SPES
Sustainability
performances,
evidence & scenarios

D9.1 Transitioning towards Harmonious Living:

A Society-Economy-Nature model with heterogeneous agents, finite resources and politics (SEN-HARP) for Europe-27

February 2025

Funded by
the European Union

Funded by the Horizon Europe Programme under Grant Agreement No. 101094551

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Acknowledgments

The authors would like to thank all SPES partners for their inputs provided in several SPES meetings and communications.

Cite as

Funalot, P., Rougier, E., Saint Jean, M., (2025) *Transitioning towards Harmonious Living: A Society-Economy-Nature model with heterogeneous agents, finite resources and politics (SEN-HARP) for Europe-27*. SPES Working Paper no. 9.1, SPES project – Sustainability Performances, Evidence and Scenarios. Florence: University of Florence. Available at: https://www.sustainabilityperformances.eu/publications-deliverables

Disclaimer

This Working paper 9.1 for the project SPES has been prepared by Bordeaux University, Bordeaux School of Economics, as part of Task 9.1 "Synthesizing the evidence on synergies and trade-offs in the making of a just transition" / Work Package 9. This Work Package aims to map and hierarchize the main synergies and trade-offs in country-level data by mapping the multidimensional correlations of a large set of policy and attainment variables drawn from the review analysis.

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

Funded by the European Union under Grant Agreement No. 101094551.

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Abstract

The urgent need to mitigate climate change demands rapid and extensive de-carbonization of global economies. Transition to net-zero carbon is not merely technical but a complex socio-political endeavour with significant trade-offs involving inequality, well-being, sustainability, and political acceptability. If perceived as unfair, the transition risks rejection and political backlash. Still, a just and inclusive transition can also enhance social cohesion and accelerate sustainable policy adoption. In this paper, we introduce a new Agent-Based Model (ABM) called SEN-HARP which integrates biophysical and socio-political modules through original feedback loops to study how these interactions might shape the feasibility and effectiveness of different scenarios of European Union's Green Deal: market-based and innovation, augmented Green Deal, and a disruptive post-growth called “harmonious living”. SEN-HARP articulates the micro and macro levels for simulating the joint dynamics of resource use, warming impacts, livelihood dynamics and voting behaviour the latter being based on perceived gains or losses from transition policies. By combining an Agent-Based Stock-Flow Consistent (AB-SFC) approach with an environmental biophysical module, SEN-HARP can also explore how sustainability goals interact with inequality and political acceptability within fiscal and physical boundaries. While significant progress has been made in understanding the biophysical dimensions of climate change, the socio-political aspects remain largely under-explored by assessment models. This paper therefore provides a useful tool for analysing more comprehensively the trade-offs between effectiveness, fairness and political feasibility brought by the net-zero carbon transition.

Keywords: Ecological transition; Decent living; Basic needs; Social acceptability; Political responsiveness; Agent-Based model; Stock-Flow Consistent modelling; Endogenous damage

1. Introduction

The global imperative to mitigate climate change is necessitating a rapid and far-reaching de-carbonization of economies worldwide. Given the current state of affairs, even greater efforts will be required in the near future to achieve outcomes that align with the targets set for 2050. However, the prevailing trend of setbacks and opposition highlights that transitioning to a low-carbon society is not merely a technical challenge (Thalberg et al, 2024; Vohra, 2024); rather, it is a highly complex task fraught with numerous trade-offs involving inequality, well-being, sustainability, and political acceptability and carried out under significant environmental and socio-political pressure. Identifying these trade-offs and implementing policies that can transform them into synergies is the only viable and urgent path to overcoming delay or setback in Europe as in the rest of the world. Rather than being viewed as a blocking constraint, the costs of transition and their uneven distribution should be seen by European countries as an opportunity to accelerate progress toward sustainability through sound and ambitious policies.

The de-carbonization transition is inherently disruptive, as it involves deeply reconfiguring energy systems, industrial processes, and consumption patterns. Such transformations inevitably create winners and losers, exacerbating or alleviating existing inequalities (Newell and Mulvaney, 2013; Baranzini et al., 2017; Carley and Konisky, 2020; Newell et al., 2022). For instance, the phasing out of fossil fuels may disproportionately affect workers in carbon-intensive industries, while the adoption of renewable energy technologies may benefit regions with abundant solar or wind resources. Structural transformations also embody politically-sensitive trade-offs between nature conservation and material livelihood. These distributional and structural effects have profound implications for social well-being and political stability, necessitating both careful scientific analysis and political resolution (Alkin, 2024). This highlights the central challenge of improving our understanding of how climate change, economic transformation and social acceptability interact to either support or hinder transition policies. Policy challenges are also considerable if the objective is to design actions for transforming trade-offs into synergies.

The present research develops an original and innovative Agent-Based framework for assessing the conditions of economic and socio-political feasibility of different scenarios of European Green Deal and identify policy scenario that allow mitigating the main transition trade-offs. Even if the model is developed to assess different policy scenarios of net-zero carbon transition at the 2050 horizon for the EU27 as an aggregate, the mechanisms described are general and informative of situations ion other regions. For the sake of realism, the model is stock-flow consistent in terms of monetary flows and it incorporates biophysical feedbacks from nature to the economy and society (in terms of matter scarcity and of warming). Another crucial innovation bringing more realism to the simulations is the endogenous determination of transition policy dynamics through poll results and the high degree of granularity that allows addressing spatial heterogeneities in the costs and benefits of transition.

As rightly emphasized by Peng et al (2021: 174), the computer models used by analysts to assess the routes to achieve de-carbonization goals “are missing a crucial factor: politics”. This paper seeks to address the existing gap by developing an ABM that integrates a biophysical module with a political module to study the interplay between critical dimensions of the transition. The type of IAM used by institutions strongly shapes their policies. Not all models represent the economic costs of ecological action and inaction in the same way, heterodox models being judged more efficient in describing complex interactions between the society, the economy and nature (Souffron and Jacques, 2023). Among these heterodox models, we follow an ever-increasing strand inscribed in the stock-flow consistent (SFC, Lavoie and Godley 2001, 2007) tradition. More recent works (Dafermos, Nikolaidi and Galanis 2017), like the DEFINE model (Dafermos and Nikolaidi 2022) introduced a complex environmental module.

By incorporating a biophysical module that simulates resource use and environmental impacts, alongside a socio-political module that models different sources of agent heterogeneity as well as voting behaviour based on agents' perceived gains or losses in terms of jobs and consumption from transition policies, our ABM offers a novel framework for analyzing the trade-offs and synergies inherent in the de-carbonization transition. In our model (that we call SEN-HARP for the Society Economy Nature-Heterogeneous Agents (finite) Resources and Politics)[1], the economic, social and political spheres are linked through endogenous variables that arise from the dynamics of the model and cover nine out of the twelve social thresholds identified by Raworth (2017).

Limited account of Energy-economy feedbacks is a literature gap identified by different reviews (Keppo et al., 2021; Ven Eynde et al, 2024) of existing climate policy assessment models. SEN-HARP's biophysical module draws on ecological economics principles to simulate the interactions between human activities and natural systems. It accounts for the finite nature of resources, the environmental impacts of resource extraction and use, and the potential for technological innovation to decouple economic growth from environmental degradation. However, resource availability limits, as well as pollution problems, may endanger the health of the ecological system itself and limit adaptive and innovative response strategies (Daly, 1996; Rockström et al., 2009). The bio-physical element of SEN-HARP model provides the foundation for assessing the sustainability of different de-carbonization pathways, as well as their implications for resource availability and ecosystem health.

Lack of heterogeneity and of consideration of distributive and political dimensions of the transition have also been emphasized as potential limitations of the existing models (Keppo et al., 2021; Ven Eynde et al, 2024). SEN-HARP's political module describes agents as voters who evaluate transition policies based on their perceived impacts on their well-being, which is influenced by factors such as income, employment, and access to resources. Households thus have three roles in the model: they work, consume and vote. In addition, our model includes different types of households (urban *vs* non-urban, skilled *vs* unskilled) endowed with heterogeneous behavioural characteristics and facing heterogeneous constraints. Agents who perceive themselves as winners in the transition are more likely to support de-carbonization policies, while those who perceive themselves as losers are more likely to oppose them. This module allows considering the potential for policy design to mitigate opposition by addressing distributional concerns (Baranzini et al., 2017; Carattini et al., 2019). After Piketty and Cagé's analysis (2023) of geo-classes and electoral structure by differentiating households with respect to their space of residence: urban households are those living in large cities and peripheral households live in secondary cities and rural spaces. A third type of household, which we call "top-income", influences political life by shaping the positions of parties and the overall political climate of our society (Otto et al, 2019).

In terms of the policy sets, we define three main transition policy scenarios: market-based and innovation (close to the first version of the Green Deal), augmented Green Deal, and post-growth. For each scenario, we evaluate the performance of the provisioning systems, that is to say the ways in which the economy is able to satisfy the social and human needs of the households, while preserving Nature. This allows us to evaluate the socio-ecological efficiency of the economy for each scenario, complying with the need of "systematically assessing and comparing provisioning systems and their stock-flow-service efficiencies and outcomes" (Plank et al 2021, p.11). SEN-HARP model is innovative in terms of the outcomes observed, as it bridges social outcomes, notably those defining decent life, and environmental footprints for defining the concept of harmonious living.

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[1] Even though the name may suggest it, we do not refer to Amartya Sen in our work.

Harmonious living is inspired by both the eco-development approach (Sachs 1977) and the Donut framework (Raworth, 2017). In this framework, the economy is seen as purely instrumental and is conceived as a web of provisioning factors for attaining social thresholds within biophysical limits.

An additional key foundation of our model is its Stock-Flow Consistent (SFC) framework, which provides a robust foundation for analysing the economic and financial implications of de-carbonization policies by ensuring macroeconomic consistency. This approach, rooted in the post-Keynesian tradition (Godley & Lavoie, 2007), allows us to simulate the macroeconomic effects of policy instruments—such as carbon taxes, subsidies for renewable energy, or green investment programs—while maintaining consistency in the balance sheets of households, firms, governments, and financial institutions. The SFC framework is particularly valuable for analysing the fiscal and financial implications of de-carbonization policies, as it captures the interplay between income distribution, debt dynamics, and economic growth. For example, it enables us to assess how carbon tax revenues can be recycled to mitigate inequality or finance public investments in sustainable infrastructure, and how these measures influence aggregate demand and employment.

To our knowledge, the SEN-HARP model is the first to gather an AB-SFC approach with an environmental bio-physical module and an accounting of provisioning systems as well as voting behaviour. By integrating the biophysical and socio-political modules within a Stock-Flow Consistent framework, our model allows us to explore scenarios in which the pursuit of sustainability goals interacts with the dynamics of inequality and political acceptability in the context of EU27. For example, we can examine how different policy instruments—such as carbon taxes, subsidies for renewable energy, or universal basic income—affect the distribution of costs and benefits, and how these distributional outcomes influence political support for the transition. We can also investigate the conditions under which synergies between sustainability, well-being, and political acceptability emerge, as well as the trade-offs that may arise when these objectives conflict. The model is also fitted to simulate scenarios of carbon transition in democracies, that is under the pressure of votes (Lindvall, 2021; Jordan et al, 2022). As the model is calibrated for EU27, it allows jointly assessing the conditions of socio-political feasibility and environmental effectiveness of the European Green Deal[2] in the context of a European democracy modelled as a two-party (pro- and anti-transition) system. In a context of high (geopolitical) turbulence, it is utterly important to save the European Green Deal by providing ways forward compatible with what European populations are likely to accept in terms of social model, political liberties and economic objectives.

In the following sections, we first detail the positioning in and contributions of our research to the existing literature (Section 2). Thereafter, we undertake a review of the main advances and gaps in climate-economy-society ABMs, with a focus on the innovative dimensions of our model: agents' heterogeneity, distributional impacts and political support, policy design and the integration of well-being and planet boundaries through basic needs and provisioning systems (Section 3). Then, we present the theoretical foundations and objectives of our model and describe in detail its architecture and calibration (Section 4). The main outcomes selected are presented in Section 5, and the subsequent steps of the model development are outlined in Section 6.

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[2] The European Green Deal, launched in December 2019, constitutes the European Union's (EU) strategy to make Europe the first climate-neutral continent by 2050. It is a set of policies and initiatives designed to promote sustainable economic growth while reducing greenhouse gas emissions. Key objectives have been established, including achieving climate neutrality by 2050 (i.e. reducing net greenhouse gas emissions to zero), achieving a 55% reduction in emissions by 2030 compared to 1990 levels, promoting a transition to renewable energy sources (e.g. wind, solar, and hydrogen energy), and fostering a circular economy (i.e. reducing waste and encourage recycling), sustainable agriculture (introduce greener farming practices through the Farm to Fork strategy), clean transport (phase out petrol and diesel cars, increase electric vehicles and rail transport), biodiversity protection (restore ecosystems and plant 3 billion trees by 2030), just transition (support regions and workers affected by the green transition).

2. Positioning of SEN-HARP in the climate policy assessment literature

2.1. SEN-HARP as a climate policy assessment model

Since the 1970s, and after the seminal work of the Meadows Commission (1972), the climate assessment literature has been largely focused on the core Economy-Resources and made substantial progress in the systemic understanding of the macro impact of climate change and the mechanisms of technological diffusion or energy markets (van Beek et al, 2020; Balint et al, 2021; Naumann-Woleske, 2023). By modelling human-environment interactions, IAMs provide insights into the synergies and trade-offs involved in achieving multiple goals simultaneously (Van Soest et al., 2019; Balint et al, 2021). However, they often abstract away from the socio-political heterogeneity of agents and the complexity of socio-political interactions. As a matter of fact, it is now widely acknowledged that decarbonizing our livelihoods is not only a technological and economic challenge, it is also a deeply political and social one (Carattini et al, 2018, 2019; Trutnevyte et al, 2019; Kallbekken et al, 2023; Peng et al, 2023; Hoekstra et al, 2024).

Understanding and tackling the constraints putting pressure on transition policies through complex trade-offs and feedbacks between politics, inequality and climatic outcomes requires having powerful tools of modelling and policy scenario analysis. Various methodological approach are rivalling for assessing the effects of climate change and of mitigation policies on climate change. Table 1 summarizes these different approaches and how SEN-HARP is posited in comparison to them. Emblematic models representative of these alternative approaches have been used for comparison.[3]

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[3] An emblematic example of IAM is the Dynamic Integrated Climate Economy (DICE) model by Nordhaus (1992) and Nordhaus and Yang (1996); SFCs are well represented by the Godley and Lavoie (2007)'s model; the Dystopian Schumpeter meets Keynes (DSK) model by Lamperti et al (2018) is highly representative of ABMs used for assessing the impacts of climate change and mitigation policies.

Table 1: Comparison between assessment models on a number of key epistemological dimensions

DIMENSION	IAMS (E.G. DICE)	SFC (E.G. GODLEY & LAVOIE, 2007)	ABM (E.G. DSK)	SEN-HARP
Modelling approach	Top-down (with bottom-up estimations of macro-parameters)	Top-down	Bottom-up	Bottom-up + Top-down
Type of dynamics	Ergodic (past data can predict future behaviour)	Non-ergodic	Non-ergodic (path-dependence and history matter)	Non-ergodic
Macro-consistency	Yes	Yes	Not always	Yes SFC
Decision-making	Optimization	//	Satisficing rule, bounded rationality	Satisficing rule, bounded rationality
Representation of agents	Homogeneous (e.g. single global economy or sectoral aggregates)	Aggregate accounting sectors	Heterogenous agents	Heterogenous agents
Equilibrium type	General or partial equilibrium	Out-of-equilibrium dynamics	Out-of-equilibrium dynamics	Out-of-equilibrium dynamics

Traditional economic models, such as Integrated Assessment Models (IAMs)[4], have been instrumental in exploring decarbonization pathways, particularly by modelling interactions among energy, the economy, climate, and land use (Pyndick, 2013; Weyant, 2017; Van Beek et al, 2020; IPCC, 2021). Among the main gaps identified by recent critical reviews of existing assessment models, the limited representation of the human and social parts of the system stands at the forefront (Trutnevyte et al, 2019; Beckage et al, 2020; 2022; Keppo et al, 2021). IAMs are notably blamed for not correctly capturing the dynamic cumulative patterns of public acceptance, political support and corporate investment triggered by successful policies (Peng et al, 2021).[5] By capturing the heterogeneity of agents, their interactions and the emergent properties of biophysical-socioeconomic systems, ABMs in particular provide better-fitted frameworks for assessing such complex feedbacks (Trutnevyte et al, 2019; van Beek et al, 2020; Keppo et al, 2021; Souffron and Jacques, 2023; Naumann-Woleske, 2023). Understanding these dynamics requires a systemic approach that integrates micro and macro levels, capturing the feedback loops between biophysical processes, socio-economic outcomes, and political behaviour (Savin et al, 2022). The bottom-up approach adopted by ABMs dynamically aggregates microeconomic or social behaviour into macro-

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[4] See Nordaus and Yang (1996) for a seminal model.

[5] Using expert and modeler surveys with text mining techniques on a large corpus of IAMs to map key interactions among the Sustainable Development Goals (SDGs), Van Soest et al. (2019) confirm that while IAMs generally cover SDGs related to climate, resource use, and the Earth system, other critical dimensions of the 2030 Agenda—such as socio-political equality, human development, and governance—are not well represented.

level emerging outcomes through a large variety of interaction patterns going from market transaction to influence through peer-effects.

Limited consideration of the heterogeneity within and across actor groups and behavioural dynamics also imposes constraints on understanding “real world” dynamics and acting on it through effective and fair policies in IAMs. IAMs generally limit the diversity across actor groups to aggregate producers, consumers and a fully informed benevolent social planner. As underlined by Keppo et al (2021:6), this makes harder to capture such social processes emerging from coordinated actions of few actors (lifestyle change, innovation, strategic actions, political processes) that are deemed to play a central role in transitions. IAMs are also criticized for their inability to adequately capture the trade-offs faced by policy makers, notably those reflecting heterogeneous conflicting preferences over climate policy across constituencies (Peng et al., 2021; Larcker et al, 2024). The point is that national policy-makers precisely need to have more inputs on how de-carbonization policies in transport or food production are potentially traded against electoral risk, and on the extent to which this is shaped by effectiveness and fairness in terms of policy outcomes.

These dimensions, which are central to the political feasibility of transition strategies, require that different scales of analysis are integrated and that preferences heterogeneity and their endogenous changes along with global warming consciousness and mitigation policies are more fully accounted in assessment models. Process-based models like Agent-Based Models (ABMs) are uniquely suited to capture the emergent properties of complex systems, as they allow for the representation of heterogeneous agents with bounded rationality, adaptive behaviour, and social interactions (Epstein & Axtell, 1996; Railsback & Grimm, 2019).[6]

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[6] ABMs have for example already contributed significantly to understanding the systemic nature of the carbon transition by connecting biophysical, economic, and technological subsystems (Farmer et al., 2015; Balint et al., 2017; Lamperti et al., 2019).

2.2. SEN-HARP detailed contribution to the assessment literature

This paper contributes to the climate policy literature on different dimensions. These contributions are summarized in Table 2 and contrasted with standard assessment models like the Dynamic Integrated Climate Economy (DICE) IAM (Nordhaus, 1992; Nordhaus and Yang 1996) or the Dystopian Schumpeter meets Keynes (DSK) ABM (Lamperti et al, 2018).

Table 2: SEN-HARP characteristics (partially based on the sample of assessment papers by van Eynde et al (2024)

MAIN CHARACTERISTICS	EXISTING ASSESSMENT MODELS	SEN-HARP
Flow representation	Often limited to monetary flows or aggregated resource use	Explicitly distinguishes between monetary and physical flows
Planetary boundaries	Generally not represented in ABMs and IAMs May include exogenous damage functions, limited feedbacks	Endogenizes environmental feedbacks, resource constraints, and waste dynamics
Social outcomes and equity	Rarely considers distribution or human well-being	Directly links resource flows (social metabolism) to human needs (social provisioning)
Sector diversity	DSK: Consumption good / production good / or durable/non-durable goods / energy	Need-based sectors
Social influence	Bandwagon effect (DiGuilmi, Galanis and Proano, 2023) Public opinion (Lackner et al 2024)	Bandwagon effect
Political responsiveness	Treats policy as exogenous or static Votes	Incorporates endogenous political processes and feedback between society and policy
Endogenous damage function	IAMs (Nordhaus, DICE) Not always in ABMs May include exogenous damage functions, limited feedbacks	Yes, represented as a consequence of atmospheric CO2 concentration and radiative forcing.
Agent heterogeneity	Assumes homogeneous agents and equilibrium states	Uses agent-based micro-foundations to capture heterogeneity and emergence In the present model, number of firms (60), consumers (200), workers (≤200), banks (10), political party (2), spatial characteristics (central vs peripheral)
Labour market	Generally not explicit in ABMs and IAMs	Disaggregated and interconnected labour markets

First, the SEN-HARP model advances the field of ecological economics by providing a computational framework for analysing the socio-political dimensions of sustainability transitions. Following recent contributions by Lackner et al (2024) or Di Benedetto et al (2024), we contribute to the scarce integrated assessment literature explicitly addressing how voter behaviour, political resistance, and policy acceptability influence the adoption and implementation of carbon transition policies. In our model, successive political "equilibria" shape endogenous policy scenarios, these policy scenarios then feedback on next period political equilibrium. Like Di Benedetto et al (2024), our political model opposes two parties – one supporting transition policies and the other opposing them – fighting to attract votes by households that are motivated by different parameters including incumbents' performance in terms of economic conditions and climate. Political equilibrium is determined by a function giving a probability of voting for a pro-transition party which depend on three endogenous parameters: the evolution of basic needs satisfaction which is an outcome of the socio-economic system and of policy scenario, a bandwagon effect that captures an imitation effect (variable representing the share of the electorate that switched to one party or the other), and an inertia effect, i.e. the agent's previous vote will tend to push him to vote again for the same party. In this set-up, we can shed light on how different endogenous political equilibria between green vs anti-green agendas might prompt or backlash against the green new deal agenda.

Our difference with Di Benedetto et al (2024) lies in several dimensions. First, Di Benedetto et al (2024) focus on policy implementation and political feasibility, but they do not take into account the economic losses that result from inaction on climate change. Our model includes a climate damage function as our focus is both on analysing the political conditions under which political dynamics allow or not effective transition policies and on endogenizing the impact of climate change on the economy and the polity. A second difference lies in our modelling approach of household heterogeneity in terms of skills and territory of residence that puts more realism in the transition policies' socio-political acceptability modelling. We connect political preference to voters' spatial localization in order to capture the commonly observed gap between transition costs borne by rural or sparsely-populated areas and large-cities inhabitants (Rodriguez-Pose et al, 2018). Finally, policies are modelled as fully reversible in Di Benedetto et al (2024) whereas we consider path dependency in policy, some climate measures remaining in place even when opposition parties take power which is more in line with empirical findings notably on US climate policies (Basseches et al, 2022).

Second, our model is inspired by the Dystopian Schumpeter meets Keynes (DSK) model (Lamperti et al, 2018). Yet, it goes beyond it in a crucial way. Following the seminal DSK model, most ABMs use more or less aggregated measures of economic outcomes (income, production or employment)[7] and adopt a production-centred vision of the nature-economy system. We adopt a radically different and more realistic approach by considering six sectors: Food, Housing, Energy, Transportation, Manufactured goods and Technological products and services. While all six sectors are essential sectors of the dynamics of productive systems and job provision, the four former ones are also strategic as they allow targeting central basic needs defining decent living (O'Neill et al, 2018).[8] The need-centred approach allows considering policy scenarios based on sufficiency or need-centred strategies of transition or incorporating social floors and planetary boundaries (Raworth, 2017) into the system dynamics (van Eynde et al, 2024). This framework also allows shifting the goals of the economic systems from the production of goods to the provisioning of services, including energy services. This framework also allows connecting people's wellbeing (and

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[7] Economic outcomes are generally disaggregated in the consumption-good, production-good and energy sectors (Lamperti et al, 2018).

[8] The public sector is added as the essential part of the provisioning systems associated with transition.

thus partly votes) to planetary boundaries through the satisfaction of basic-needs. To our knowledge, we are the first ones to do this.

Third, we contribute to the nascent literature on policy mix and policy sequencing and add to the growing evidence on the suitable policy package to induce an effective and orderly transition. Lamperti et al (2022) point that abrupt and aggressive climate policy excessively relying on policy instruments characterized by low political acceptability, such as carbon pricing, is likely to induce macroeconomic frictions destabilizing the economy. Our findings add to the growing evidence that mixes of regulation, price and subsidy not only bring effectiveness into the transition outcomes (Lamperti et al, 2022; Wieners et al, 2022; Stechemesser et al, 2024) but also allow alleviating public resistance to transition policies by improving fairness when they are supported by well-designed monetary policies and provisioning systems. As in Di Benedetto et al (2024), we show that a strategically chosen combination of policies leads to the best outcomes in terms of fair transition also when political realism is added to the DSK model. Yet, we propose a more complex mix incorporating monetary policies alongside with the tax and regulatory tools which are traditionally considered. Moreover, the SFC set-up of our model puts more realism to the modelling of fiscal and monetary policy tools.

Fourth, the incorporation of Stock-Flow Consistent (SFC) frameworks in ABMs is another important innovation that we adopt in our model. Caiani et al. (2016) demonstrate that adding SFC frameworks to ABM helps to ensure macroeconomic consistency while modelling the macroeconomic impacts of different kinds of policies. They claim that this approach provides a robust foundation for analysing the fiscal and financial implications of decarbonization, including the effects of redistributive policies. Various reviews of the IAMs have nevertheless underlined the lack of realistic damage functions for the economic impact of the physical consequences of climate change (Farmer et al., 2015; Van Eynde et al, 2024). In our model, we introduce explicit damage functions for accounting for the endogenous feedbacks of the Nature module on the rest of the system. These damages essentially concern temperature rise, on productivity and the stock of capital. Following Dafermos, Galanis and Nikolaidi (2018), we extend the Stock-Flow Consistency to matter use. To our knowledge, this is the first time that an ABM is Stock-Flow consistent on both money and matters and includes an ambitious socio-political module generating endogenous political fluctuations.

3. Assessing trade-offs and feedbacks on transitioning towards harmonious living: A review of advances and gaps

This section proposes an assessment of how ABMs have addressed or failed to address the trade-offs and feedbacks between politics, inequality and climate as we speak. The review is in no way exhaustive.[9] We instead focus on the improvement directions pinpointed in the literature that we have tried to address in the present contribution – agents heterogeneity, distributional aspects, politics, policy design, planetary limits and the needs approach – and the way our model addresses these gaps.

3.1. Agents heterogeneity

Although plenty and diversified, IAMs have only recently attempted to capture the complex social processes that play a central role in transition trajectories (Holtz et al, 2015; McCollum et al, 2017; Hirt et al, 2020; Keppo et al, 2021). Relatedly, it is also widely observed that IAMs have only marginally focused on the distributional impacts of transition policies so far (Rao et al, 2017; Trutnevyte et al, 2019; Keppo et al, 2021). These limitations are partially explained by the set-up of numbers of IAMs that narrow agent diversity to sets of homogenous producers, consumers and a fully informed benevolent social planner (Keppo et al; 2021). This restrictive setup has for consequence that the vast majority of existing IAMs are poorly equipped for capturing patterns emerging from heterogeneous individuals' coordinated actions like lifestyle change, inequality-led frustration or political swings (Trutnevyte et al, 2019; Beckage et al, 2020; Beckage et al, 2022).

Modelling social or territorial heterogeneity inherently means representing the individual parts of something that initially is treated as a whole. This can be applied at different scales, for example, from the population as a whole to different social groups, or from regional to neighbourhood level down to the individuals (Keppo et al, 2021). This can also reflect different modelling objectives, some models putting more heterogeneity in the aim of assessing differential impacts of targeted policies across groups or regions, while others aim more at capturing inter-individual interaction dynamics through imitation or learning[10] (Keppo et al, 2021). Simulation models – like ABMs – are better fitted than optimization models to address behavioral heterogeneity (Souffon and Jacques, 2023; Naumann-Woleske, 2023). Yet, putting more complexity in the model also has to be traded against increased uncertainties over the models' long-time horizons (Keppo et al, 2021). Modelling heterogeneity is not only relevant in terms of knowledge, it is also crucial in terms of policy. Czupryna et al (2020)'s simulations show that variations in heterogeneity as per consumption parameters, initial wealth distribution, within-sector firms' characteristics or temperature-related damages do influence the aggregated economic patterns and trade-offs between economic welfare and climate protection. The high-heterogeneity scenario indeed leads to both lower GDP growth rates and

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[9] For more complete reviews of the contribution of ABMs to the analysis of integrated social-economic-environmental systems and the literature gaps, see Keppo et al (2021) and Trutnevyte et al (2019); for methodological and technical issues raised by the use of ABMs, see Thober et al (2017).

[10] See respectively Mercure and Lam (2015) and Edelenbosch et al (2018) for illustrations of these two objectives.

greater temperature-related damage than what is forecast by models with solely homogeneous (representative) agents. These findings highlight the great relevance of putting more heterogeneity in simulation exercises for assessing the impacts of more fine-grained calibrations or targeting of policy instruments and mixes.

For Trutnevyte et al (2019), in order to make climate-economy models more "socially-conscious", they should more largely integrate insights from social sciences, their societal assumptions should be more systematically assessed and discussed, and generalizable and quantifiable patterns from observational research should feed into them. This is precisely the line adopted in this paper by defining two spatial setups where households live and work: the large cities and the peripheral areas including suburban and secondary cities and more remote rural areas. Recent episodes in Europe of political protest against carbon tax (France) or rural-based protests fuelled by rising costs and perceived unfair EU climate policies (Germany, Netherlands, Poland), point out the relevance of differentiating households' behavioural and preference parameters across these two types of living spaces. The distribution of the readiness for the green transitions across European countries and regions exhibits a clear urban/rural divide (Maucorps et al., 2022). Urban and metropolitan regions, particularly those specializing in knowledge-intensive services, exhibit higher readiness levels for climate and digital transitions. This positions them to lead the transition and capitalize on emerging opportunities, thereby exacerbating the initial gap between urban and rural areas in the potential for reaping benefits from the green transition. In contrast, rural and agricultural regions, especially in countries like Romania, Poland, France, Czechia, Slovakia, and Sweden, face significant challenges due to their reliance on carbon-intensive sectors such as agriculture, low-tech industries, and mining. These regions are not only less prepared but also bear higher costs for climate adaptation, risking further economic marginalization (Maucorps et al., 2022).

Concentration of discontent in remote and peripheral European regions has been evidenced by a series of recent empirical studies (Rodriguez-Pose, 2020; Rodriguez-Pose et al, 2023, 2024; Sotoriou et al, 2025). The impact of place-based resentment and of the feeling of spatial marginalization on preferences and votes for populist parties is also widely documented by a large literature dealing with European regions (Maxwell and Minkof, 2014; Ansell and Adler, 2019; Dijkstra et al, 2019; Rodriguez-Pose et al, 2024).[11] The impact of place-based resentment on voting for anti-green transition parties is another growing area of research, particularly as green policies often exacerbate regional inequalities or are perceived as favouring urban elites (Mildenberger and Leiserowitz, 2017). Biased perceptions of green policies as urban-centric and elitist are framed by populist and nationalist parties, particularly in carbon-intensive and rural region (Buzogány and Mohamad-Klotzbach, 2021), exploiting regional disparities and place-based resentment to oppose the European Green Deal (Lockwood, 2018).[12]

Besides place-based heterogeneity, our model also integrates occupation- and skill-based heterogeneity through the different profiles of individual skills (high, low) and occupations (brown, green) used for matching the supply and demand of labour all along the economic dynamic. From this process of matching, we are able to draw a rich diversity of unemployment and labour income outcomes that will partly determine households' voting behaviour. People will therefore vote based on the way the green or non-green policies conducted by the incumbent government has changed their economic situation, with employment and wage level standing as central assets.

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[11] Various studies provide evidence on individual countries: France (Cagé and Piketty, 2025), the UK (Becker et al, 2017), Italy (Giovannini and Vampa, 2019) or the US (Cramer, 2016, Monnat and Brown, 2017).

[12] Evidence also exists that place-based resentment, particularly in rural and industrial areas, also influences opposition to climate policies and support for anti-green transition candidates in the US context (McCright and Dunlap, 2011; Stokes and Warshaw, 2017; Mayer and Smith, 2019).

3.2. Distributional aspects

Undoubtedly, the distributional impacts of de-carbonization stand in a central position in the definition and assessment of feasible policy scenarios. Inequality is a central concern in the de-carbonization transition, as the costs and benefits of transition policies are often unevenly distributed. Känzig (2023) provides empirical evidence that the European Union ETS scheme had significant unequal impacts across social groups on income, consumption and employment. The significant increase in energy prices comes at the cost of temporarily lower economic activity and higher inflation that hit poorer households who have to lower their consumption significantly to adapt to the fall in their income. This unequal distribution of the cost of energy transition goes through different mechanisms. First, poorer households are more exposed to carbon pricing because of their higher energy expenditure share. Second, they also experience a larger fall in their income, notably as they are more widely employed in sectors with high levels of demand sensitivity than high-income households.

ABM frameworks feature integrated assessment implicitly considering the distributional impacts of sustainability transitions in one way or the other. Most models incorporate aggregate outcomes and are not designed to generate inter-individual or inter-regional distributional outcomes. Agent heterogeneity in terms of skills, occupation, region or income source (labour or capital) need to be introduced into the model to address the distributional impact of various policy scenarios. Inequality logically raises the concern of the political feedback against transition policies. Higher levels of inequality are theoretically associated with greater political polarization and resistance to climate policies, as disadvantaged groups are more likely to perceive the transition as unfair (Antonio and Brulle, 2011). The French Yellow Vests crisis has showcased how perceptions of the impacts on social equity and individual hardship are central in shaping the social support to transition policies. The crisis exploded because the French government's decision to impose a fuel tax was seen as unfair by the people who had to suffer the most from sharp price rises, while being not given back under the form of monetary redistribution or public investment (Carattini et al, 2019).

It is now widely accepted that policies that address inequality and ensure a just transition are more likely to gain political acceptance (IPCC, 2024; Hoekstra et al, 2024). If the transition is perceived as too costly or unfair—whether in terms of consumption adjustments or job redistribution—it risks being rejected and triggering political backlash. Conversely, it is widely acknowledged that a just and inclusive transition (Wang and Lo, 2021) could enhance social cohesion and accelerate the adoption of sustainable policies (Newell & Mulvaney, 2013; Carattini et al., 2019). Indeed, the IPCC (2023) argues that social and environmental policies can yield co-beneficial effects that need to be more widely documented and shared.

Public preference for fair transition policies is well documented in the literature. Douenne and Fabre (2020) provide evidence that, although the French Yellow Vests rejected carbon taxation as unfair[13], they are ready to support stricter regulations and more ambitious green policies if it can improve their future quality of life. Numerous examples of carbon tax rejection around the world show that people tend to overestimate drawbacks such as increase of transportation costs while

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[13] The Yellow Vests movement, which began in France in 2018, underscores the critical importance of carefully addressing the differentiated constraints and needs of the population when implementing transition policies. Mobility in remote areas, for example, is both costly and highly carbon-intensive, compounded by limited investment in green transport infrastructure. Examples of such movements include Fridays for Future (FFF), a pan-European climate movement, started in 2018 by Greta Thunberg in Sweden, and the German Farmers' Protests (2023–2024). These movements demonstrate that citizens are becoming increasingly dissatisfied with government policies, particularly those relating to climate and economic decisions.

underestimating the benefits of carbon taxes in terms of lower emissions (Carattini et al, 2018). Dechezleprêtre et al (2022)'s large-scale surveys of 40,000 respondents from 20 countries confirms that public support is lower when transition policies are suspected to hit more negatively low-income households. Likewise, Carattini et al (2019)'s survey conducted in five countries (India, the US; Australia, the UK, South-Africa) show that a majority of people surveyed in all five countries favoured strategies for distributing revenues from a global carbon tax through sharing them among citizens, notably nationally and lowering income taxes.

The importance of compensating transition losers, such as workers in carbon-intensive industries to build political support for climate policies. Recycling carbon tax revenues to fund social programs or green investments and lump-sum transfers or tax rebates can compensate for the transition costs and enhance the political feasibility of de-carbonization (Carattini et al, 2018, 2019). Känzig (2023)'s empirical evidence of EU-ETS policy distributive effects suggests that redistributing some of the carbon revenues to the most affected groups would reduce the economic costs of carbon pricing that disproportionately hit the most vulnerable and may help strengthen their support.

It is not clear however what kind of redistribution or revenue recycling measures people prefer. Douenne and Fabre (2020) conduct a survey of a large panel of French people to elicit their perceptions of climate change and relate them to attitudes towards climate policies. Respondents largely reject the carbon tax, yet their support would increase for some forms of revenue recycling or accompanying policies. Indeed, respondents' preferences largely go to green investments (housing, transport, renewable) and more stringent norms, while support for lump-sum transfers (targeted or not) is surprisingly lower.[14] Interestingly, this finding holds for both ecologists and supporters of Yellow vests. Urban and more educated respondents are also more supportive of tax-based climate policies. IAMs should therefore incorporate more elaborate political modules to assess how the mitigation effects of different mixes of tax revenue recycling are mediated and shaped by socio-political acceptability and responsiveness.

Yet, political mechanisms are central in the design and effectiveness of the compensations of the unequal social costs of transition. Alkin (2024) considers just transition policies as a solution to a strategic problem and not as due compensations to vulnerable workers. He shows that the likelihood that compensation policy will allow phasing out fossil fuels is highest when the government has a strong preference for climate mitigation, when workers have good alternative options compared to their fossil fuel jobs, and when political mobilization is not too easy. Alkin (2024) also insists on the territorial aspect of transition policies as fossil fuel industries are strongly anchored in local communities through jobs and other benefits, and that entire regions are threatened by phase-out policies. Other actors, such as unions, have ambiguous roles that may either facilitate a just transition or hamper it.

Political aspects of the carbon transition are therefore both central and complex. They need to be addressed and elucidated by IAMs through careful attention to the stakeholders' network of interests and influence. Our focus in this paper is on three central stakeholders: workers and firms, through job provisioning in different sectors and firms' profits, and the government. Political influence on policy design goes through votes and more marginally through lobbying.

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[14] Purchasing power is nonetheless a worry as VAT cuts rank high in expressed preferences.

3.3. Politics

While technology or economic cost-benefit analysis have largely been prioritized by IAMs, issues of political and social feasibility have largely been overlooked until recent years (Trutnevyte et al, 2019; Keppo et al, 2021). Still, the interplay between social dynamics and public support plays a central role in climate policy effectiveness that need to be better understood (Carattini et al, 2025; Beckage et al., 2020; Peng et al., 2021; Beckage et al., 2022). Opinion dynamics in environmental debates have been a focus of various studies using network analysis methods (Van den Bergh et al., 2019; Moore et al., 2022; Konc et al, 2022; Lipari et al., 2024). They explore how social interactions influence the diffusion of pro-environmental behaviour and political support for sustainability policies. They show that different mechanisms like social influence, opinion segregation or exposure to information about environmental change shape public opinions and shift them in support of transition policies.[15] While these studies integrate social and political systems by examining opinion dynamics within the electorate, they do not consider endogenous feedback within the macroeconomic system. Observational and experimental studies investigating the psychological and collective mechanisms of majority support to transition policies have multiplied in recent years (Sælen and Kallbekken, 2011; Beiser-McGrath and Bernauer, 2019; Fairbrother et al, 2019; Lévi, 2021; Fremstad et al, 2022).[16]

Various IAMs have also put more focus on the societal dimension of transitions and how the costs and benefits are distributed (Isley et al., 2015; Liu et al, 2016, Bertram et al, 2018, Fujimori et al, 2019). Close to our approach in this paper, ABMs have been augmented to study the political economy of climate policies emphasizing how voter preferences or public opinion shape policy outcomes (Lackner et al, 2025; Di Benedetto et al, 2024). These studies generally integrate a political module to simulate how voters or public opinion respond to climate policies based on their perceived costs and benefits. Agents evaluate policies based on their economic well-being, and those who perceive themselves as losers in the transition are more likely to oppose the policies. This feedback loop between policy impacts and political acceptability is critical for understanding the feasibility of decarbonization pathways. These models show that policies perceived as unfair or inequitable are more likely to face political backlash, which can derail the transition.

Di Benedetto et al. (2024) enriches the DSK model with a two-party election model (only one party supports transition policies) in which policy-makers impose economic policies under the control of voters. A high carbon tax leading to unemployment can make it difficult for a green party to stay in power and maintain its policy. As voters are influenced by both economic performance and climatic evolution, simulations show that climate policy can be totally or partially undone in case of political turnover. Nonetheless, strategically selected combinations of tax and redistribution policies can reduce political uncertainty and lead to more effective mitigation measures. Also highly relevant is Lackner et al (2024) which assesses the interaction of the DSK climate-macro system and the political sphere through the changes in public opinion about transitions policies in Europe. Public opinion is shaped by complex interactions determining individual economic conditions and perception of climate change, as well as by industry-led (mis-)information and social influence. Lackner et al (2025) employ an elaborate estimation procedure to calibrate the opinion dynamics model to Euro-Barometer panel survey data over 2011-2019. Their simulations show that carbon tax undermines public support for transition policy in the first place, mainly because of substantial

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[15] Douenne and Fabre (2020)'s estimations for example show that rather than ideological or partisan motivations, it is more a lack of knowledge and awareness of the potential benefits of climate policies that explains resistance to transition policies.

[16] See Kalbekken et al (2023) for a recent overview.

macroeconomic transition costs. Yet, an effective carbon tax can reach a positive public acceptance "tipping point" in the next steps as the fossil fuel-based industry's political influence vanishes. Simulations also show that public support can be increased from the inception of the carbon tax if well-designed revenue recycling strategies combining green subsidies with climate dividends are implemented in parallel with the tax.

Studying public support for policy is not only a matter of identifying majorities. Majority support is only crucial in specific situations like elections or binding public referendums. Instead, the level of public support is one of several factors influencing a policy's legitimacy and political feasibility (Kalbekken, 2023). In economic systems, the intensity of preferences and resistance from small, strongly interested groups can be equally important. The literature often acknowledges other sources of policy opposition, such as industry opposition or political parties, but rarely analyzes these actors simultaneously even though the balance of support and opposition from different organized actors may significantly alter transition trajectories and policy recommendations (Kalbekken et al, 2023).

To date, the IAM literature has only marginally investigated the political impacts of the transition costs for industrial stakeholders and how policy design should address them. Isley et al. (2015)'s extended DSK model for example shows that it is possible to create a political constituency for continued carbon pricing policy by recycling carbon tax revenues to firms proportionally to their market share. Meckling et al (2015, 2017) have also addressed the issue of industrial opposition to transition policies and the opportunity of creating policy incentives for broadening pro-transition coalitions to carbon-intensive industries.[17] Although highly relevant, this political coalition aspect is only marginally incorporated in our model. Policy scenarios in which industries would organize to compound majority voting for transition through lobbying should be assessed as they might lead to significant alterations of outcome trajectories.

3.4. Policy design

The literature on policy design has addressed the complex issues of the policy mix and policy sequencing. Mitigating global warming requires a combination of multiple complementary policies (Levin et al. 2012; Rogge and Reichardt, 2016; Kalbekken et al, 2023) for targeting with sufficient effectiveness a large array of societal goals including inequality reduction (Givoni et al, 2013; Bouma et al, 2019; Dubash et al, 2022). For instance, there is a consensus today on the idea that carbon taxation alone is not only ineffective but also self-defeating because of the risks of public rejection related to unfair transition costs. Associating to carbon tax revenue recycling in the form of subsidies, other tax cuts or green investments are conditions for effectiveness and acceptability (Carattini et al, 2018, 2019; Känzig, 2023).[18] In this spirit, Lackner et al (2025) analyse a large range of hybrid carbon tax revenue usage in an augmented DSK model and provide evidence of

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[17] Utilising the findings of empirical research which demonstrate that the provision of benefits to the economic winners of climate change policies fosters robust and effective policy-making, while the application of penalties to industrial polluters does not, Meckling et al. (2015, 2017) propose a policy design that could potentially generate the momentum for subsequent, more substantial action (taxation or regulation). This policy would see the formation of coalitions between carbon-reducing industries for the purpose of de-carbonisation through the implementation of green industrial policies. The costs of transition in terms of technological shift and production costs would be compensated for in a first stage, and a carbon pricing policy would be put in place before the implementation of these two policies in a third and final stage, once large public support has been gained.

[18] See Alkin (2024) for a theoretical case. See Douenne and Fabre (2020) for empirical evidence on France.

combinations of green energy subsidies and climate dividends that can lead to a desirable tipping point in public support for climate policy.

Whether or not labelled as a policy package, many countries are developing a broad climate policy portfolio where multiple policy instruments co-exist and interact. Kalbekken (2023) observes that while properties of a policy package might not be the mere sum of its constituent parts and interactions between the instruments might produce better or worse outcomes than separate actions, only few of the several studies of multiple policy instruments actually consider the interactions between the instruments.[19] Using a quasi-experimental approach to scan data on 1 500 climate policies implemented between 1998 and 2022 across 41 countries, Stechemesser et al (2024) confirms that well-designed combinations of price-based instrument, information, regulation and subsidies increase the effectiveness of each single policy instrument, with these combinations being heterogeneous across sectors (housing, transportation, energy).

Yet, it is generally emphasized that risks are likely to be higher – and public support more problematic – when transition policy takes the form of a complex policy mix whose effectiveness and fairness is affected by potential synergies and trade-offs between instruments (Kallbekken, 2023). The underlying mechanisms explaining these aggregate impacts therefore need to be investigated and elucidated in order to improve the design of effectiveness- and fairness-led policy mixes. IAMs and ABMs allow testing various policy mixes and delving into the mechanics of policy complementarity by focusing on subsystems dynamics. Various policy mixes can be assessed to fix the various macroeconomic risks prompted by the transition (Mercure et al., 2018; Klenert et al., 2018; Carattini et al., 2018; Lamperti and Roventini, 2022; Muth, 2023). Lamperti and Roventini (2022)'s DSK model various mixes of policies and concludes on the superiority of regulation and innovations policies over carbon taxation for limiting the macroeconomic risks of the transition. Likewise, Lamperti et al (2022)'s ABM characterizes various policies' trade-offs and identifies ensembles of industrial regulations and innovation policies supporting a rapid and orderly transition with a neutral impact on public finances.

Part of the recent literature has also elaborated on the idea that policy sequencing might maximize public support for policies while making them more environmentally effective (Meckling et al., 2015, 2017; Pahle et al., 2018; Kallbekken, 2023; Montfort et al., 2023; Di Benedetto et al, 2024). Experience also shows that while the public tends to overestimate the costs of policies *ex ante*, social acceptance generally increases once the policy is enacted (Carattini et al, 2019) and support for action can flip radically on the back of success (Peng et al, 2021). This suggests that tax implementation should be gradual, therefore preserving its effectiveness and raising its acceptability in the same move, all the more as people are convinced that costs are borne mainly by those most able to pay. Then, growing public perception of effectiveness will allow ratcheting up the tax (Meckling et al, 2015, 2017). This is confirmed by the conclusion of Bergquist et al (2022)'s meta-analysis of fifteen determinants of public opinion about climate change taxes and laws from 51 articles covering 33 countries and a total sample of 119,465 participants that among all factors, perceived fairness and effectiveness were the most important determinants of public support for transition policies, while knowledge and personal values actually don't matter.

Kallbekken (2023) claims that the literature should broaden its scope to include more types of policy instruments and policy packages, studying actual policies as well as more hypothetical ones. Broadening the scope for research on public support raises methodological challenges as the effect of policy packages is analytically less tractable, requiring increased methodological diversity. Conjoint analyses based on simulations (e.g., combining policy impact, policy support and policy design modules in an integrated model framework as exemplified by the studies above) are acknowledged as particularly useful to explore temporal dynamics (Kallbekken, 2023). Our paper

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[19] Exceptions are Fesenfeld et al (2020) or Wicki et al (2019).

contributes to this objective by simulating various policy scenarios and various sequencing of the individual policy tools within the policy mix.

3.5. Planetary boundaries, the needs approach and provisioning systems

In their analytical review of fifty macro-models, Van Eynde et al. (2024) identified feedback between different model components and evaluated the extent to which they covered 15 environmental and 21 social indicators. They also investigate how environmental and social indicators are linked to macroeconomic drivers in a smaller sample of 15 models representing the diversity in modelling approaches and indicator coverage. Indicator coverage is best for climate change, energy use, and land conversion, regarding the environment, with environmental impact being largely driven by GDP and agricultural production. As for society, they find that coverage is best for jobs, income (wages and inequality), and productivity, with social outcomes being largely driven by income per capita, government spending and governance. Based on their results, Van Eynde et al (2024) claim that modellers should rely less on economic variables as determinants of social and environmental outcomes and consider exploring new provisioning systems allowing their models to explore growth-agnostic ways of achieving a good life for all within environmental limits.

Various reviews of the IAMs have also underlined the lack of realistic damage functions for the economic impact of the physical consequences of climate change (Farmer et al., 2015; Van Eynde et al, 2024). Bio-physical patterns are paradoxically often absent from macro-models of transition, notably in terms of feedback (Farmer et al, 2015). In their recent analytical review of fifty macro-models, Van Eynde et al (2024) observe that very few models actually contain feedback from the environment to the economy or include biophysical limits. They explain this gap by the fact that the focus of these models on monetary flows logically limits understanding of the interconnections between environmental and economic systems that go through material damages. In these models, climate change is modelled to affect economic activity in certain sectors or in the whole economy as already emphasized by Rose et al (2017). The difficulties raised by the estimation of damage functions and feedback mechanisms and the risks of implementing them in the models is another explanation for the weak consideration of environmental feedback in existing ABMs.

Most ABMs use more or less aggregated economic outcomes like income, production, or employment. In the DSK model, these economic outcomes can be disaggregated in the consumption-good, production-good and energy sectors (Lamperti et al, 2018; Lamperti and Roventini, 2022).[20] By doing so, they stick to a production-centred vision of the society-economy-nature system. As basic needs are not modelled, this production-centred approach does not allow considering policy scenarios based on sufficiency or need-centred strategies of transition or incorporating social floors and planetary boundaries (Raworth, 2017) into the system dynamics (van Eynde et al, 2024). In line with recent recommendations by van Eynde et al (2018), we use the decent living framework (O'Neill et al, 2018) as the main benchmark for our individual and aggregate (socio)economic outcomes. This approach advocates for a *eudaimonic* need-centred understanding of human well-being, that is "*focusing on what one can do or be in one's life*" (O'Neill, 2006, 165), as opposed to the traditional *hedonic* subjective view, namely the sum of one's subjective experiences

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[20] Some versions disaggregate the economy in durable-good, non-durable good and energy sectors (Di Benedetto et al, 2024).

and satisfaction (Brand-Correa and Steinberger, 2017).[21] Decent living is widely used by the broad literature decomposing carbon or energy intensities by basic need for measuring energy requirements of well-being (Rao and Min, 2018; Millward-Hopkins et al, 2020). This framework allows shifting the goals of the economic systems from the production of goods to the provisioning of services, including energy services. This framework also allows connecting people's well-being (and therefore votes) to planetary boundaries through the satisfaction of basic-needs.

Out of the different dimensions of basic needs generally incorporated in multidimensional decent living indicators, four are covered by our analysis: Nutrition, Housing, energy and Mobility. For each dimension, we are able to match supply and demand sides by using Eurostat National Account Data (disposable income), population data (population by territory), household survey data HBS and a correspondence table between NACE (productive sector) and COICOP (consumption needs) for calibrating the consumption, production, employment structures of the economy.

4. The SEN-HARP model

4.1. Objectives, calibration and scenarios

Objectives

In this paper, we develop a biophysical AB-SFC model of the safe and just transition (Raworth 2017) that allows addressing various current hot topics for both research and policy.

First, we can assess the extent to which democracy and political alternation changes transition trajectories. This is an important question as democracy is sometimes presented as a hindrance for acting against climate change under the pressure of contradictory interests and political influence.

Second, our model goes beyond the traditional outcomes used for evaluating the effectiveness, fairness and responsiveness of transition policies: employment, income and consumption. The decent living approach consisting in evaluating the degree of objective basic need satisfaction instead of assessing subjective utility or happiness allows addressing the question of carbon transition within the planetary boundaries framework. The harmonious living variable, computed as a socio-ecological efficiency coefficient, is one of the main results of the SEN-HARP model. It encapsulates satisfaction of basic needs into the planet boundaries as defined by Raworth (2017) and allows translation into dimensional social floors. Voting behaviour is determined by individual and aggregate harmonious living outcomes.

Our model therefore assesses together the climatic, economic, and socio-political feasibility of various policy scenarios.

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[21] For more on the link between this approach and the capability approach, see O'Neill (2011).

Calibration

The model is micro- and macro-calibrated on the EU27 taken as an aggregate unified region. Base year is 2021-22 for calibration. The total time step is 25 years which allows simulating trajectories until 2050, that is the main deadline for decarbonization commitments (net-zero) made by the international community.

Macro-parameters have been calibrated by using Eurostat statistical resources. Consumption disaggregated by COICOP sector and territory has been estimated by using data from Eurostat National Account Data (disposable income), population data (population by territory), household survey data HBS for propensity to consume, budgetary coefficients by territory). A correspondence table between NACE (production sectors) and COICOP (consumption needs) classifications has been built. The methodology is available on demand. Data on finance is taken from various sources: European Investment Bank, Global Climate Finance and European Climate Finance. European Central Bank and Climate Policy Initiative. Wage data by sector NACE is taken from the Eurostat National Account data, the Labour cost survey by NACE Rev. 2 activity. Green wage premiums by sector have been estimated in Vona et al (2018) and EBRD (2023). Employment by sector NACE is taken from the European Labour Force Survey provided by Eurostat. Employment share in green and brown jobs by sector NACE is taken from Vandeplas et al (2022) and Maldonado et al (2024). Cross-classification of fixed assets and Gross Fixed Capital Formation by NACE industry and by asset type are taken from Eurostat National Account Data. Estimations of shares of green and brown capital are taken from ECB (2023). Profits and output by sector NACE are estimated from National Account Data provided by Eurostat.

Micro-parameters of behaviour (propensities, elasticities) have been calibrated by using parameters estimated by relevant micro-empirical studies on EU27. Lexicographic preferences are based on various sources including Eurostat[22], European Environment Agency (2024). Income elasticities by COICOP sector are taken from Temursho and Weitzel (2024). For parameterizing the model's damage function, we use the elasticities of consumption and income to warming estimated on EU27 by European Economic and Social Committee (2023). Parameters of investment functions are taken from estimated coefficients of UE firms investment function conducted by European Investment Bank (2024). Perceptions of constraints on European firms are also taken from the Report on investment 2022-23 published by the European Investment Bank (2024). More details on the procedures and on the sources of parameters can be shared on demand.

Policy scenarios

Besides the baseline - business as usual - scenario, we simulate three other policy scenarios: innovation and market-based, augmented Green Deal, and Harmonious living.

The **innovation and market-based scenario** (Green_Deal) associates policies of carbon pricing and use of tax revenues to provide support to green innovation. This roughly amounts to the version 1 of the European Green Deal[23], that is the policy conducted for the last decade by European authorities and national governments.

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[22] https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=608042&utm_

[23] Following its establishment in December 2019, the European Green Deal has undergone several revisions in 2024, achieving significant legislative milestones, including the establishment of the Nature Restoration Law, the Right to Repair Directive, and the Net Zero Industry Act. Concurrently, the European Commission is currently under pressure to consider a series of requests. These requests include the streamlining of requirements (e.g. CSR Directive), the

The **augmented Green Deal** represents an extension of the previous policy package. We simulate three alternative versions of the augmented Green Deal. Aug_Green_Deal_1 constitutes a Green Deal augmented by an active and offensive industrial policy. The objective of this policy is to accelerate European reindustrialisation in green activities and to phase out carbon industries. This approach is to be implemented as a first step before ratcheting up carbon pricing and norms. This will occur once industrial actors have joined the decarbonisation coalition. Aug_Green_Deal_2 is the Green Deal, augmented by redistributive measures in favour of transition losers (i.e. consumers and industries) in order to compensate for losses incurred due to high carbon prices and structural change towards green activities. Aug_Green_Deal_1 corresponds to a supply-led transition scenario while Aug_Green_Deal_2 is more consistent with a demand-led transition scenario. The maximalist Aug_Green_Deal_3 combines demand- and supply-led policy scenarios, with a view to investigating the fiscal and monetary space for making this combination feasible.

Harmonious Living (HL) is a pioneering strategy that prioritises decent living and environmental targets over income and technology targets. The scenario articulates carbon pricing and norms with revenue recycling through substantial investment in public and private provisioning systems that support low-carbon basic needs satisfaction and positive loops between nature, the economy and society. This scenario corresponds to a breakthrough scenario, insofar as it implies a deep revision of the European welfare model, together with a post-growth orientation. If implemented abruptly, this scenario may well provoke opposition from large parts of the European population. A crucial aspect to explore here is the policy mix and sequencing that might render this breakthrough scenario both economically and politically feasible.

4.2. Biophysical Agent-Based Stock-Flow Consistent modelling

The literature displays several papers that integrate agent-based and stock-flow consistent modelling. Caiani et al (2016) introduced the main advantages of integrating the two methods. In a seminal model, Dosi et al (2010) engage a discussion between micro and macroeconomics, through a mixed Keynesian-Evolutionist approach. Our model builds on this and uses Stock-Flow Consistent modelling. The Stock-Flow Consistent modelling technique (Godley and Lavoie 2001, 2007) has been specifically developed to keep track of all monetary flows and stocks, and is grounded in rigorous national accounting.

Agent-Based Stock-Flow Consistent (AB-SFC) modelling emerged as a credible technique in the 2010s (Chiarella and Di Guilmi 2013), but still lacks comprehension of the interactions of human societies with Nature, despite cutting edge contributions in terms of policy recommendations, such as in the EURACE model (Dawid et al 2012, Raberto et al 2019).

On that note, the specific field of macroeconomics was further enriched when Dafermos, Galanis and Nikolaidi (2018) included biophysical variables (energy and matter) in an SFC model. The authors accounted for novel phenomena (in economic modelling) such as the entropy principle (Georgescu-Roegen 1971), creating their “Stock-Flow-Fund” approach, thus considering Georgescu-Roegen’s “flow of funds” concept. The application of the Second Law of Thermodynamics to economic systems reveals that economic activity is fundamentally constrained by the irreversible degradation of energy and an inescapable dependency on matter. In a similar but less

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relaxation of regulations (e.g. CAFE regulation from French automotive industry), and the enhancement of EU support and trade protections to facilitate green investments (e.g. green steel).

comprehensive manner, Lamperti et al (2018) develop an agent-based integrated assessment model (AB-IAM) following the DSK (Dystopian Schumpeter meets Keynes) model with a temperature equation and stochastic damage function.

However rich the contemporary developments in economic modelling, Van Eynde et al (2024) consider that the field still lacks the ability to represent social and political phenomena in a consistent way. Taking stock of these contributions and shortcomings, our model inscribes itself in this body of literature, aiming at contributing to filling this gap.

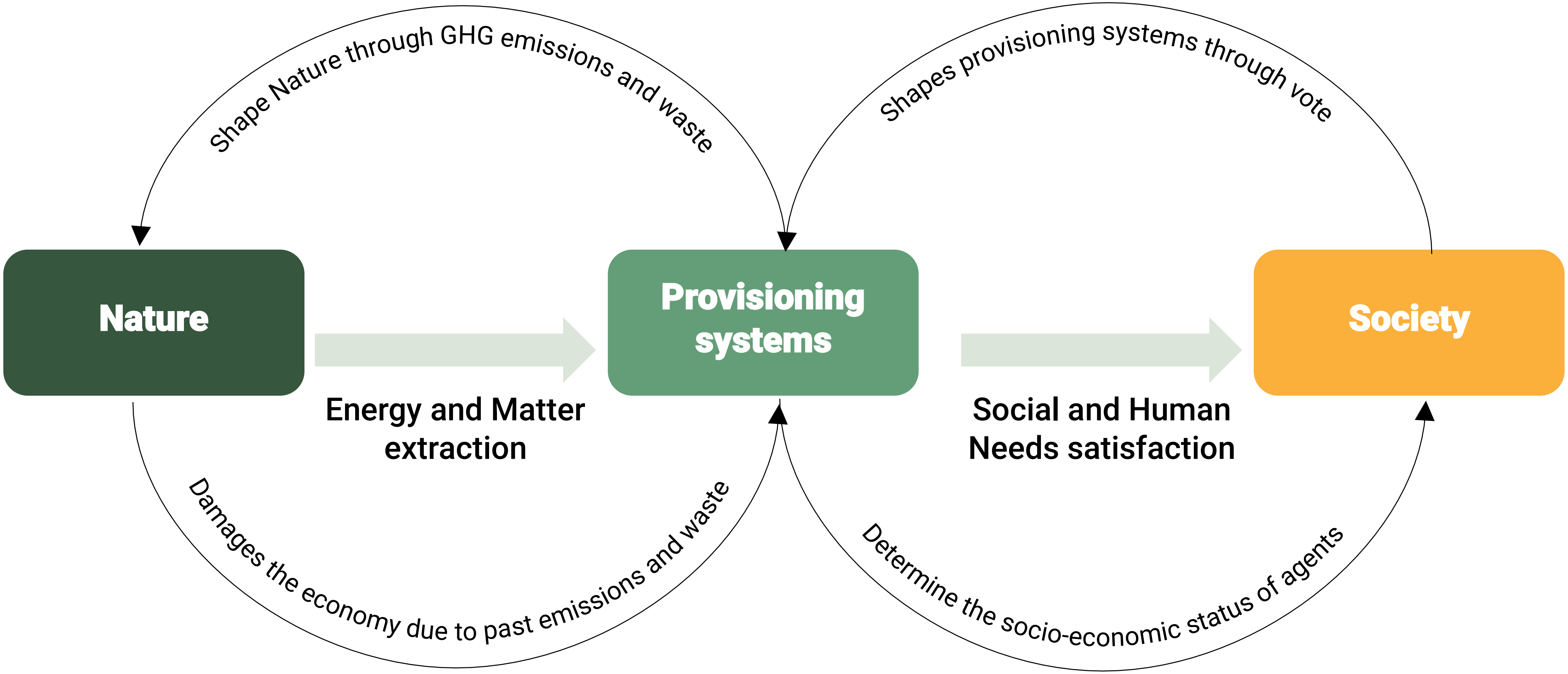
Our biophysical AB-SFC model thus displays political behaviour through a voting equation, and political responsiveness on the parties' end. Di Guilmi, Galanis and Proano (2023) have developed an ABM displaying a voting function with bounded rationality typed agents, and political science literature also comports political ABMs (Fowler and Smirnov 2005, Duggan 2009, Fieldhouse et al 2016). The novelty in our model lies in the fact that we base it on the agents' needs satisfaction, and that we integrate it to a complex macroeconomic framework with biophysical variables and an atmospheric temperature function that creates endogenous damages.

Besides the literature on modelling itself, our model builds on a multifaceted theoretical background, between provisioning systems and social metabolism (De Molina and Toledo 2014). It was built around the need to understand the qualitative reshaping of provisioning systems, i.e. the lowering of our material footprint accompanied with an increase in social and human needs satisfaction. This will allow us to evaluate the socio-ecological efficiency of the economy for each scenario, complying with the need of "systematically assessing and comparing provisioning systems and their stock-flow-service efficiencies and outcomes" (Plank et al 2021, p.11).

More generally, social provisioning consists in "the process that provides the flow of goods and services required by society to meet the needs of those who participate in its activities" (Lee 2005, p.30). Evolving provisioning systems intrinsically mean different mutual relations between economies, societies and nature. Indeed, as they are primarily social operations, provisioning processes cannot by essence remain still. Jo and Todorova (2017) state that provisioning varies over time, as, among other factors, employment, welfare, technology and income evolve. We consider the biophysical AB-SFC approach to be an adequate method to study these processes.

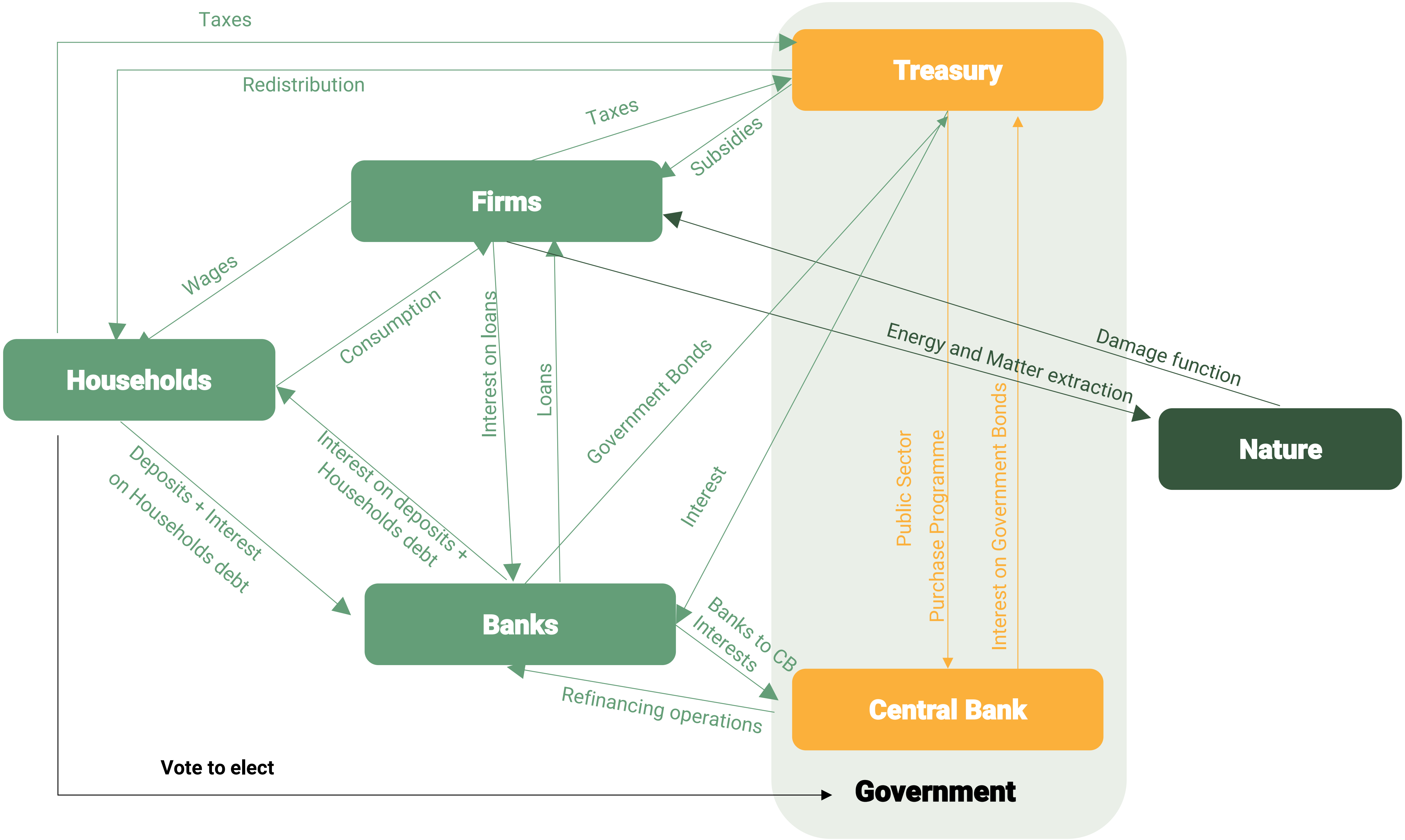
As figure 1 shows, SEN-HARP aims at representing the interactions between Nature, society and the economy under the lens of the provisioning systems approach. According to this conception, the economy is a matrix that transforms energy consumption and matter extraction into needs satisfaction. Society has an influence on the economy (i.e. provisioning systems) through the ability of agents to vote for two different parties, that will implement opposed transition policies, thus reshaping provisioning systems dynamically. The economy – seen as a web of provisioning systems, has an influence on Nature due to socio-metabolism processes (De Molina and Toledo 2014): in order to function, the economy emits greenhouse gases and generates waste. The subsequent degradation of ecosystems engenders damages on the economy. These are mainly dependant on temperature rises overtime. Finally, provisioning systems determine many socio-economic outcomes for individuals, as well as the satisfaction of their needs. This, in turn, has an important influence on their voting behaviour.

Figure 1: SEN-HARP as a representation of the provisioning systems approach



As shown in figure 2, even though we conceive the economy as a means rather than an end in itself (i.e. an object that allows needs satisfaction under biophysical constraints), its depiction in SEN-HARP remains complex.

Figure 2: The monetary and biophysical flows in SEN-HARP



The following tables present the monetary flows and the stocks to which they contribute. Appendix 1 provides an overview of the monetary flows, or social accounting matrix, while Table 3 presents the balance sheet matrix of SEN-HARP.

Table 3: the Balance Sheet matrix of SEN-HARP

	HOUSEHOLDS	FIRMS	BANKS	TREASURY	CENTRAL BANK	TOTAL
Fixed capital		K				K
Savings	S		-S			0
Household Debt	-HHD		HHD			0
Loans		-L	L			0
Green Bonds		-GB	GB			0
Government Bonds			Gov_B	-Gov_B		0
High-Powered Money			HPM		-HPM	0
Total	**0**	**K**	**0**	**0**	**0**	**K**

The interactions of the biophysical, economic, and political modules, as well as the monetary stocks and flows are determined by behavioural equations. The subsequent subsections will explicate the construction of these equations.

4.3. Industrial dynamics and technology

Technological change and industrial dynamics are modelled as evolutionary processes. Several key characteristics are essential for such a modelling (Dosi and Nelson, 2010). First, technological progress follows distinct paradigms that define the heuristics of innovation within industries. These paradigms guide search processes, shaping incremental and radical innovations. Second, innovation is cumulative, meaning past technological choices influence future developments. This leads to path-dependent evolution where initial conditions and historical events shape long-term industry structures. Third, firms differ in capabilities, resources, and learning processes, leading to persistent heterogeneity in productivity and innovation performance. Some firms follow exploratory, experimental learning, while others rely on incremental refinements. Fourth, industrial dynamics are characterized by imperfect competition, where firms continuously innovate to maintain competitive advantages. Market selection mechanisms filter firms based on efficiency, technological capabilities, and strategic positioning.

Contrary to general equilibrium models in mainstream economics, technological and industrial evolution involves constant disruptions, uncertainty, and non-linear growth patterns. Technological evolution is embedded in broader socio-economic structures, where institutions, policies, and regulations shape industry trajectories.

Following Brouillat & Saint Jean (2020), we consider that firms develop, produce, and sell to customers, products based on particular technologies. Two types of product-related technologies are considered: T1 (brown tech) and T2 (green tech). Customers buy and use one type of product (T1-based or T2-based). Each family of technology (T1 or T2) is able to provide a wide range of applications. However, they radically differ in their capacity to provide high quality performance and to contain harmful substances with adverse health and/or environmental effects, thus partly determining different prices (T1 and T2 belong to different technological paradigms).

In a Lancasterian way (Lancaster, 1966), products are depicted as multi-characteristic technologies. Each product is described by four attributes: technical quality, price, environmental quality at the production level, and environmental quality at the use level. *Technical quality* is a multi-criterion dimension reflecting the performance of the technical attributes of the product during the use phase. The higher the value, the better the technical quality. *Price* relates to productive efficiency which represents the firm's capacity to efficiently use and combine resources and material inputs (productivity, yields, and delays) when producing. The higher productive efficiency is, the more efficient the firm, the lower the price should be[24]. *Environmental quality at the production level* reflects the impact on human health and the environment during the manufacturing process. The lower this attribute is, the lower the environmental/health risk for workers. *Environmental quality at the use level* refers to the impact on human health and the environment during use by the consumer (and even beyond, during end of life). The lower this attribute is, the lower the environmental/health risk for direct users.

Depending on the technology embedded in the product (T1 or T2), differences will appear in terms of what is currently achievable (initial values) and potential of progress (technological frontier). In the model, initial values as well as extreme limits for each of these variables are set to account for these differences. T2 being a greener technology, its outer limits regarding environmental and health characteristics are better than the limits of the brown technology T1. However, T1 and T2 also differ in terms of initial values: T2 is an emergent technology and is initially more expensive and less

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[24] We also consider that firms will apply a mark-up rate over the production costs. The mark-up rate changes over time by taking into account the individual market share of the firm and the industry concentration.

performing in terms of technical quality than T1, but it is much better in terms of safety and polluting emissions.

In the context of regulatory or societal pressures to preserve the environment and public health, the emergence of novel paradigms, underpinned by diverse core technologies or employing innovative architectures (T2), has the potential to challenge established techniques (T1). However, when evaluated in terms of the preferences of established markets, these challenging technologies frequently exhibit inferior characteristics (higher costs, new unfamiliar functions). Consequently, they are initially adopted in new or remote market segments where preferences are more closely aligned with the capabilities of the new technology (Christensen & Rosenbloom, 1995). In the present model, a decision that firms must make in relation to innovation is whether to adopt T2 if it does not form part of their existing portfolio (Table 4). Since new competencies are generally required by new technological paradigms, firms will first consider the knowledge stock they have accumulated on T2. The decision of firms to adopt T2 is then contingent on their attacker profile and their budget to overcome the switching costs.

Table 4: Decision process for T2 adoption

STEP 1	Each firm compares its accumulated knowledge stock on T2 (K) with a firm-specific threshold. If K is above the threshold, then the accumulated knowledge is considered as sufficient to adopt T2 and the firm moves to the second step; if not, the supplier relinquishes to adopt T2 in the current period.
STEP 2	The firm compares the total market share of T2 (MsT2) with a firm-specific threshold. If MsT2 is above the threshold, then the supplier considers that T2 has sufficiently diffused in the market and the firm moves to the third step; if not, the firm renounces to adopt T2 in the current period.
STEP 3	The firm compares his budget with the switching costs related to T2. If his budget is sufficient to bear the switching costs, then the firm adopts T2; if not, he relinquishes to adopt T2 in the current period.

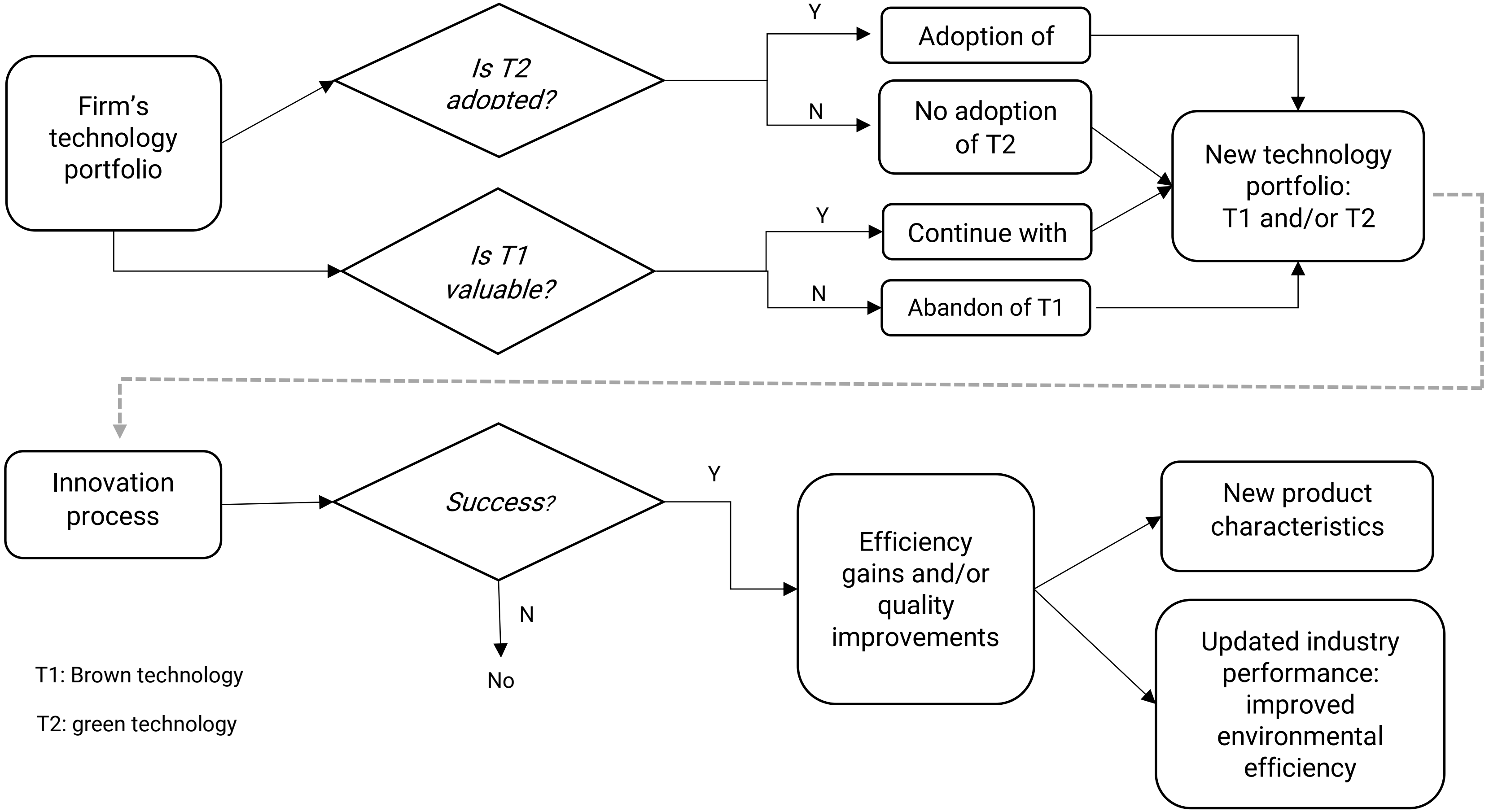
Based on their technology portfolio, firms decide to invest in R&D and develop improved or new product characteristics following a sequence of steps described in Table 5.

Table 5: Steps in the innovation process

STEP 1	Firms allocate budget between improving T1 and developing T2
STEP 2	Depending on the R&D investment allocated to the technology, firms have a certain probability to succeed but can also fail. In formalised terms, success occurs for technology Tk (k=1 or k=2) if the following condition is satisfied: $1 - e^{-\alpha \times RD_{Tk,i,t}} \geq u(0,1)$
STEP 3	In case of success, a new value is obtained for each product characteristic, depending on the efficiency of the R&D activity and on the distance to the technological frontier associated with each product characteristic. The new value for the product characteristic X follows the equation: $X_{k,i,t} = X_{k,i,t-1} + \beta_X \times u(0,1) \times \left(X_{max_k} - X_{k,i,t-1}\right)$

As illustrated in Figure 3, the innovation module of the model is summarized.

Figure 3: The innovation module



Heterogeneous firms compete with each other and obtain different returns. Profit opportunities and innovation drive entry of new firms while high costs, debt, or low profitability force exit of firms. The entry and exit of firms thus play a fundamental role in shaping industrial dynamics. In the model, new firms enter the market based on technological potential. Entry is positively correlated with unexploited technological opportunities. If successful, new entrants imitate incumbents but may overperform or underperform due to differences in absorptive capacity. Firms exit the market when their budgets turn negative. The model assumes that if a supplier's financial situation deteriorates below a threshold, they leave the market.

4.4. Households

As outlined in Section 2, the classification of the 200 households into two distinct categories, namely urban and rural, is a relevant consideration. In the SEN-HARP model, this distinction is not determined by behavioural equations but rather by initial values. To illustrate this, the allocation of disposable income is shown to vary according to the transportation costs faced by individuals, contingent on their geographical location, whether residing in a rural area with individual cars or an urban environment with more developed public transportation services.

Households are distinguished on the basis of two further criteria: their skill level (low-skilled or high-skilled) and their employment status (unemployed, employed in a green or brown sector, state-guaranteed employment, professional retraining, cf. Table 7). Both of these criteria are instrumental in determining their income.

Table 6: The seven employment status in SEN-HARP

STATUS	MEANING	INCOME
Unemployed	Unemployed individual on the job market.	Unemployment benefit
Low-skilled brown job	Low-skilled worker in a brown job.	Base wage (> to minimum wage)
Low-skilled green job	Low-skilled worker in a green job.	Base wage (+/- green premium)
High-skilled brown job	High-skilled worker in a brown job.	Base wage (+ skill premium)
High-skilled green job	High-skilled worker in a green job.	Base wage (+skill and green premium)
Reskilling trainee	In training to go from low-skilled to high-skilled during a two-period time.	Unemployment benefit
Job Guarantee worker	Transitory in the Job Guarantee Programme until hired by a private company.	Minimum wage (> to unemployment benefit)

On the basis of the income they receive, households then start a consumption process, which implies flows (consumption out of disposable income) and stocks (evolution of savings and potential undertaking of household debt) (see Table 7).

Table 7: Decision process for the monetary value of consumption and household debt

STEP 1	Households have a disposable income, composed of their income, fiscal transfers, financial income (mainly interests on deposits), diminished by taxes and the debt service they owe to their bank. They first have to spend the amount of their base consumption, which is identical for all households, composed of agricultural, housing, energy, and transportation goods and services, and the monetary value of which increases over time with inflation.
STEP 2	If their disposable income plus past savings are lower than the monetary value of base consumption, meaning that their savings dried up, they take on debt at the bank of their choice (see section 3.4) to finance the remaining part, and their consumption process stops here. If $BC > Y_D^i + S_{-1}^i$, then $\Delta HDebt^i = BC - Y_D^i + S_{-1}^i$ Else, $C^i = BC + \alpha_0^i (Y_D^i - BC) + \alpha_1^i S_{-1}^i$
STEP 3	If their disposable income plus past savings are higher than the monetary value of base consumption, they allocate part of the remaining part of their disposable income to consumption, following a traditional Keynesian consumption function displaying a propensity to consume disposable income and past savings. The result at this stage is a purely quantitative monetary value. The remaining part of their disposable income goes into their savings.
STEP 4	Finally, depending on their individual randomized preferences, they allocate the monetary value they determined et step 3 between the six sectors of the economy (agriculture, energy, housing, transportation, industry, technology and communication).

Once consumers allocate their disposable income between different sectors (food, energy, housing, transportation etc.), they have to decide which type of product (T1-based or T2-based) to buy. The model uses the “Take-the-Max Rule”, proposed by Gigerenzer & Goldstein (1996), as a heuristic decision-making strategy. Each consumer chooses between options by comparing their most important attribute first and selecting the one with the highest value. It is a fast and frugal heuristic, meaning it simplifies decision-making by using minimal information. Unlike traditional utility models that weigh all attributes, it ignores less important product features, reflecting bounded rationality where agents use simple rules for effective decisions rather than complex optimization. The decision process for purchase (Table 8) is similar to the one used in Brouillat & Saint Jean (2020).

Table 8: Decision process for purchase

STEP 1	In each sector, each consumer randomly chooses one product characteristic. The probability of a characteristic being chosen is proportional to the consumer-specific preferences of technical quality of products, price, environmental quality at the production or at the use stage.
STEP 2	The consumer scans all the products marketed by each firm and gives them a score proportional to the selected characteristic in the previous step. A score function is used for characteristic X such as: $U_{k,i,t} = \left(X_{k,i,t-1} - A\right) \times \left(Ms_{i,t-1} + u(0{,}0.1)\right)^{e}$ where A is a technical parameter used only to avoid negative terms in the calculation; $u(0,0.1)$ is drawn from a uniform distribution with values between 0 and 0.1 to avoid U = 0 when the market share (Ms) of the product is null. The parameter e is indicative of a bandwagon effect reflecting imitation behaviours.
STEP 3	The consumer randomly selects one product. The probability of a product being chosen is proportional to its score U.
STEP 4	Each consumer is also supposed to be limited by economic and technical constraints, so we assume a reserve price and a minimum technical quality requirement for each client. If the selected product does not satisfy one of these constraints, it is discarded and the consumer goes back to Step 2 to select another product. If there is no product that satisfies these constraints, the customer does not buy and does not own any product during the period.

A realistic consumer decision rule for keeping or leaving a supplier is used in the model (Table 9). Key consumer criteria such as satisfaction with the last purchase, maintained affordability (price considerations) and no negative shocks leading to a bad experience explain why consumers stay loyal out of habit. If circumstances change, a consumer might look for alternatives and might switch to a competitor (del Campo et al., 2016).

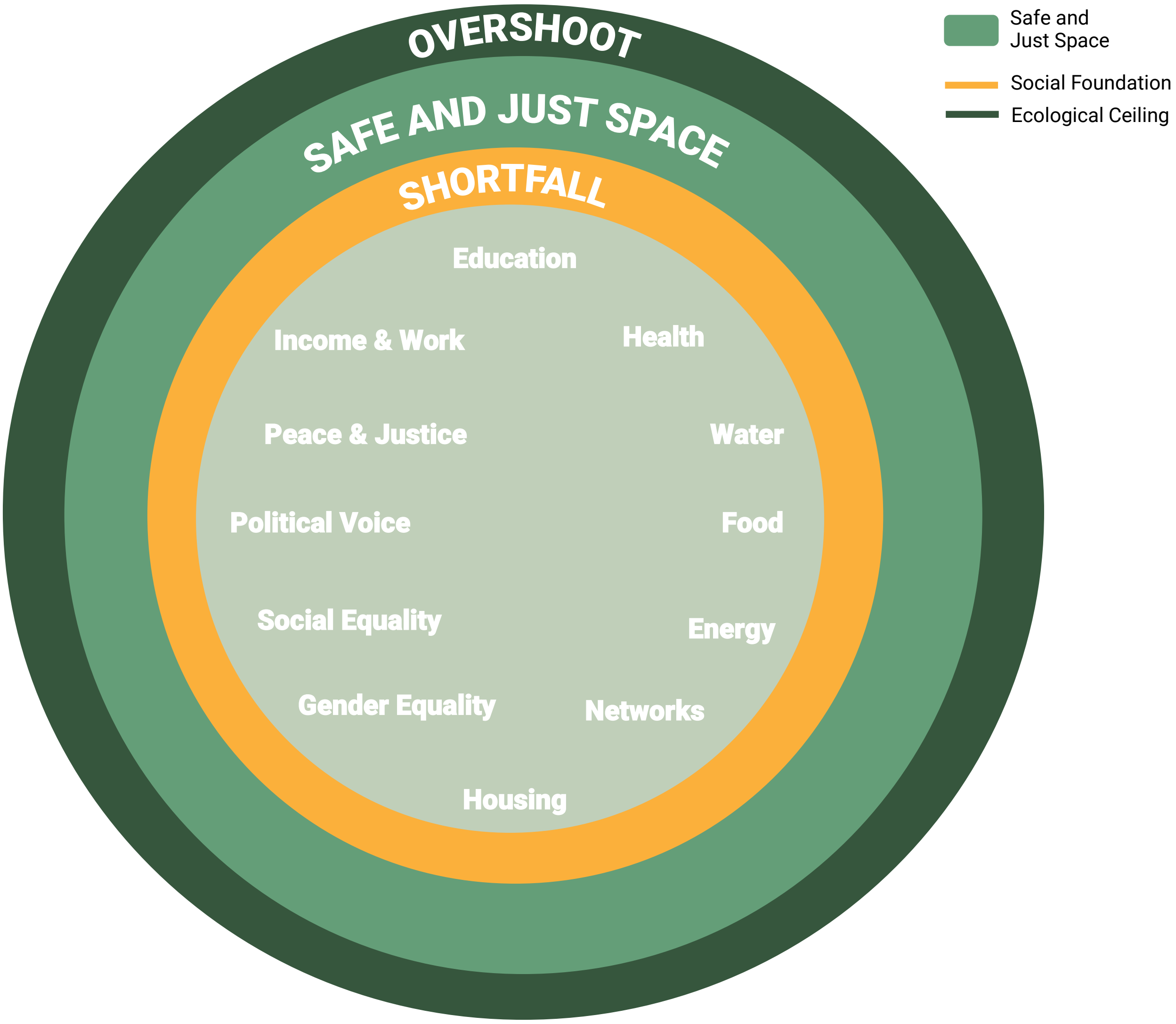
Table 9: Decision process for keeping or leaving a supplier

STEP 1	The consumer randomly chooses one product characteristic with probabilities proportional to its specific preferences.
STEP 2	The consumer assigns a score to the product marketed by its current supplier. This score is negatively dependent on the price and positively dependent on the performance feature selected in Step 1. The consumer compares this score with the best industry score achieved. The latter is weighted by a coefficient allowing a certain zone of tolerance according to which a consumer may accept variation within a range of performances. If the score of its current supplier is below the weighted best industry performance, the consumer leaves its current supplier and chooses another one through the purchase procedure; otherwise, the consumer keeps the same supplier.

Beyond consumers: households’ needs satisfaction

Following the provisioning systems approach, we model needs satisfaction following the safe and just space framework of the doughnut (Raworth 2017) represented in figure 4.

Figure 4: the doughnut (adapted from Raworth 2017) as a theoretical foundation for SEN-HARP



We primarily focus on three elements: ability to satisfy basic needs, perception of inequalities, and access to public services. The growth rate of the needs satisfaction index is given in the following equation:

$$Needs_{gr}^{i} = hum_0 \left(1 - \frac{BC}{Y_D^{i}}\right) + hum_1 \frac{Y_D^{i}}{Y_D^{mean}} + hum_2 \; PubServ_{Access}^{i}$$

The first element is the ratio of base consumption, *which is the same for all agents*, relative to their individual disposable income. It captures elements such as food and water security, dependency on transportation, housing security, or energy and heating security. The second element relates to the perception of inequalities, and roughly captures the social equity and income and work basic needs from the doughnut, through a comparison of the agent's disposable income relative to the mean disposable income in the economy. Finally, the access to public services, such as health and education in the doughnut framework, is captured by a microeconomic variable of access to public services.

Benefiting from public services, and therefore enhancing the fulfilment of needs such as health and education (Raworth 2018), is of crucial importance. However, access to public services is not guaranteed by public spending alone. The specific question of unequal access to public services has been studied for the urban environment through the lens of spatial justice theory (Setianto and Gamal 2021). Van Vulpen and Bock (2020) argue that spatial justice can be applied to non-urban territories. Following their view, we represent spatial justice through the following equation, which includes the share of transportation consumption in disposable income, as well as redistribution transfers from the State, in the sense that accessibility through transportation and transfers from the State are crucial in determining access to public services (idem). This equation, multiplied by the level of spending in public services by the State, gives the individual level of access to public services of every household.

$$SpJ^i = sp_0(sp_1\,(\frac{C_T^i}{Y_D^i}) + sp_2 Red)$$

4.5. Banking system and endogenous money

The model displays endogenous money (Moore 1988), thus money is created *ex nihilo* by banks, and the economy is a monetary economy of production (i.e. money is an advance on production). However, banks are not perfectly accommodating, as in Le Héron (1984, 1986), who extended Keynes' theory of the liquidity preference to banks, with the consequence of adding a constraint to monetary creation: thus, banks overcome their role of mere financial intermediaries to become active forces in the determination of capital accumulation. Mehrling (2010) concurs, stating that monetary creation materializes itself in the "money view", under a liquidity (finance view) and a solvency (economic view) constraints. Building on that, we introduce later an ecological credit control policy, which essentially aims at adding a state-managed sustainability constraint (environmental view, Funalot 2024) to monetary creation.

Loans are granted to firms and households on demand, however credit constraint variables apply both in price (on the interest rate charged) and in quantity (the amount of the loan granted) and are defined simply after Le Héron and Mouakil (2008) in a manner that the higher the leverage of the firm asking for a credit in respect with a target leverage considered by the bank as safe, the higher the credit constraint:

$$\Delta L_f^i = L_D(1 - lr_b^f)$$

$$i_L^f = i_{CB} + \mu_b^b + lr_b^f$$

$$lr_b^f \;=\; \chi_b\,(lev_{-1}^f - lev_b^t)$$

Table 10: Firm's decision process on banks

STEP 1	The firm checks that its current bank did not go bankrupt. If it did, it needs to find another bank.
STEP 2	All firms check the interest rate given by banks. If the bank of a given firm offers an interest rate lower than the mean interest rate on the market, the firm keeps the same bank.
STEP 3	Otherwise, the firm will look for another bank on the market. If it finds another bank with a cheaper interest rate, it will switch banks and bring its past loans along.

Following Le Héron (2020), we consider banks to be "entrepreneurs in the money creation process" (p.146). Thus, we introduce in the model their animal spirits in a similar but simplified manner as Chiarella, Di Guilmi and Zhi (2020), by endogenizing χ_b, which represents the state of confidence of bank "b". When the bank is optimistic (pessimistic), χ_b is low (high). The probability to switch from one state to the other is given by the following equation, where op represents the general state of confidence in the banking system, $(fail_{-1} - fail)$ gap between the number of failures of firms at the previous period and failures at the present period, and d a constant to include potential institutional factors.

$$\chi_b \;= \chi_0 op + \chi_1(fail_{-1} - fail) + d$$

Table 11: Household's decision process on banks

Step 1	We assume that a household will ask for a credit at the bank where they hold their deposits. If their bank failed, the household will have to find a new bank. If not, the household will still look around on the market.
Step 2	The household will look for a bank with a higher interest on deposits, and a lower rate on household debt. We also assume a preference for green banks. Thus the household will scope all the banks one by one. When they find one that offers a higher level of financial income (interest on deposits minus interest owed on loans) and that displays a higher green asset ratio, they will choose it.
Step 3	If both conditions are not satisfied, they keep their bank. If both conditions are satisfied, they switch banks, they take their deposits back and give them to their new bank, and their new bank buys back their loans to their former bank.

Finally, banks earn profits composed of the interest perceived on loans to firms and households, the distributed profits of firms, minus potential bank penalties imposed by the State and interest paid on deposits, as well as interest paid on reserves at the ECB. Banks profits are fully redistributed to a small class of capitalist households.

4.6. The political system: endogenous political responsiveness

The model also includes a bidimensional political module, represented by two political parties (one is pro-transition and the other is against) that voters can elect once every five years (five time periods in our model).

The voting behaviour equation draws on the outcomes of the economic module through the evolution of the human needs index introduced in section 4.4.

Our agents are not purely maximisers of their utility (which would correspond here to the satisfaction of their needs), in the sense that following Di Guilmi, Galanis and Proano (2023), we take the bandwagon effect into account. We do so through the ratio of voters who switched towards a party to the total voters of this party at the previous period. Finally, we consider inertia in voting patterns: an agent will be more likely to vote as they have voted before.

$$Vot \; = \gamma_0 (Hum^i - Hum^i_{-1}) + \gamma_1 x + \gamma_2 Vot^i_{-1}$$

This equation gives the probability for an agent to vote for a pro-transition party. A random draw is established at each period, and if the number is lower than the value taken by Vot, the agent will vote for the pro-transition party. Otherwise, the agent will vote for the anti-transition party. This method leaves room for unpredictable voting behaviour, which could be explained by variables not considered in the model, such as identity, immigration, religion, or climate-sceptic ideology.

The authors identify that the rural areas represented by rural households consist in what Rodriguez-Pose (2020) qualifies as “places that don’t matter”. In accordance with the findings of Rodríguez-Pose, Terrero-Dávila and Lee (2023), it is hypothesised that the "left-behind" regions exhibit low or stagnating regional GDP per capita, a phenomenon which the author identifies as a contributing factor to the rise in populism. Furthermore, Guriev and Papaioannou (2022) posit that the prolonged exposure of these regions to international trade and technological progress – through major transformations of the labour market - has been a contributing factor to the rise of populism. We consider this to be the initial stage of the model.

Then, the evolving situation of agents shapes their voting behaviour.

The model works as follows: once every 5 periods, the model computes the voting behaviour of agents, and the party that obtains the majority gets to implement its programme for the duration of the mandate. We thus assume political responsiveness. At the end of the mandate, households are called to the voting booth again. If the government in power is re-elected, it pursues its programme. Otherwise, the opposition takes over and another policy package is implemented.

4.7. The biophysical module: accounting for matter, energy and endogenous temperature trajectories

Before presenting the interactions between the socio-economic system and the biosphere, we shall present the biophysical elements present in our model. Basically, two types of environmental factors are introduced: matter, and energy. These are the inputs, and with respect to the first and second laws of thermodynamics (Georgescu-Roegen 1971), the outputs are waste, Co2 emissions, and a raise in the socio-economic stock. These principles are gathered in the following table (reproduced from Dafermos, Nikolaidi, and Galanis 2017).

Table 12: The stock-flow-fund dimension of the model

	Material Balance	Energy Balance
Inputs		
Extracted Matter	M	
Non-Renewable energy	CEN	EN
Renewable energy		ER
Oxygen	O2	
Outputs		
Industrial Co2 emissions	-EMIS_IN	
Waste	-W	
Dissipated energy		-ED
Change in Socio-Economic Stock	-D(SES)	
Total	**0**	**0**

For instance, in this table, the second law of thermodynamics is represented, as the inputs consist in low entropy energy, whereas the outputs are high-entropy energy (like thermal energy).

4.7.1. Matter and energy, waste and GHG emissions

Matter

The evolution of the variables introduced in table 12 is organized through a number of equations, that we will now present.

$$MY = \mu Y$$

With MY the matter use induced by the level of production at each period, and μ being the matter intensity of production. The final flow of matter drawn in the biosphere is obtained by subtracting recycled discarded socio-economic stock DEM, as the following equations show:

$$M = MY - REC$$

$$REC = \rho DEM$$

The discarded capital is defined in the following equation, as the material amount of the depreciation of physical capital, and the destruction of durable consumption goods:

$$DEM = \mu(\delta K_{-1} + \xi DC_{-1})$$

The socio-economic stock is augmented with annual production and diminished by discarded capital:

$$SES = SES_{-1} + MY - DEM$$

Waste plays an essential role in the model. It is defined following table 12, as the sum of inputs of the material balance, diminished by the outputs.

$$W = M + CEN + O2 - EMIS_{IN} - \Delta SES$$

The carbon mass of non-renewable energy CEN is defined as the industrial emissions divided by car, which is the conversion factor of carbon emissions to Co2 emissions.

$$CEN = \frac{EMIS_{IN}}{car}$$

The part of oxygen present in Co2 emissions is defined as the current emissions minus the carbon mass: in other terms, among the emissions of Co2, we subtract the carbon part:

$$O2 = EMIS_{IN} - \mathrm{CEN}$$

As for waste (W), only a part of it is hazardous, that is to say harmful for the biosphere or the human species.

$$HWS = HWS_{-1} + haz.W$$

The following variable is expressed as a ratio between hazardous waste (in Gigatons) and earth surface (in millions Km2).

$$hazratio = \frac{HWS}{SURF}$$

The level of reserves of matter is given by its past stock, the resources converted in reserves, and negatively, the matter extracted.

$$REV_M = REV_{-1}^{M} + CON_M - M$$

With:

$$CON_M = con_M RES_{-1}^{M}$$

Available material resources are defined as follows:

$$RES_M = RES_{-1}^{M} - CON_M$$

Finally, scarcity in material resources is introduced through a parameter depM, defined as a ratio of matter extracted to the reserves of the past period:

$$dep_M = \frac{M}{REV_{-1}^{M}}$$

Energy

Energy required for production is simply defined as an energy intensity parameter ε multiplied by the output:

$$E = \varepsilon Y$$

The energy required for production is divided into a demand for renewable and non-renewable energy.

$$ER = \theta E$$

$$EN = E - ER$$

We show below a more precise view of the dynamics involved in the non-renewable energy sector. First, we introduce reserves (such as fossil fuel for instance):

$$REV_E = REV_{-1}^E - CON_E - EN$$

It means that current reserves in non-renewable energy are augmented by energy resources converted into reserves (following the same principle exposed using the case of matter) and diminished by the amount of non-renewable energy produced.

$$CON_E = con_E RES_{-1}^E$$

Conversely, reserves are defined as:

$$RES_E = RES_{-1}^E - CON_E$$

Finally, an energy depletion ratio completes the energy module:

$$dep_E = \frac{EN}{REV_{-1}^E}$$

Emissions and Climate Change

Co2 emissions are defined as a relation between carbon intensity and non-renewable energy consumed.

$$EMIS_{IN} = \omega EN$$

The second type of emissions is land-use induced Co2 emissions, defined in a quite similar way.

$$EMIS_L = EMIS_{-1}^{L}(1 - lr)$$

It follows that:

$$EMIS = EMIS_{IN} + EMIS_L$$

Co2 concentration is divided in three parts. We therefore model the carbon cycle, with the flows of Co2 between the atmosphere ($CO2_{AT}$), the upper ocean-biosphere ($CO2_{UP}$), and the lower ocean ($CO2_{LO}$).

$$CO2_{AT} = EMIS + \phi_{11}CO2_{-1}^{AT} + \phi_{21}CO2_{-1}^{UP}$$

$$CO2_{UP} = \phi_{12}CO2_{-1}^{AT} + \phi_{22}CO2_{-1}^{UP} + \phi_{32}CO2_{-1}^{LO}$$

$$CO2_{LO} = \phi_{23}CO2_{-1}^{UP} + \phi_{33}CO2_{-1}^{LO}$$

Radiative forcing is influenced by Co2 concentration:

$$F = F_{2XCO2} log_2 \frac{CO2_{AT}}{CO2_{AT-PRE}} + F_{EX}$$

With $CO2AT{-}PRE$ corresponding to the atmospheric concentration of Co2 in the preindustrial era, $F2XCO2$ being the increase in radiative forcing since the pre-industrial times, and FEX the exogenously-determined variable representing the radiative forcing not due to Co2 concentration.

$$F_{EX} = F_{-1}^{EX} + f_{ex}$$

Finally, we focus on two types of temperatures: the atmospheric temperature and the lower ocean temperature.

$$T_{AT} = T_{-1}^{AT} + t_1(F - \frac{F_{2XCO2}}{S} T_{-1}^{AT} - (t_2 T_{-1}^{AT} - T_{-1}^{LO}))$$

$$T_{LO} = T_{-1}^{LO} + t_3(T_{-1}^{AT} - T_{-1}^{LO})$$

Where S represents the equilibrium climate sensitivity, i.e. the increase in equilibrium temperature due to the doubling of CO2 concentration from pre-industrial levels (°C). The aim of the Stock-Flow-Fund approach is to integrate different measure units in a single model. We presented in this subsection Co2 concentration and Kilojoules. We will now expose how we can integrate them with monetary values and flows.

4.7.2. Feedback loops and damage functions

The idea of introducing a damage function goes back to the works of Nordhaus. Augier (2019) considers that this function underestimates the damages on the economy, as it is solely defined as the square of the temperature raise. He also affirms that this damage function should also apply on capital.

The question of environmental and technological efficiency

Following Dafermos, Nikolaidi and Galanis (2017), we establish the following equations but at the microeconomic level (respectively the green capital ratio, energy intensity, matter intensity, and recycling rate):

$$\kappa^i = \frac{K_V^i}{K_B^i}$$

$$\varepsilon^i = \kappa_{-1}^i \varepsilon_V + (1 - \kappa_{-1}^i)\varepsilon_B$$

$$\mu^i = \kappa_{-1}^i \mu_V + (1 - \kappa_{-1}^i)\mu_B$$

$$\rho^i = \kappa_{-1}^i \rho_V + (1 - \kappa_{-1}^i)\rho_B$$

The microeconomic foundations of SEN-HARP allow us to have a more granular depiction of the concept of energy intensity. If the company has adopted the clean technology (introduced above as T2), following the process described in the preceding sections, its energy intensity will be decreased more rapidly (but still with decreasing returns) depending on the level of its green capital ratio. Without the adoption of the green technology, green capital will lower the energy intensity of the firm, but at a slower pace. A mixed technology portfolio composed of the brown technology (T1) and T2 will improve the energy efficiency of the firm, but in a less important manner than if the firm only used T2. This is captured with variable εV (and the same goes for the recycling rate through ρ_V). However, we do not consider that the matter intensity μ^i will decrease with the clean technology, as its use by the firm will still require an important amount of matter, even if it can be a different one. Solan panels are a relevant example of that.

The damage functions

The effects of climate-induced damages were introduced above. Here, we present the form of their functions:

$$D_T = 1 - \frac{1}{1 + \eta_1 T_{AT} + \eta_2 T_{AT}^2 + \eta_3 T_{AT}^{6,754}}$$

D_T is the damage function, which links atmospheric temperature to damages (following Weitzmann 2012, it overcomes the issues of using a simple quadratic function) and has an effect on potential output and demand. The following equation describes the climate damages on productivity:

$$D_{TP} = pD_T$$

Finally, the following equation represents the climate damages on investment demand and consumption:

$$D_{TF} = 1 - \frac{1 - D_T}{1 - D_{TP}}$$

Thus, we develop in this model a consistent representation of the interactions between the monetary sphere and the biophysical sphere.

4.8. Public policies: the Central Bank and the Treasury

Public policies can be categorized into four distinct groups: welfare state interventions, labour policies, investment strategies, and innovation policies (as previously introduced in Section 4.3).

Three labour policies are considered: a raise in the minimum wage, requalification policies, and a Job Guarantee (JG) programme. The latter would allow for less total employment fluctuations and could improve *private* employment (Tcherneva 2018). It consists in a programme offering a job paid at the minimum wage to any unemployed individual seeking for a job. Lower paid green jobs could be occupied by JG benefactors. From an institutional perspective and using the US case, Tcherneva suggests the implementation of a National Care Act as a basis for the JG.

Two other policies are implemented: an increase in the minimum wage in order to keep pace with inflation, and policies designed to facilitate the acquisition of new skills. The objective of the programme is to upgrade the skill status of participating households. Over a two-year period, these households will receive compensation at the level of unemployment benefits. Subsequent to the programme's conclusion, however, they will be eligible to apply for high-skilled employment. The JG and the increases in minimum wage are only implemented during periods of pro-transition party governance.

In the context of investment, and in accordance with the principles of the Green Deal, policy measures are predominantly oriented towards the decarbonisation of corporate balance sheets rather than the improvement of their material footprint. This objective is pursued through the implementation of public investments. These investments are made by the State in specific companies within each sector, selected randomly by the model.

Dafermos and Nikolaidi (2019) identify two challenges for green fiscal policy. Firstly, whilst taxes can have a positive impact on global warming, they could also create a "climate Minsky moment" by increasing financial fragility through decreasing profits in the private sector. Secondly, whilst public investments and subsidies are more efficient in terms of environmental preservation, their positive effects could be decreased through a rebound effect, which would increase pressures on material availability by the start of the next century. The authors thus suggest a policy mix. Utilising the sectoral decomposition of the model and its agent-based structure facilitates a more nuanced understanding of these policies.

Decarbonizing the economy

In order to decarbonize the economy, the state can implement three additional constraining policies: the imposition of penalties on the basis of the use of brown capital, credit control to orient monetary creation towards green activities, and the stranding of assets (see Daumas 2023).

Finally, our model displays two main ways of financing policies for the transition: taxes and monetary financing through the European Central Bank (ECB).

The European Central Bank

The European Central Bank is modelled explicitly. This institution is responsible for maintaining comprehensive records of all balance sheet operations within the interbank system, in addition to overseeing the implementation of monetary policies. In accordance with Funalot (2024), these policies can be categorised into three distinct components: firstly, the implementation of differentiated refinancing interest rates; secondly, the execution of a Spread Targeting strategy, which encompasses the Public Sector Purchase Programme and the Ecological Sector Purchase Programme; and thirdly, the implementation of climate-aligned haircuts.

With regard to the first monetary policy rule, it pertains to refinancing operations, accompanied by differentiated interest rates. The greener the balance sheet of a given bank (measured by its green asset ratio), the lower its refinancing rate.

$$i_{CB}^{b} = r_0 + x_{CB}^{0}(GAR_b - GAR^t)$$

The second component is the growth rate of the asset stock held by the ECB. For the purpose of monetary policy, this stock is assumed to grow at a rate gr_{AMP}. This policy is referred to as "spread targeting" (Funalot, 2024), with the objective being to reduce (or increase) the interest rate of a specific asset to the target set by the ECB. Within the model, the policy is implemented on public debt (the Public Sector Purchase Programme) and green bonds (the Ecological Sector Purchase Programme).

$$gr_{AMP} = x_{CB}^{1}(i_{PD}^{i} - i_{PD}^{t}) + x_{CB}^{2}(i_{GB}^{i} - i_{GB}^{t})$$

The third monetary policy implemented in the model consists of climate-aligned haircuts[25] (Vestergaard 2022), which imply that the Central Bank will gradually and continuously increase the haircuts on brown assets taken as collateral of central bank money, ultimately reaching 100% and no longer accepting them as collateral. The principal effect anticipated is a decline in the liquidity of brown assets, which could motivate agents to retain and generate green assets. The variable mat_k is employed to account for the maturity risk associated with each asset.

$$h_k^t = x_{CB_k}^{3} + x_{CB_k}^{4} mat_k$$

$$With\ k = (b; g)$$

$$x_{CB_G}^{n} < x_{CB_B}^{n}$$

$$x_{CB_B}^{3} = x_{CB_B}^{3^{-1}}(1 + x_{CB}^{5})$$

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[25] Haircuts represent the share of an asset taken by the Central Bank that will be deducted when giving high-powered money to the bank that gave the asset as a collateral.

$$0 < x_{CB}^{5} < 1$$

Finally, the Central Bank generates profits from its refinancing operations and the interest accrued on the bonds listed on its balance sheet. These profits are subsequently passed on to the fiscal authority in their entirety.

4.9. Indicators and model variables

The integration of social metabolism and social provisioning into a framework necessitates the consideration of alternative indicators, given the limitations of traditional metrics such as GDP in capturing the complexity of societal progress. The utilisation of alternative indicators is imperative for conducting holistic assessments, thereby transcending the confines of monetary transactions and overall economic growth. The measurement of resource extraction, transformation, and waste (social metabolism) alongside the assessment of social needs (social provisioning) provides a more comprehensive perspective on progress. Economic growth measured by GDP can hide inequality. Indicators derived from social provisioning focus on the fair distribution of resources and well-being across different social groups. By using alternative indicators, policymakers can better understand where interventions are needed—whether to improve resource efficiency, reduce environmental impact, or enhance social well-being.

The objective of this study is to identify and monitor variables and indicators that will facilitate the interpretation of the SEN-HARP model's results in the different modules (biophysical, firms etc.) and at different levels of aggregation (micro, meso, macro). The utilisation of alternative indicators provides a multidimensional view of progress that acknowledges the limits of natural resources, the complexity of societal needs, and the interconnectedness of economic, ecological, and social systems.

The policy module utilises indicators to facilitate comprehension of policy adjustments or policy shifts. In certain instances, sustained protests have been known to prompt governments to reconsider or make adjustments to policies. These movements have the capacity to compel political parties to address issues that may have been marginalised. When workers, farmers, or industry groups mobilise against perceived unfair environmental policies, politicians often recalibrate their agendas to capture or retain voter support in those regions. The combination of economic and climate-related concerns in protest movements has, on occasion, contributed to a more polarised political landscape, creating conditions that are conducive to the emergence of populist parties that emphasise the divide between urban and rural or working-class voters. These populist parties have been able to capitalise on these dynamics to gain ground. For these reasons, we incorporate indicators following such voting decisions.

The subsequent table provides a synopsis of the indicators to be monitored in accordance with the provisioning system approach and the integration of political responsiveness—through policy concessions, agenda shifts, or the emergence of new political forces.

Table 13: Indicators for tracking socio-technical transitions across modules (biophysical, households, firms, policy, banks) and levels (micro, meso, macro) in the SEN-HARP model

Module Level	**Biophysical** (climate, energy, materials and waste)	**Households** (well-being, consumption, labor)	**Firms** (production, innovation, investment)	**Policy** (Regulation, public spending and policy shifts)	**Banks** (finance, credit allocation, stability)
Micro (individual, firm level)	Personal Carbon & Material Footprint Household Energy Mix (En renew/En total) Local Temperature Anomalies (Tcurrent – T historical_avg) Waste Generation per Capita	Basic Needs Satisfaction Index (Food, Energy, Housing, Transport, Public Service Access) Household Energy & Transport Affordability Index ((cost energy + cost transport)/income Worker mobility and reskilling rate	Firm-Level Energy Mix (% renewable vs. fossil fuels) Financial Leverage Ratio (Debt/Equity) Corporate Green Asset Ratio (Green Inv/Total Assets)	Vote in favour of the pro-transition party (Binary: 1 = yes or 0 = no)	Household Debt-to-Income Ratio (debt HH/Income HH) Green Investment Portfolio Share (Funds green/Funds total)
Meso (sectoral level)	Sector-specific environmental footprint Sectoral energy mix (% share of different energy sources)	Labor market polarization ((job highskill – jobhighskill)/job total) Wage growth in green sectors Energy burden on low-income households (% of income spent on energy)	Industry concentration (HHI) Average markup Firm entry and exit rates in green and brown sectors Rate of green tech adoption by industry Sectoral Energy Consumption Intensity (kWh/GDP sector) Sectoral Circular Economy Transition Index (recycled materials / total materials)	Effectiveness of active labour market policies (job creation, skills) Subsidies for green tech adoption Lobbying/delay and postponement of political measures	Corporate Debt Risk in High-Pollution & High-Energy Sectors
Macro (national, global level)	Global & National Temperature Increase (DTglobal = Tcurrent – Tpre-industrial) National Resource Productivity (GDP/Material Input) Energy Intensity of the Economy (Energy/GDP) Planetary boundaries compliance (impact/threshold)	Harmonious living index Green savings for future generations' needs Employment to population ratio Income inequality	Productivity growth in green sectors vs brown sectors National energy self-sufficiency (% of domestic vs imported energy sources) Trade Balance in Critical Raw Materials (Dependency on Imports)	Vote share for pro-transition political parties Achievement gap to net-zero target (commitment credibility) Government spending on sustainability and just transition Growth in public debt excluding green investment	National Green Asset Ratio (green loans/total loans)

6. Conclusions

While decent living is necessary - and crucial for the political acceptability of ecological transition strategies, the energy and material cost of needs satisfaction cannot be overlooked in the 21st century. In this context, favouring the harmony between human and natural systems may call for yet untried post-growth strategies. Likewise, the provision of decent living for all supposes that the cost of transition is well distributed and changes are broadly accepted and politically supported. The transition to sustainability is inherently disruptive, necessitating societal acceptance and robust political engagement. The SEN-HARP model is specifically designed to address these challenges by investigating the potential for a reinforced Green Deal in the EU27. It employs a comprehensive assessment framework encompassing bio-physical and socio-political outcomes.

The SEN-HARP model is currently being finalized for conducting the scenario simulations at both the macro and micro levels. We envisage to provide a stabilized set of scenario simulations at these levels in May 2025. In the next weeks, the focus will be on specific mechanisms within the general model, with sectoral dynamics (on employment, financial fragility, industrial concentration, etc.) being given particular attention. Furthermore, an increased focus on inequality at the micro level will allow for the analysis of political dynamics and the alternating cycles of parties in power through the capture of distortions in political responsiveness, as well as the dynamics of the society-economy-nature system in terms of living conditions, inequality, notably through the identification of the patterns of social stratification involved in the different policy scenarios. Agent-Based modelling allows for the identification of specific regions, and therefore the investigation of the patterns of spatial inequality and how they shape political outcomes will also be conducted. The full version of the model also introduces feedback loops from nature to the economy and the society through the damage functions. When available, the elasticities estimated from EU micro data by LSE and IIASA will allow us to study the impacts of extreme climate events, respectively on income/consumption and political perceptions. For the time being, we use estimated elasticities found in the literature (see Section 4.1).

Secondly, the model enables the examination of more granular policies tailored to specific sectors. In the agricultural sector, for instance, Coronese et al. (2014) have identified the necessity for prompt action to transition away from conventional farming, encompassing both land use (preserving forests) and food security. In the energy sector, a feed-in tariff policy will be implemented, following a model similar to that outlined by Ponta et al (2018). This policy will incorporate three key features: long-term fixed prices, grid priority for energy produced from renewable sources, and financing through a reallocation charge and general taxation.

Finally, the concept of harmonious living, a central pillar of the SEN-HARP model, will be further explored to ascertain its potential to pave the way for a comprehensive research programme investigating the decoupling of economic growth from the satisfaction of social and human needs, in accordance with the provisioning systems approach. The European Union is in an urgent need for a robust and innovative socio-economic and political model grounded in sustainable welfare, in order to effectively contend with the intense global technological and economic competition imposed by the United States and China. History has demonstrated that this transition has occurred previously, when Europe underwent a period of profound transformation to achieve similar levels of economic and social development as the United States, while concurrently countering the growing economic influence of East Asia during the latter half of the 20th century.

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Appendix 1: the social accounting matrix of SEN-HARP

OPERATIONS	HHS	FIRMS (CURRENT)	FIRMS (CAPITAL)	BANKS (CURRENT)	BANKS (CAPITAL)	TREASURY	CB	TOTAL
Consumption	- C	C						0
Wages	W	- W						0
Taxes	-TH	-TF				T		0
Savings (variation)	- d(S)				d(S)			0
Interest on savings	is*S(-1)			-is*S(-1)				0
Household Debt (variation)	d(HHD)				-d(HHD)			0
Interest on Household Debt	-iHHD*HHD(-1)			iHHD*HHD(-1)				0
Loans (variation)			d(L)		-d(L)			0
Interest on loans		-iL*L(-1)		iL*L(-1)				0
Investment		-I	I					0
Profits (firms)		-PF	PundF	PdF				0
Profits (banks)	PB			-PB				0
Subsidies		Sub				-Sub		0
Public Investment			PubI			-PubI		0
Social benefits programmes	SocP					-SocP		0

Government bonds					-d(GovB)	d(GovB)		0
Green Bonds		d(GB)			-d(GB)			0
High Powered Money					-d(HPM)		d(HPM)	0
Refinancing Operations					d(REF)		-d(REF)	0
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

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