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The Roads Towards Raw Materials Sustainability: a French Case Study

by

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Abstract

Circular Economy (CE) has become increasingly influential in policy-making for the past fifteen years. Governments and institutions have seen CE as a way to achieve high levels of sustainability while maintaining GDP growth. This paper describes how waste generation and Raw materials use were modeled in the Environmentally-Extended Input-Output tables of the Eurogreen model. It also explains how Material Flow Analysis (MFA) was used to model Residual Waste Management, Closing Supply-Chains, Waste Efficiency and Material Efficiency. Through the design of several policy scenarios (Business-As-Usual, Techno-Efficiency, Cradle-to-Cradle, Circular Growth, Optimistic Circular Growth and Circular Degrowth), this paper also assesses the efficacy of different Circular Economy policies in delivering a decrease in Raw Materials Extraction and in CO2 emissions in France from 2014 to 2050.

Keywords: Circular Economy, Raw Materials, Input-Output Analysis, Waste Treatment, Recycling, Ecological Economics

1 Introduction :

The Circular Economy (CE) narrative has become increasingly trendy in France since the 2010s. From late heatwaves to severe droughts in large parts of the country, the effects of climate change have put populations and institutions under strain. As the

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climate emergency is becoming every day more visible , the Circular Economy (CE) framework is increasingly seen by key actors of the public space as a possible way out of the deadlock. For instance, conservative columnist and former Minister of Education Luc Ferry has publicly advocated for Circular Economy in the media [1]. He sees it as a "positive" environmentalism, which could conciliate economic growth and climate action. In his opinion, a Circular Economy is one in which "everything can be recycled indefinitely, so if we take it as a model, we can not only reduce costs and make profits by not wasting useful materials, but also build an ecological future that, by integrating itself into the economy, will promote growth and consumption instead of reducing them to a trickle". Circular Economy is gaining momentum among actors of the private sector [2].

This vision of the Circular Economy as a possible driver of "green growth" has also gained momentum in French [3] and European [4] policy-making. In 2015, the "law on the energy transition for green growth" [5] first introduced the concept of circular economy in French legislation. This statute set important Circular Economy targets, namely "achieving a 65% recycling rate for non-hazardous non-inert waste by 2025" and "a 30% increase by 2030 in the ratio between GDP and domestic consumption of materials". As part of Emmanuel Macron's *#MakeOurPlanetGreatAgain* initiative - by which he intended to put France at the forefront of the fight against climate change – two French ministries released a Roadmap for the circular economy [6] which listed "50 measures for a 100% circular economy". Key members of the Ellen McArthur Foundation, a major think tank advocating for the implementation of Circular Economy in public spheres, actively contributed to this initiative. This roadmap became the groundwork of the 2020 Anti-waste law for a circular economy [7]. The main aim of these policies is clearly stated: "to decouple growth from material consumption" [8] as part of an effort to achieve a green economy, in a sustainability thinking framework that deems green growth as being both an attainable and positive policy goal for society. The European Union has also drafted

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[1] https://www.lefigaro.fr/vox/economie/luc-ferry-contre-l-ecoterrorisme-l-economie-circulaire-20230628

[2] https://www.worldcement.com/africa-middle-east/10032023/mckinsey-co-circular-economy-of-cement-could-be

[3] https://www.ecologie.gouv.fr/loi-anti-gaspillage-economie-circulaire

[4] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

[5] https://www.ecologie.gouv.fr/loi-transition-energetique-croissance-verte

[6] https://www.ecologie.gouv.fr/feuille-route-economie-circulaire-frec

[7] https://www.ecologie.gouv.fr/loi-anti-gaspillage-economie-circulaire

[8] https://www.ecologie.gouv.fr/leconomie-circulaire

a “Circular economy action plan” as part of the European Green New Deal. It describes “the transition to a Circular Economy as a way will reduce pressure on natural resources and will create sustainable growth and jobs”. [9]

As policy expectations are high regarding the Circular Economy policy framework, it seems interesting to investigate whether Circular Economy policy interventions can practically deliver what they are expected to achieve. Can Circular Economy policies enable us to reach important sustainability thresholds i.e., a constant and absolute decrease in environmental pressures caused by the French economy? Moreover, is it possible to achieve a “100% circular economy”, in which all waste would indefinitely replace Primary Raw Materials from “cradle to cradle” (Braungart and McDonough, 2009)? Is it thus possible to “eliminate the concept of waste” [10]? In a broader perspective, what are the potential effects of CE interventions on a macroeconomic and macroecological scale?

2 Literature Review :

The concept of Circular Economy has been increasingly cited as a reference for policy-making since the 2010’s [11] [12]. According to the Ellen McArthur Foundation, Circular Economy is “a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution”. It “is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature. It is underpinned by a transition to renewable energy and materials. Transitioning to a circular economy entails decoupling economic activity from the consumption of finite resources.” [13]. Research has therefore focused on trying to fathom the efficacy and impacts of CE policy interventions (Kagawa, Tasaki, and Moriguchi, Kagawa et al.; Geng, Sarkis, and Ulgiati, Geng et al.; Geng, Fu, Sarkis, and Xue, Geng et al.; Luzzati, Distefano, Ialenti, and Andreoni, Luzzati et al.).

Leontief’s Input-Ouput analysis has been frequently used in this endeavor (Kon-

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[9] `https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en`

[10] `https://mcdonough.com/cradle-to-cradle/`

[11] `https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en`

[12] `https://www.ecologie.gouv.fr/loi-anti-gaspillage-economie-circulaire`

[13] `https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview`

ing, Koning). Input-Output tables enable us to know the volume of inputs provided by each sector for a certain final demand (Leontief, Leontief). Leontief's approach has been extended to represent physical entities embedded in each sector's chain of value. Environmentally Extended Input Output (EEIO) tables (Duchin, Duchin) have been particularly used to model the waste (Nakamura and Kondo, Nakamura and Kondo; Towa, Zeller, and Achten, Towa et al.) and carbon footprint of the different sectors of the economy. EEIO analysis has been frequently used to model the effects of Circular Economy policy interventions on a macroeconomic scale (McCarthy, Dellink, and Bibas, McCarthy et al.; Aguilar-Hernandez, Sigüenza-Sanchez, Donati, Rodrigues, and Tukker, Aguilar-Hernandez et al.).

Closing Supply Chains (CSC) is one of the main mechanisms of the Circular Economy. CSC policies (Donati, Aguilar-Hernandez, Sigüenza-Sánchez, de Koning, Rodrigues, and Tukker, Donati et al.) aim to create a waste treatment system enabling waste created during the production process to be reused as new inputs in a circular pattern (Nakamura, Nakamura; Chen and Ma, Chen and Ma). Closing Supply Chains and Residual Waste Management (RWM), (e.g., waste treatment mechanisms) are therefore closely intertwined. Waste, here considered as a secondary product (Merciai and Schmidt, Merciai and Schmidt) is meant to come as an input in substitution of Primary Raw Materials (Beylot, Vaxelaire, and Villeneuve, Beylot et al.). This substitution enables to limit the extraction of raw materials, as well as the emission of GHG into the atmosphere. Instead of creating a new sector related to waste treatment in I-O tables, some researchers managed to integrate Secondary Raw Materials (SRM) into EEIO in Closing Supply Chain scenarios. Towa et. alii, in line with other researchers (Beylot, Vaxelaire, and Villeneuve, Beylot et al.; Lenzen and Reynolds, Lenzen and Reynolds; Zeller, Towa, Degrez, and Achten, Zeller et al.; Towa, Zeller, and Achten, Towa et al.) has stressed that it is possible to model a substitution of Primary Raw Materials by Secondary Raw Materials (or "PRM/SRM substitution") as new inputs. The only condition is to be able to estimate the recycling and backfilling rate of waste in the economy.

Another main mechanism of the Circular Economy framework is Material and Waste Efficiency (Aguilar-Hernandez, Sigüenza-Sanchez, Donati, Rodrigues, and Tukker, Aguilar-Hernandez et al.). Material Efficiency is usually linked to the role of technology and technological innovation in the production process. It has been modeled through a technology-driven reduction in waste generation (Donati, Aguilar-Hernandez, Sigüenza-Sánchez, de Koning, Rodrigues, and Tukker, Donati et al.) as well as a decrease in material use under the assumption of a lack of rebound effect (Donati, Aguilar-Hernandez, Sigüenza-Sánchez, de Koning, Rodrigues, and Tukker, Donati et al.). Design improvements [14] is also considered to be a main driver of efficiency (Donati, Aguilar-Hernandez, Sigüenza-Sánchez, de Koning, Rodrigues, and Tukker, Donati et al.).

3 The Model :

3.1 Scenarios :

This extension of the Eurogreen model enables the visualization of four additional policy scenarios applied to the French economy from 2014 to 2050. The "Business as usual" (BAU) scenario describes the continuation of already observable trends in the French economy. The Techno-Efficiency (TE) scenario represents a situation in which innovation drives a sharp increase in material/waste efficiency in all sectors of the economy. The "Cradle-to-Cradle" (C2C) scenario describes a fictional situation in which the recycling and backfilling rate of treated waste gradually increases to 100% in 2050. In this scenario, the eco-design policy, and the full substitution of primary materials for Secondary materials leads to changes in the volume and structure of the output. The Circular Growth (CG) scenario combines the effects of increased recycling and material efficiency with a baseline PRM/SRM substitution rate, as the maximization of the output is prioritized over sobriety and environmental concerns. As the baseline PRM/SRM substitution coefficient lacks accuracy because of a lack of data, we modeled an alternative, more Optimistic Circular Growth scenario (OCG) which is identic to the original one, except for the fact that we added full PRM/SRM substitution. The Circular Degrowth (CD) scenario measures the effects of combined degrowth and cradle-to-cradle policy interventions.

3.2 Calibration :

When activated, the substitution of Primary Raw Materials by Secondary Raw Materials is set to begin in 2024. The increased recycling rate scenario also bears its first effects in

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[14] https://www.ellenmacarthurfoundation.org/topics/circular-design/overview

2024. The techno-efficiency scenario also exogenously comes into effect in 2024, onwards. The consequences of PRM/SRM substitution on treated waste and on the output are designed to begin in 2024. It is also in 2024 that the "Eco-design" policy is activated in relevant scenarios.

4 Results :

4.1 GDP growth :

Figure 1: GDP growth real

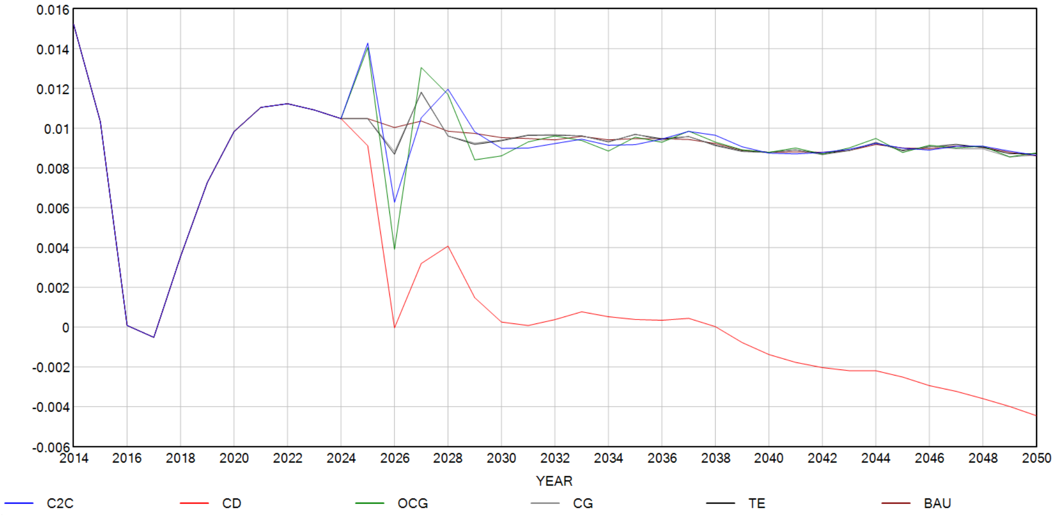
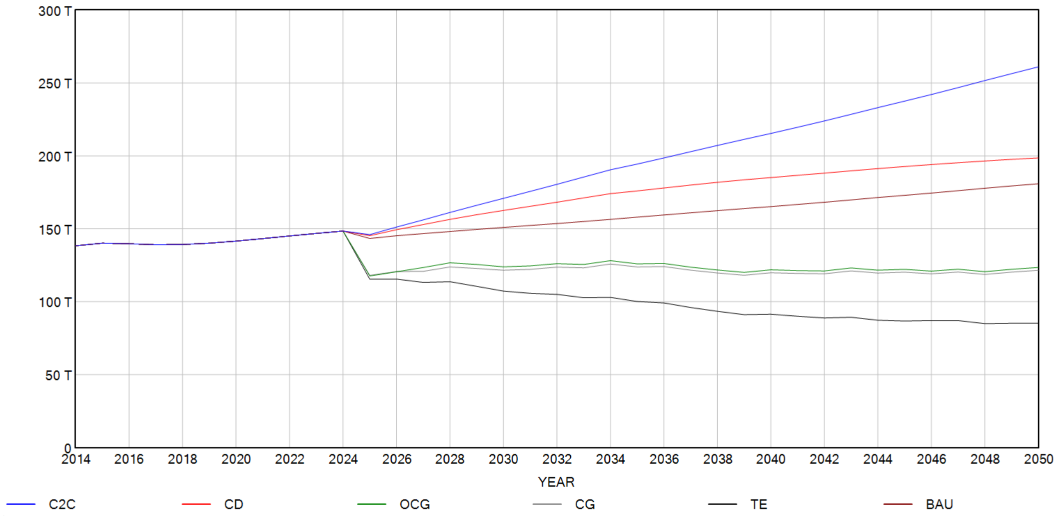


Figure 1 displays the real GDP growth coefficient (0.01 = 1% GDP growth) for France from 2014 to 2050. In the BAU scenario, the French economy sustains a real GDP growth rate of nearly 1% per year. If the real GDP rate follows an oscillatory behavior in all of the curves, the spread is higher for the OCG scenario compared to the other ones. Apart from the CD scenario, all the curves follow the same approximate path. They all reach a similar real GDP growth rate in 2050, at around 0.8% per year. The Circular Degrowth curve differs from the others. Indeed, negative real GDP rates are achieved from 2038 in our simulations. The real degrowth rate is even increasing over time, to reach approximately 0.4% per year in 2050.

Figure 2: Production of Secondary Raw Materials



4.2 Secondary Raw Materials :

Figure 2 shows the total amount of Secondary Raw Materials produced by the French economy per year (expressed in 10,000 tons of Raw material equivalents). The total quantity of Secondary Raw Materials produced changes a lot depending on the policy scenario. First of all, we can observe an oscillation of certain curves in this graph. This is due to the oscillation of the raw materials demand. This oscillatory behavior can be seen in an exacerbated way in the three bottom curves (CG, OCG, and TE scenarios). Indeed, each of these scenarios contains an increase in technology-driven material and waste efficiency. As material efficiency makes waste generation dwindle, this oscillation become more apparent compared to the other curves. Still, for all scenarios, the orientation of the curve changes. As the quantity of SRM increases, the following year, the quantity of waste decreases. This phenomenon is created by the “Primary waste equivalent ratio” which accounts for the role of entropy in the decrease in the recycling and backfilling rate of already recycled waste along time. Due to the substitution of Extracted Primary Raw Materials by Secondary Raw Materials (or ”PRM/SRM substitution”), the waste which has already been recycled once or more can be less recycled, as this waste’s quantity and quality have decreased because of entropy. The subsequent change in total treated waste on a year-to-year basis thus impacts every year, in different proportions, the amount of Secondary Raw Materials produced within the French economy.

The scenario with the highest production of Secondary Raw Materials is the Cradle-to-Cradle scenario, which makes the amount of produced Secondary Materials increase by a third compared to the BAU scenario. The Circular Degrowth scenario is the second ranked in terms of Secondary Materials' generation. The latter is approximately 10% higher than the SRM generation in the BAU scenario. The CD scenario achieves this performance despite the reduced waste induced by degrowth. In the Circular Growth scenario, the amount of SRM created is substantially reduced because of an innovation-driven reduction in waste production. The amount of SRM generated in the CG and OCG scenarios are almost the same. With a yearly generation of SRM almost halved in 2050 compared to the baseline scenario, the Techno-Efficiency scenario economy creates a mere third of the total amount of secondary materials generated in the C2C scenario.

4.3 Extraction Demand :

Figure 3: Raw Materials Extraction Demand

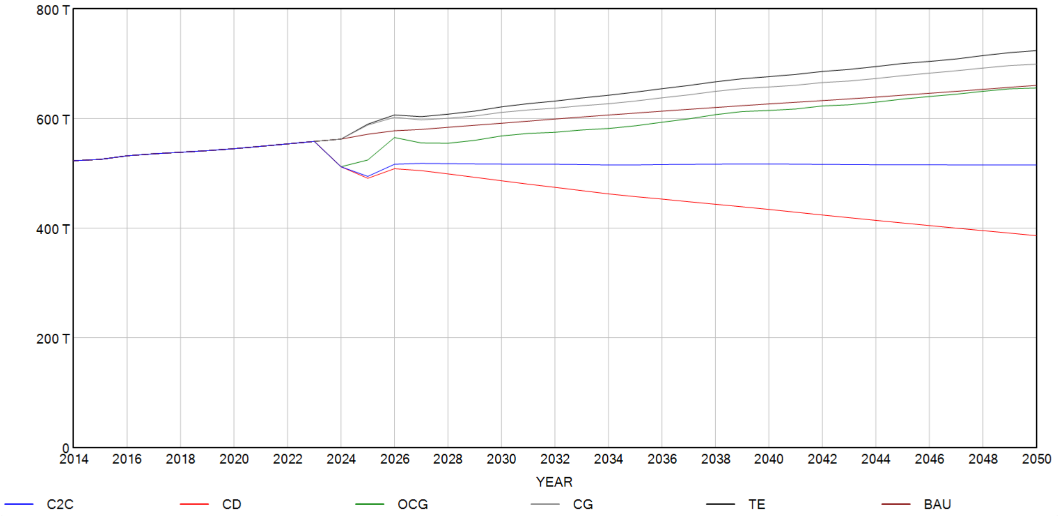


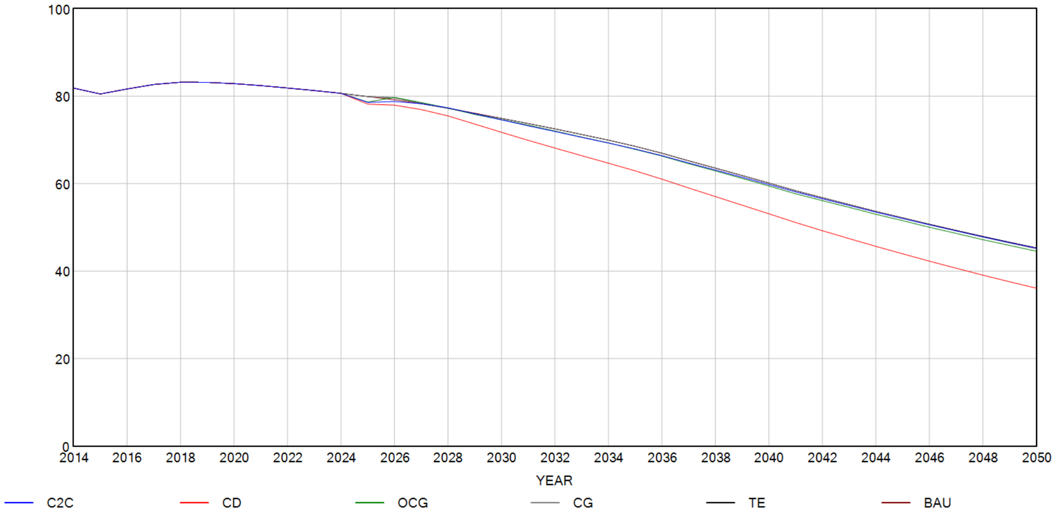
Figure 3 compares the dynamics of the Primary Raw Materials Demand, expressed in thousands of tons of RME per year. This variable represents the amount of Primary Raw Materials which needs to be extracted to respond to the French economy's demand for new inputs.

First of all, we can notice that the same oscillatory phenomenon can be witnessed for some of these curves. As expected, it can especially be observed for the Circular Growth, Optimistic Circular Growth, and Techno-efficiency curves. The TE scenario stands out as being the one that requires the highest demand in Raw Materials Extraction. It is closely followed by the CG scenario, which has a slightly reduced material footprint. Then, the BAU scenario and the OCG scenarios carry almost the same implications in terms of Raw Materials Extraction Demand. These four scenarios create a yearly extraction demand in 2050 which is much higher than the material footprint of the French economy in 2014. The C2C scenario and the CD scenario see a decrease, in 2050, in the Extraction Demand compared to 2014 levels. Their impacts are still very different from one another. Indeed, due to its high level of recycled inputs, the Cradle-to-Cradle scenario demand in materials extraction is reduced compared to the baseline. In a stocks and flows analysis, this does not mean that the stocks of "natural resources" and ecosystems regenerate. The pressure still exists, but it is less strong than before. Additionally, we can see that the diminution in yearly extraction demand in the C2C scenario is very small over time. We can almost talk of a stagnation of yearly Raw Materials Extraction at the 2014 levels. The Circular Degrowth scenario is the one which reaches the highest decrease in Raw Materials Extraction among all tested policy scenarios. It namely achieves a reduction in yearly materials extraction of more than 20% in 2050 compared to 2014.

4.4 Reduction in CO2 emissions :

Figure 4 plots the reduction in CO2 emissions created by each scenario compared to 1990 levels (index 1990 = 100). In this graph, we see that two kinds of dynamics can be clearly distinguished. Firstly, 5 curves closely follow the almost exact same path (BAU, OCG, CG, C2C, TE). These scenarios would enable our societies to achieve a decrease in CO2 emissions of approximately 55% in 2050 compared to 1990 levels. Once again, the Circular Degrowth scenario stands out by enabling the highest reduction in CO2 emissions compared to 1990, with a combined decrease in emissions of 64%.

Figure 4: Reduction in CO2 emissions compared to 1990 levels



5 Discussion

5.1 Future applications and limitations :

The analysis of feedback loops, stocks, and flows in a system dynamics modeling framework can help to better understand the complexity of the relations between our economies and the biosphere. Ecological macroeconomics, through the use of various metrics (tons of RME, tons of RMWeq, euros, tons of CO2 emissions) in an Environmentally Extended Input/Output analysis, is all the more useful as it enables to take into account the multidimensional features of our economy's throughput. By taking some elements from ecological economics and complexity theory, this model also enables the comprehension of the various stresses our economic systems induce on the different planetary boundaries. It also paves the way for a comprehensive representation of the potential dynamics, trade-offs, and synergies between social and ecological targets in a Doughnut Economics framework. This model is especially useful in its ability to compare the impacts of varying sets of policy interventions on a range of ecological, social, and economic indicators.The simulation's results here suggest that Circular Economy policy tools cannot always deliver a reduction in the environmental pressure the French economy causes on planetary limits.

First of all, this simulation confirms the potential benefits of an increased waste recycling and backfilling ratio. Indeed, the Cradle-to-cradle enables a diminution in Extracted Primary Raw Materials Demand in 2050 compared to the baseline, but this diminution is small compared to the one offered by other scenarios. This model also demonstrates the impossibility to achieve a perfectly Circular Economy "from cradle to cradle". As Giampietro had already concluded, waste cannot disappear from an economic organism as this would contradict the laws of thermodynamics. Additionally, C2C scenario's failure in attaining high levels of raw materials sustainability is mainly due to the oscillation of the Secondary Raw Materials production, which is itself due to the introduction of the entropy coefficient which represents the losses in waste quality and quantity due to industrial processes. This oscillation creates a yearly fluctuation (or change in slope angle) of the Raw Materials demand curve, which cannot thus persistently drop if the output stays unchanged.

This simulation also represents the possibly counter-effective consequences of technology-induced material efficiency. Indeed, the Techno-Efficiency scenario creates a slump in waste generation, which itself provokes a decrease in the production of Secondary Raw Materials. This drives an increase in demand for raw materials, creating further pressure on planetary boundaries. We can here also watch the potential trade-offs between different sustainability goals and indicators. The reduction in waste production (novel entities) created by the Techno-Efficiency scenario indeed comes at the price of an increased raw materials demand. We can here observe the potential dangers of close-sightedness in the vision of "sustainability", which can generate trade-offs between the attainment of different sustainability goals. One of the overarching results of this study is that Circular Economy policy interventions do not prove to be a means towards the achievement of "green growth". Indeed, the Circular Growth and Techno-Efficiency scenarios, which both combine Circularity interventions and the prioritization of GDP growth maximization over sobriety, are lowly efficient in reaching sustainability thresholds.

A combination of Circular Economy policy interventions with Degrowth (Circular Degrowth) is in this model the most expedient way to achieve raw materials sustainability as well as the reduction of the overshoot of all the measured planetary boundaries (CO2 emissions and raw materials demand). We should here take note that these encouraging results might also prove helpful in reducing pressure on other environmental aggregates.

For instance, it has been underlined that both climate change and materials extraction (through changes in land use) are main drivers of biodiversity loss (IPBES, 2019). If further research needs to be done to confirm these findings, we can cautiously state that Circular Economy mechanisms should not be implemented without questioning the current growth-centered paradigm, as it may prove either counter-effective or inefficient in achieving sustainability goals in the context of the ecological emergency. However, the implementation of a 'Circular Growth'-inspired policy scheme might prove to be highly rewarding to the private sector, which could make substantial economies and increase economic performance through gains in material and waste efficiency [15]. Instead, the combination of Circular and Degrowth policies is, in our simulations, the most effective way for the French economy to reduce both its intake of raw materials and its CO2 emissions. The implementation of such a policy would, according to our simulation, bring France one step closer to achieving its target to reduce emissions by 75% compared to 1990 levels, as it is described in its National Low-Carbon Strategy [16].

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[15] https://www.worldcement.com/africa-middle-east/10032023/mckinsey-co-circular-economy-of-cement-could-be

[16] See: https://www.ecologie.gouv.fr/strategie-nationale-bas-carbone-snbc

Appendix :

A Data and definitions :

In our efforts to model flows of Secondary Raw Materials and waste treatment in an Environmentally Extended Input Output (EEIO) framework, we extracted, analyzed, and uniformized data from an extensive number of databases. We will here provide a comprehensive list of the sources we mobilized for this work :

- Eurostat provides data on waste generation per sector [17] and waste treatment [18] for France in 2014. We also used the newly created "Eurostat Country RME tool" database[19] [20], in which key figures about the material footprint of the French economy are detailed.

- The NIOT database [21] also provided us with the input-output tables for France.

- The data and methodology of the Eurogreen model (D'Alessandro et al., 2020) serve as a groundwork from which this paper tries to offer an extension. All the data that are not listed higher in this section were extracted from the Eurogreen database.

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[17] https://ec.europa.eu/eurostat/databrowser/view/TEN00106/default/table?lang=en&category=env.env_was.env_wasgt7

[18] https://ec.europa.eu/eurostat/databrowser/view/ENV_WASTRT__custom_7223128/settings_1/table?lang=en

[19] https://ec.europa.eu/eurostat/databrowser/view/env_ac_rme/default/table?lang=en

[20] https://ec.europa.eu/eurostat/web/environment/information-data/material-flows-resource-productivity

[21] https://www.rug.nl/ggdc/valuechain/wiod/wiod-2016-release

B Methodology :

We will here describe the methodology used to model waste treatment and Secondary Raw Materials flows into the Eurogreen model.

Harmonization of data :

First of all, we reorganized the data provided by the “Eurostat RME Country tool - March 2023”, to fit the taxonomy of sectors used in the Eurogreen model. For clarity purposes, the sectors as classified in the “Eurostat Country RME tool - March 2023” (NACE rev.2) will be put in quotes (“Manufacturing” sector). The sectors as described in the Eurogreen model will always begin with a capital letter (Manufacturing sector).

We had to reorganize the Eurostat database to create Eurogreen’s Fossil Fuels sector, which does not exist independently in Eurostat’s NACE V2 classification of economic activities. Indeed, in the Eurostat database, the economic activities we attributed to the Fossil Fuels sector are embedded in the NACE ”Manufacturing sector”. The details of these operations can be found in the “Supplementary information” of previous Eurogreen papers [22].

Firstly, we tried to estimate the amount of waste generated by the Fossil Fuels sector. For that purpose, we calculated ratios of raw materials (expressed in tons of Raw Materials Equivalents, or RME) footprint per output for both the Fossil Fuels and the Mining and Quarrying sectors. By dividing these two ratios, we found that in 2014, the Mining and Quarrying sector was using 39% less raw materials per unit of output than the Fossil Fuels sector. This latter percentage was then multiplied by the amount of waste generated by the Mining and Quarrying sector to find the approximate waste generated by the Fossil Fuels sector. The underlying assumption is that a difference in RME per output between two sectors would imply a proportional difference in the waste they generate.

$$WasteFF = WasteMQ * \frac{RMEperoutputFF}{RMEperoutputMQ} \tag{1}$$

In Eurostat’s NACE Rev.2 classification, the economic activities of the Fossil Fuels sector are attributed to the “Manufacturing” sector. We thus subtracted the waste

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[22] See: https://zenodo.org/records/3549756

generated by the Fossil Fuels sector from the waste produced by the "Manufacturing" sector to get an accurate assessment of waste generation by these two sectors.

$$WasteMcorr = WasteM – WasteFF \tag{2}$$

Similarly, as described in the Eurogreen sector taxonomy, we reaggregated Eurostat data on waste generation to find the waste generated by the Non-financial and social economy sector as well as the Public sector. For instance, the "Services (except wholesale of waste and scrap)" sector and "Wholesale of waste and scrap" were aggregated to form a Non-financial and social economy sector. The waste produced by the "Water collection, treatment, and supply; sewerage; remediation activities and other waste management services" and "Waste collection, treatment and disposal activities; materials recovery" sectors were added to a newly created Public sector.

Due to gaps in data, the Financial and Other sectors were given the value of 0.

With this reassembled set of data, we created a vector of waste generation per sector. We used these figures to create a vector of ratios, which represent the material waste generated per million of euros of output per sector.

This ratio was calculated in the following way :

$$InitialWastecoeffperOutputi = \frac{materialwastepersectori}{realoutputpersector} \tag{3}$$

Extracted Raw Materials Consumption :

We use the methods of Material Flows Analysis (MFA) to model waste treatment in a systems dynamic I/O framework. We chose here to differentiate Primary Raw Materials from Extracted Primary Raw Materials to represent the activities of waste treatment carried out in the 'technosphere'. According to (Giampietro, Giampietro), waste is treated in different ways in the biosphere and in the technosphere sub-system. In the biosphere, ecosystems process degradable matters. Waste therefore stays organic, and can be used by living ecosystems. Within the technosphere, waste is processed through industrial operations in order to be used as new inputs in the economy.

Therefore, we will here distinguish two sorts of Primary Raw Materials. The first kind of Primary Raw Materials is biomass. Biomass is produced by the Agricultural sector. The Primary Raw Materials embedded in the Agricultural sector are assumed to be renewable as the sun provides natural systems with energy through photosynthesis. We are however conscious that a nutrient balance is necessary for biomass production not to increase the degradation of the quality of the soils (Bouwman, Beusen, Lassaletta, van Apeldoorn, van Grinsven, Zhang, and Ittersum van, Bouwman et al.). Waste generated by the Agricultural sector is assumed to be mainly composed of biomass, which can be processed by ecosystems without human action. On the other hand, we describe "Extracted Primary Raw Materials" as all the inputs which originally were extracted from deep inside the soils. These raw materials are assumed to be nonrenewable in a human time scale. The Extracted Primary Raw Materials therefore contribute to the depletion of a stock of "resources". When these inputs become waste, they are processed through industrial opearations within the technosphere, as it would take too long for them to be biodegraded.

Three sectors and one sub-sector can be counted as sectors providing raw materials according to Eurostat : the Agricultural sector, the Mining sector, the Fossil Fuels sector, and the plastics production sub-sector (which is part of the Manufacturing sector). We will here concentrate our analysis on the "Extractive" industries producing Extracted Primary Raw Materials: the Mining and Quarrying industry, the Fossil Fuels industry, and the Plastics production industry. To differentiate the Primary Raw Materials use from the Extractive Materials use, we create an "Extraction share" of total Raw material used in the economy.

$$Extractionshare = \frac{FFwaste + MQwaste + Plasticswaste}{Agriculturewaste + FFwaste + MQwaste + Plasticswaste} \tag{4}$$

The average waste generation between 2014 and 2020 is here used as a proxy for the Raw Materials Footprint used by each of these sectors of the economy. To estimate the waste produced by the production of plastics (embedded in the manufacturing sector), we used data from the NIOT tables, for France, in 2014. We converted the value of the output of the “Manufacturing of Plastics and Rubber” economic activities, from dollars into euros. We then calculated the percentage this sub-sector represents in the whole Manufacturing sector. For simplification purposes, we here assume that the output of this sub-sector represents the plastics output of the French economy in 2014. We then assumed that, as the “Plastics manufacturing” activities represent 3.54% of the output of the Manufacturing sector, the Plastics production would also account for 3.54% of its waste. We eventually found that the Extraction share was 0.6924 in 2014. This ratio will be assumed to stay constant over time.

Waste efficiency :

Waste and material efficiency are one of the main elements of the Circular Economy narrative. We thus decided to represent the impact of technological change on waste generation. To account for technology-induced efficiency gains, we assumed that the “Energy conversion efficiency” (eta) of a sector would be an accurate proxy for waste efficiency. We assumed that a sector equipped with energy-saving hardware would also be more efficient with the materials it uses. An increased “Energy conversion efficiency” for a sector would therefore induce a reduced waste generation per unit of output.

We multiplied the initial waste per output coefficient vector by this proxy for resource efficiency to model the impact of technological change on waste generation.

$$Wastecoeffi = etacoeffperindustry * InitialWastecoeffperOutputi \tag{5}$$

Resource efficiency is one of the pillars of the Circular Economy framework. To assess the potential impacts of technological change and increased resource efficiency on waste production, we created an increased resource efficiency scenario. We calibrated this resource efficiency scenario to be implemented in 2024 to represent the potential effects of Circular Economy efficiency policies in the coming years. We defined the waste generation by sector as the product between the waste coefficient vector and the output (in monetary terms) per industry.

$$Wastepersectori = WastecoeffI * realoutputpersectori \tag{6}$$

As mentioned earlier, we here model waste management inside the technosphere of nonbiomass waste. To account for the material waste that can be re-manufactured, reused, and recycled, we thus multiply the sum of industrial waste by the Extraction share.

$$Wastetoti = sum(Wastepersectori) * extractionshare \tag{7}$$

We still needed to add household waste to the waste generated per sector to obtain the total waste generation of the French economy. For that purpose, we calculated the ratio of household waste per unit of total household domestic consumption ("total cyv real"). We then accounted for the generation of waste by households in France. We found that households created 27.76 tons of waste per million euros of total household domestic consumption in 2014. As this value was almost constant in the following years, we assumed that this value would stay unchanged over time. Then, we modeled household-generated waste by multiplying the monetary value of domestic household consumption by the household waste generation coefficient.

$$HHwaste = HHwastecoefficient * HHrealconsumption \tag{8}$$

We could then calculate the total amount of generated waste in the French economy by adding industry and household-generated waste.

$$Totwaste = sum(Wastepersectori) + HHwaste \tag{9}$$

Waste treatment :

To obtain the yearly amount of treated waste in the French economy, we calculated a coefficient of global waste treatment from publicly available Eurostat data. We were able to assess that the gaps and leaks in the French waste collection system accounted for approximately 8% of the generated waste in 2014. The waste treatment coefficient being stable at 0.92, it was deemed to be constant over time.

We modeled total treated waste as the multiplication of this waste treatment coefficient by the total amount of waste generated.

$$Tottreatedwaste = wastetreatmentcoeff * totwaste \tag{10}$$

The global amount of waste treated is distributed along different waste treatment techniques. With the help of statistics from Eurostat, we created waste treatment coefficients by technique. By dividing the amount of “Disposal - landfill and other (D1-D7, D12)” waste, “Disposal - incineration (D10)” waste, “Recovery - energy recovery (R1)” waste and “Recovery - recycling and backfilling (R2-R11) waste by the total treated waste, we could obtain 4 coefficients representing the share of total treated waste by treatment technique : the landfilling coefficient, the incineration coefficient, the energy recovery coefficient, and the recycling and backfilling coefficient. The recycling and backfilling coefficient was calculated as follows :

$$Recyclingcoefficient = \frac{recycledwaste}{totalwastetreated} \tag{11}$$

We obtained 0.65 as the average recycling and backfilling coefficient between 2014 and 2020. This coefficient is assumed to stay constant in a baseline scenario. When multiplying this coefficient with the amount of treated waste, the model can endogenously determine the global amount of recycled waste each year.

$$Recycledwaste = recyclingcoefficient * treatedwaste \tag{12}$$

As the scientific literature finds it hard to determine a comprehensive average amount of energy recovered by tons of undifferentiated treated waste, we chose here not to model the new inputs (or Secondary Raw Materials) created through energy recovery in an input-output framework.

The second pillar of the Circular Economy framework is the idea that waste can be transformed into new inputs (or Secondary Raw Materials), replacing our linear system with a circular one “from cradle to cradle”. We created another scenario to test the macroeconomic and environmental effects of this part of the Circular Economy framework. We used two assumptions in this scenario, aiming to represent the Circular Economy’s main representation of “cradle to cradle” policies.

The first one is that all Secondary Raw Materials could replace Primary Raw Materials as the same inputs in the production process. This scenario’s assumption states that a circular economy would prioritize a diminution in primary resource use over the maximization of the output. Instead of putting new products on the market with these recycled materials, the French economy would keep the same approximate level of output, with a maximum of primary materials replaced by secondary ones. This assumption is purely theoretical and represents a “best-case scenario”, in which the Secondary Raw Materials would keep the same qualitative properties as the Primary Raw Materials, thus enabling them to fulfill the same tasks.

The second assumption is that an increased recycling and backfilling rate could enable an economy to become “circular” e.g., to enable a long-lasting and sufficient diminution of the economy’s intake of Primary Raw Materials (natural “resources”). The potential effects of a 100% waste recycling percentage scenario on sustainability will be developed further in the article. We are fully aware that these assumptions are at least partially unrealistic. We here want to test the possible efficacy of the Circular Economy policy framework in a “best-case scenario”.

Substitution of primary materials by recycled materials :

We modeled the substitution of primary materials for secondary materials, as previously described, in a “best case scenario”.

Secondary Raw Materials are here modeled as waste transformed into newly ready-for-use inputs through an industrial process, which itself is not exempted from entropy. As stated in the second law of thermodynamics, matter invariably degrades over time both in quantity and quality. Consequently, the ability of a matter to be reused or recycled into a new input invariably decreases along the number of times it is recycled. In an industrial process, waste coming from an already-recycled product can be less recycled than a ton of primary raw materials which is about to get recycled for the first time. The waste treatment process is here not represented as a closed loop, which would contradict the second law of thermodynamics.

To represent this state of affairs in the Eurogreen model, we chose to create a new concept: the tons of Raw Materials Waste equivalent (or eq-rmW). This kind of measurement is already used in physics, with for instance CO2 equivalents (eq-co2). The CO2 equivalents is a unit in which is expressed the radiative forcing of Greenhouse Gases. It can be taken as the measurement of the radiative forcing of one unit of CO2 emissions.

In the waste treatment process, one unit of raw materials waste equivalent (eq-rmW) represents the amount of waste whose quantitative and qualitative features are equivalent to one unit of raw materials recycled for the first time. We take here as a reference for recycling the quantity and quality of primary raw materials waste. This new unit enables us to describe heterogeneous matter in a functionally homogeneous way while accounting for the effects of entropy on waste recycling.

We put the entropy rate at 0.2, meaning that we expect waste to lose 20% of its qualitative/quantitative features at each recycling cycle. More literature could help to put this entropy coefficient at an accurate and objective rate.

The "tons of eqRMW coefficient" is defined as follows:

$$TeqRMWcoefficient = \frac{(RMCtot - SRM * (entropycoeff))}{RMCtot} \tag{13}$$

The degradation of matter over time drives the generation of a lesser amount of waste, which impacts Secondary Raw Materials production. This gap is compensated by renewed Raw Materials Extraction to meet the demand.

The equation for total waste treated, thus expressed in tons of eqRMW, is defined as such :

$$TotwasteeqRM = (totwaste * Wastetreatedcoeff) * TeqRMwastecoefficientdelay) \tag{14}$$

Extracted Raw Materials Footprint :

In line with the Eurostat RME Country tool database, we use Raw material equivalents (RME) as an indicator evaluating the amount of raw materials (in tons) embedded in a unit of output. In order to model the primary Raw material use in an input-output framework, we calculated the Raw Material Consumption per sector of the French economy. Raw Material Consumption is the quantity of resources (in tons of Raw Materials Equivalents) embedded in the goods and services consumed by a country's domestic demand. It can be calculated in the following way, in which the domestic extraction (DE), the imports (M), and the exports (X) are expressed in tons of Raw material Equivalents.

$$RMC = DE + M – X \tag{15}$$

We used the data from the Eurostat RMC Country Tool to model these variables in the Eurogreen model. As our attempts to disaggregate the data on raw materials footprint per sector proved to be unsatisfying, further research and data production may be needed to assess the exact amount of raw materials embedded in each sector's production. Despite this key data gap, we assessed France's Raw Material Consumption in an aggregated manner. We calculated average ratios for the period 2014 – 2020, which eventually enabled us to infer France's RMC. We used both France's Supply-Use tables and Eurostat data on aggregated Raw Material Consumption.

Firstly, to endogenously model France's Domestic Extraction, we calculated a ratio of Domestic Extraction (in tons of RME) by a unit of domestic demand (in euros). By calculating the average of these ratios from 2014 to 2020, we obtained a coefficient of 0.835885 thousand tons of RME per million euros of French domestic demand. We found that the standard deviation of the data about this average ratio was low (0.04). We could thus model in a fairly accurate manner the French Domestic Extraction as the multiplication between this Domestic Extraction coefficient and the real French total domestic demand.

$$RMDEtot = RMDEcoeff * sum(Zdom) \tag{16}$$

We used the same method to model the raw materials embedded in France's exports and imports. On average, for the same period, we calculated that one million euros of imports had a material footprint of 2.02 thousand tons of RME (standard deviation of 0,09).

Thus :

$$RMimptot = RMImpcoeff * totalZimpreal \tag{17}$$

To calculate the average raw materials footprint per unit of exports, we divided the aggregated material footprint of exports (estimated by Eurostat) by the value of real exports for France. We obtained 0.85 as the average value for the 2014–2020 time span (standard deviation of 0,04). We could therefore, and with a certain accuracy, model the raw materials footprint of French exports as the multiplication of the raw material export coefficient by the real value of exports.

$$RMexptot = RMexpcoeff * totalexpreal) \tag{18}$$

For the calculation of these values, we always assume that the coefficients are constant because of their low standard derivations.

Once these values were estimated, we could assess the Raw Material Consumption of France as :

$$RMCtot = RMDEtot + RMimptot - RMexptot \tag{19}$$

In order to only account for the nonrenewable part of the Raw Material Consumption, we multiplied the Raw Material Consumption by the Extraction share to create the Extracted Raw Material Consumption.

$$ExtractedRMC = RMC * extractionshare \tag{20}$$

Domestic Extraction Demand :

We then modeled the Extraction Demand as the Extracted Raw Material Consumption from which is subtracted the amount of Secondary Raw Materials produced in a certain year. This variable is an indicator of an economy's intake of natural resources, and of the strain it creates on key sustainability indicators. We chose to insert a substitution coefficient in this equation in order to model the impact of the increased substitution of Primary Materials by Secondary Materials. We here assume that the substitution rate is at least partly exogenous depending on political actors' might to prioritize raw materials sustainability over higher input and GDP growth. The substitution coefficient is changed exogenously depending on the scenarios. As the literature on this issue is still nascent, we here assume that the baseline substitution scenario coefficient is 0.80. We acknowledge that further research needs to be done to better assess the scale of this mechanism. In an optimistic scenario, the maximal substitution coefficient of 1 can still be applied to this model.

$$ExtractionDemand = ERMC–(SecondaryRM * substitutioncoefficient) \tag{21}$$

This extraction demand can also be expressed through an aggregated ratio of Extracted Materials per Total Material use :

$$ExtractedMaterialsUseratio = \frac{ExtractionDemand}{ERMCtot} \tag{22}$$

As an additional indicator of ecological performance, we calculated the extracted Raw materials Extraction per unit of output.

It can be defined as :

$$Extractionperoutput = \frac{DomPrimaryRMDemand}{output} \tag{23}$$

Materials substitution “from cradle to cradle” :

The Extracted Materials Use ratio can be considered to be an indicator of the evolution of the demand for Extracted Raw Materials. We calculated the evolution rate of this indicator in order to provide an indication of the potential changes in extractive sectors' output over time.

$$Extractionevolutionratio = \frac{ExtractedMaterialsUseratio}{ExtractedMaterialsUseratiodelay} \tag{24}$$

In order to replicate the effects of this change in demand extractive sector's output, we created an extraction substitution coefficient. We assume that the extraction evolution ratio has the same effect on the output of all the sectors. The Extraction substitution coefficient is equal to the Extractive industry evolution coefficient delayed. We had to create this delay in order to avoid a ‘close loop’ modeling error, which prevented running the model. We were then able to model the decrease in output of the extractive industries because of Secondary Raw Materials substitution. We multiplied Fossil Fuels and Mining and Quarrying initial technological coefficient vectors (A coeff) by the newly created Extraction substitution coefficient in order to replicate the evolution of the demand on the output of extractive sectors.

$$AcoeffMQ = initialAcoeffMQ * Extractionsubstitutioncoefficient \tag{25}$$

$$AcoeffFF = initialAcoeffFF * Extractionsubstitutioncoefficient \tag{26}$$

We operated in the same way for the Plastics manufacturing sub-sector. Indeed, in order to create the Manufacturing sector substitution coefficient, we multiplied the plastics share of the manufacturing sector by the inverse of the extractive industry evolution coefficient.

Eco-design scenario :

In 2020, the French anti-waste law for a circular economy set as a target the end of single-use plastics in 2040. This Circular Economy policy is strongly influenced by the Ellen McArthur Foundation, which sets eco-design as one of the most important Circular Economy mechanisms. According to the latter, the best way to make an economy circular is a maximum reduction in waste generation "by design". We thus aimed to model the consequences of eco-design on the output of extractive industries.

The French administration stated in 2022 that 46% of the plastics in France were consumed as packaging. To provide a first assessment on the impacts of eco-design on the economy in a Circul Economy policy scenario, we assume that the same proportion of the French plastics output is embedded in packaging. We also assume that, as packaging is most of the time only used once, this percentage of the Plastics manufacturing sub-sector might be targeted by this new law. Then, we assessed the possible consequences of this law in a "sobriety" scenario, in which profits and GDP are not maximized through the attainment of "efficient" output levels. To assess the consequence of this scenario on the output, we created an indicator representing the share of single-use plastics (SUP) among total plastics sub-sector's output. This single-use plastics share is the inverse of the durable plastics share (54%).

$$SUPshare = 1 – DPshare \tag{27}$$

Then, we created a share of single-use plastics production out of the whole manufacturing output in order to account for the impact of the gradual decrease in production of single-use plastics on the manufacturing technological coefficient vector. We assumed that the whole production of single-use plastics could not fully disappear, and that a small proportion of single-use plastics would still be produced in 2050.

$$SUPshareM = initialSUPshareM - 0.0254 * \frac{0.46 - SUPshare}{0.46} \tag{28}$$

Once the share of single-use plastics calculated, we created a substitution rate of single-use plastics.The initial single-use plastics share of the manufacturing sector is here equal to 0,16284.

$$SUPsubstratio = 1 - \frac{SUPshareM}{initialSUPsharemanuf} \tag{29}$$

This ratio was then replicated on the technical coefficient of the Manufacturing sector.

$$AcoeffM = initialAcoeffM * Extractionsubstcoeff * SUPsubstratio \tag{30}$$

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