac{k_{t,i}}{v_{t,i}}\right) h_{t,i}^{work} = h^{m} otherwise \end{cases}$$

18. Firms define credit demand, employed workers receive wages, unemployed receive unemployment benefits;
19. Matching in the consumption market:

In case the supplier cannot satisfy its demand, the consumer turns to another firm until he exhausts his demand or all firms have run out of inventories. The public sector distributes its demand among firms according to their productive capacity;

20. Computing firms cash inflows and outflows. Some firms, if necessary, can apply for additional financing, those that do not meet the requirements go bankrupt;
21. Computing firms and bank profits, capitalists receive dividends;
22. Computing CB profits, public deficit and the supply of public bonds supply. Bonds are firstly bought by households, the remaining part by BC.

Inverse Leontief Matrix for circular and non-circular economy:

$$L_{ce} = (I-A)^{-1} =$$

$$\begin{bmatrix} \frac{1-r_c}{\sigma} & \frac{e_k(1-r_c)}{\sigma} & \frac{(1-r_c)(\beta e_k + e_r)}{\sigma} & \frac{e_c + e_{r^s} + e_k(\omega+\gamma) + r_{r^s}(\beta e_k + e_r)}{\sigma} & \frac{e_c + e_{r^s} r_c + e_k(\omega + \gamma r_c) + r_c r_{r^s}(\beta e_k + e_r)}{\sigma} \\ \frac{\vartheta(1-r_c)}{\sigma} & \frac{1-r_c}{\sigma} & \frac{(1-r_c)(\beta e_k + \vartheta e_r)}{\sigma} & \frac{\vartheta(e_c + e_{r^s}) + \omega(1+\vartheta) + r_{r^s}(\beta + \vartheta e_r)}{\sigma} & \frac{\vartheta(e_c + r_c e_{r^s}) + \omega + \gamma r_c + r_c r_{r^s}(\beta + \varphi e_r)}{\sigma} \\ 0 & 0 & 1 & \frac{r_{r^s}(1-\vartheta e_k)}{\sigma} & \frac{r_c r_{r^s}(1-\vartheta e_k)}{\sigma} \\ 0 & 0 & 0 & \frac{1-\vartheta e_k}{\sigma} & \frac{r_c - \vartheta e_k}{\sigma} \\ 0 & 0 & 0 & \frac{1-\vartheta e_k}{\sigma} & \frac{1-\vartheta e_k}{\sigma} \end{bmatrix}$$

$$L_{n-ce} = (I-A)^{-1} == \begin{bmatrix} \frac{1}{1-\vartheta e_k} & \frac{e_k}{1-\vartheta e_k} & \frac{\beta e_k + e_r}{1-\vartheta e_k} & \frac{e_c + e_k\omega + r_c(\beta e_k + e_r)}{1-\vartheta e_k} \\ \frac{\vartheta}{1-\vartheta e_k} & \frac{1}{1-\vartheta e_k} & \frac{\beta + \vartheta e_r}{1-\vartheta e_k} & \frac{\vartheta e_c + \omega + r_c(\beta + \vartheta e_r)}{1-\vartheta e_k} \\ 0 & 0 & 1 & \frac{r_c(1-\vartheta e_k)}{1-\vartheta e_k} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Appendix B Measures of capital intensity

IO models are characterized by heterogenous capital, intermediate and consumer goods and capital intensity can be measured only in value terms by applying the system of relative prices. The system of value can change because of changes in technological coefficients, interest rate and profit rate. However, only changes in the capital intensity due to improvements in energy efficiency or sectoral capital-to-output ratios can affect GDP and energy intensity. Therefore, the relation between capital intensity and macro-environmental variables needs to be analyzed by considering the supply chain capital-to-output ratios of each specific capital good. We consider the consumer good as an output. Only in such a way, it is possible to measure specific capital intensity in real terms. Figure B1 shows the different supply chain capital-to-output ratios ($K_i^{s.c.}$) included in the model and their computation.

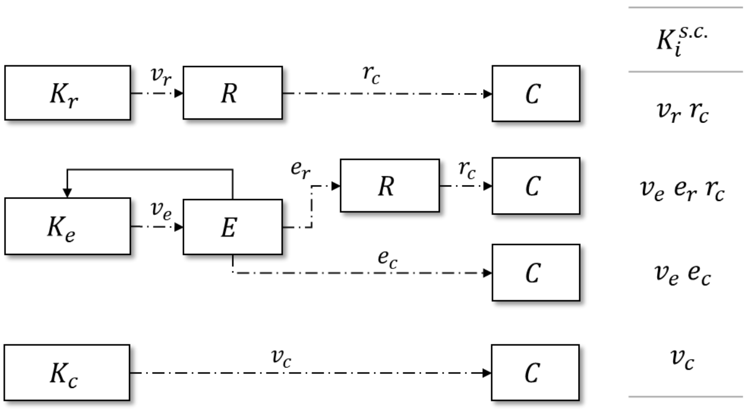

Figure B1 Supply chain capital-to-output ratios for each specific capital good.

Appendix C The impact of public spending on growth

In the baseline model simulations, the growth rate of public spending is positive, which drives the GDP growth. Below, we discuss the impact of innovations in the capital sector on GDP when real public spending is kept constant and unemployment benefits are zero. Figure C1 illustrates that, in this case , the GDP exhibits a declining trend, while the unemployment rate is increasing. The decline in the GDP is caused by improvements in factor productivities due to innovations in the K-sector. Such innovations reduce the capital intensity of the economy undermining aggregate demand, the GDP growth and technical change. Finally, the long-run trend of the employment rate is declining due to a decrease in the capital intensity and the capital-to-labor ratio over time. The former affects both GDP and employment, while the latter affects only employment.

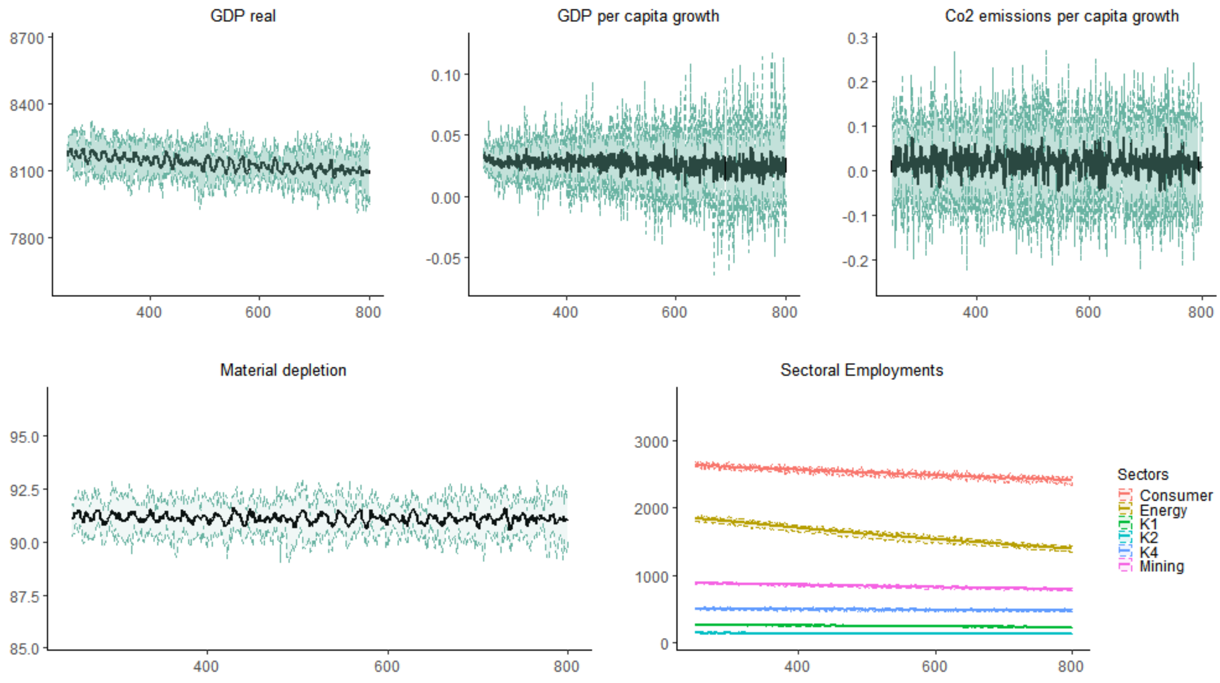

Figure C1 Main macroeconomic variables in the baseline scenario with constant public spending.
Note: Values correspond to the averages of 50 Monte Carlo runs.

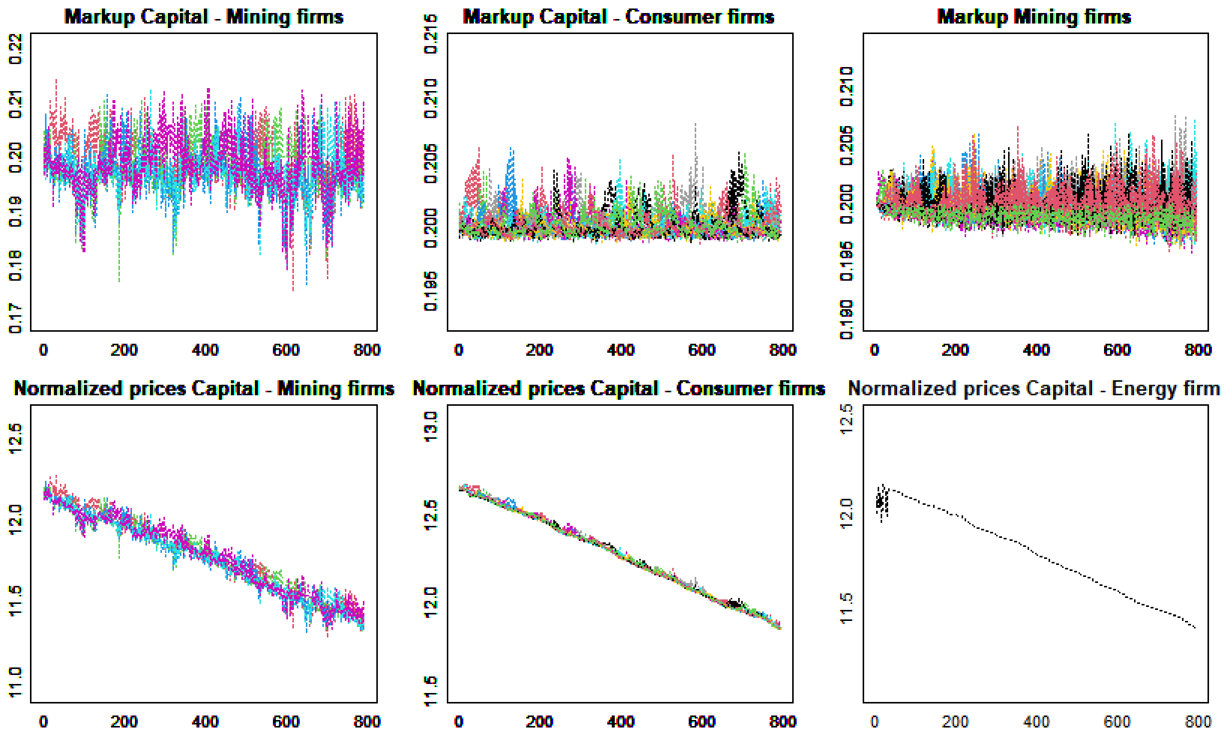

Figure C2. Markups and normalized price for inflation wage in Capital sectors.

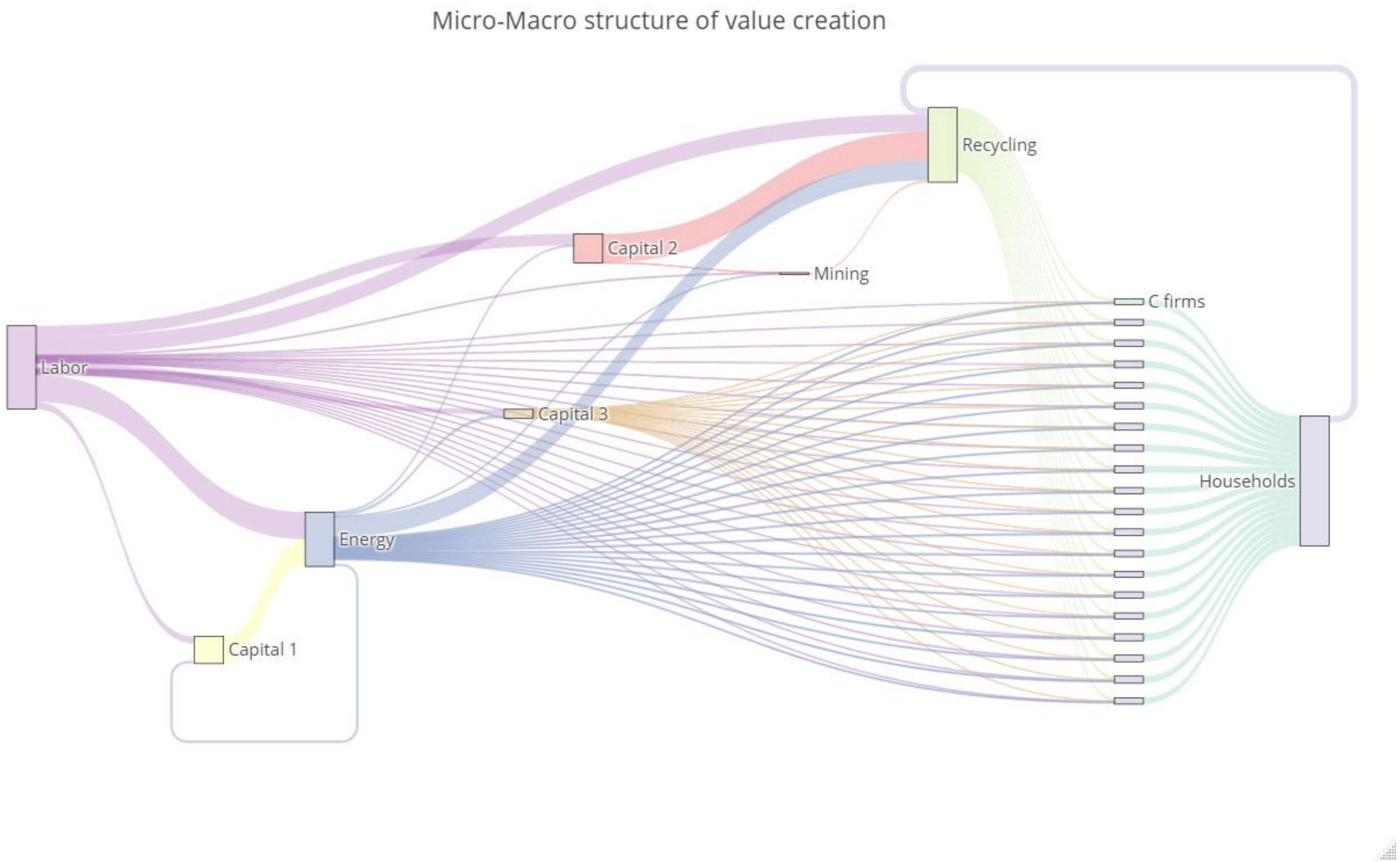
Micro-Macro structure of value creation
Recycling
Capital 2
Mining
C firms
Labor
Capital 3
Households
Energy
Capital 1

Table C1. Parameters in the baseline scenario:

Description	Symbol	Value
Montecarlo replications	MC	100
Time sample	T	800
Number of firms in the capital-good sector 1 (E)	F_{k_1}	1
Number of firms in the capital-good sector 2 (R)	F_{k_2}	8
Number of firms in the capital-good sector 3 (R^R)	F_{k_3}	8
Number of firms in the capital-good sector 4 (C)	F_{k_4}	20
Number of firms in the energy sector	F_e	1
Number of firms in the mining sector	F_r	30
Number of firms in the recycling sector	F_{r_s}	30
Number of firms in the consumption-good sector	F_c	200
Capital-good firms markup	φ_k	0.2
Energy firms markup	φ_e	0.2
Mining firms markup	φ_r	0.2
Recycling firms markup	φ_{r_s}	0.2
Consumption-good firms markup	φ_c	0.2
Normal (desired) degree of capacity utilization	u_n	0.8
Capital-to-output in the energy sector	v_e	0.3
Capital-to-labor in the energy sector	α_e	0.6
Capital-to-output in the mining sector	v_r	0.45
Capital-to-labor in the mining sector	α_r	0.7
Capital-to-output in the recycling sector	v_{r_s}	0.5
Capital-to-labor in the recycling sector	α_{r_s}	0.7
Capital-to-output in the consumption-good sector	v_c	0.4
Capital-to-labor in the consumption-good sector	α_c	0.8
Energy intensity in the capital-good sector 1 (E)	e_{k_1}	0.7
Energy intensity in the capital-good sector 2 (R)	e_{k_2}	0.7
Energy intensity in the capital-good sector 3 (R_s)	e_{k_3}	0.7
Energy intensity in the capital-good sector 4 (C)	e_{k_4}	0.7
Energy intensity in the mining sector	e_r	0.3
Energy intensity in the recycling	e_{r_s}	0.28
Energy intensity in the consumer-good sector	e_c	0.33
Material intensity in the consumption-good sector	r_c	0.25
Labor productivity in the capital-good sector 1 (E)	ϑ_{k_1}	0.2
Labor productivity in the capital-good sector 2 (R)	ϑ_{k_2}	0.2
Labor productivity in the capital-good sector 3 (R_s)	ϑ_{k_3}	0.2
Labor productivity in the capital-good sector 4 (C)	ϑ_{k_4}	0.2
Capital-good lifetime	z	30
Number of periods to produce the capital good	dk	3
Innovation likelihood parameter	ε	0.08
Share of profits financing R&D	β	0.1
Desired inventories-to-sales ratio	σ^T	0.02
Threshold for the periods in which σ has been below than σ^T	$\rho^{lim,dec}$	3
Threshold for the periods in which σ has been above than σ^T	$\rho^{lim,inc}$	3
Expectation parameter	γ	0.6
Tax rate	θ	0.2
Unemployment subsidy rate	ρ	0.3
Interest rate on loans	r_l	0 (0.02)
Interest rate on public bonds	r_b	0 (0.03)
Interest rate on deposit	r_d	0 (0.01)
Interest rate on reserves	r_r	0 (0.01)
Interest rate on advances	r_a	0 (0.01)
Payback time of long term loans	z_z	50
Payback time of short term loans	z_s	10
Ponzi limit	l^{ponzi}	5
Dividends distribution rate	ω	1
Desired leverage	l^T	1
Initial public expenditure rate	$\bar{\tau}$	0.1
Public expenditure growth rate	g_G	0.001
Propensity to consume out-of-income of workers	c_w^y	0.8
Propensity to consume out-of-wealth of workers	c_w^V	0.03
Propensity to consume out-of-income of capitalists	c_π^y	0.6
Propensity to consume out-of-wealth of capitalists	c_π^V	0.02