




## An assessment of different transition pathways to a green global economy

Soheil Shayegh <sup>1</sup>, Severin Reissl<sup>1</sup>, Elnaz Roshan<sup>2</sup> & Matteo Calcaterra <sup>1</sup>

Transitioning to a green economy is urgently needed to achieve the climate targets by the end of this century. Here we investigate alternative pathways for the transition of the global economy from one dominated by the fossil-fueled (brown) sector to one dominated by the low-emission (green) sector. We modify a well-known integrated assessment model of climate change and economy to consider three transition pathways: Linear, Delayed, and Fast. Our results indicate that the main burden of the green transition lies on capital formation, accumulation, and transfers facilitated by full R&D investment in the green sector's productivity. We also find that transition pathways rely on different mechanisms to achieve their targets. The Delayed pathway relies on the combination of higher green capital investment and an increase in green capital productivity through R&D investment, while the Fast pathway requires substantial transfers of capital from the brown sector coupled with high abatement efforts.

<sup>1</sup>RFF-CMCC European Institute on Economics and the Environment (EIEE), Centro Euro-Mediterraneo sui Cambiamenti Climatici, Milano, Italy. <sup>2</sup>Research Unit Sustainability and Global Change, University of Hamburg, Hamburg, Germany. email: [soheil.shayegh@cmcc.it](mailto:soheil.shayegh@cmcc.it)

Achieving the United Nations' Sustainable Development Goals (SDGs) and climate targets such as those laid out by the Paris agreement requires a major increase in investments in renewable energy technologies<sup>1</sup>, and mitigating emissions from economic activities<sup>2</sup>. Therefore, green industrial policies should aim not only at reducing emissions but also minimizing negative consequences of diverting capital and human resources from fossil-fueled economic activities<sup>3</sup>. As a result, green growth policies such as the European Green Deal<sup>4</sup> have been explicitly designed to address climate change by decoupling economic growth and fossil-fuel energy consumption<sup>5</sup>. This paper focuses on the issues at the intersection of green transitions, economic growth, and decarbonization. In particular, we are asking “what are the key requirements of green transition pathways in terms of physical and human capital resources?”, “How do research and development (R&D) investments in capital and labor productivity differ across different transition pathways?”, and “How are mitigation efforts impacted by the speed and intensity of the green transition?”. In answering these questions, we show how the transfer of capital and labor between economic sectors can facilitate the green transition and lower the cost of abating green house gas (GHG) emissions in the future.

The green transition requires investment in economic activities and technologies that reduce the dependency on fossil fuels and provide cleaner products or services with lower or no CO<sub>2</sub> emissions<sup>6</sup>. Although possibility of a full decoupling of GDP growth from resource use has been questioned in a series of empirical studies<sup>7</sup>, the key premise underlying green growth policies can still be achieved if the green transition also fosters mitigation efforts. Nevertheless, relying solely on renewable energy sources such as solar and wind, despite its appeal<sup>8</sup>, has been shown to entail important spatial and temporal mismatches between renewable resource availability and energy demand, which may challenge the reliability of energy systems and hinder the full transition to net-zero emission energy systems<sup>9–11</sup>. Furthermore, the green transition may not necessarily translate into GHG reductions; there are several socioeconomic and technology-specific factors that may affect the relationship between renewable energy expansion and GHG emissions in the long term<sup>12</sup>. Such concerns about the limitations of the green transition have led to a broadening of the concept of the green transition and the recognition of the crucial role of mitigation and carbon dioxide removal in achieving net-zero targets<sup>13,14</sup>. We build on this evolving field and consider green transition pathways which include the development and deployment of renewable and low-carbon energy systems, coupled with explicit policies aimed at reducing carbon emissions from both direct and indirect consumption of fossil fuels<sup>15</sup>. Our results indicate a strong coupling between green growth and decarbonization efforts, especially in the Fast transition pathway with a high emphasis on early greening of the economy.

As a result, by broadening the implications of the green transition in our framework, we investigate not only investment in clean energy technologies, but also their spillover effect through endogenous technological change on decarbonization methods, as well as the employment opportunities that such a transition may bring about<sup>16</sup>. Empirical evidence has shown that investment in clean technologies coupled with environmental policies and regulations can have positive impacts on overall employment<sup>17</sup> in addition to the reduction of GHG emissions<sup>18</sup>. Furthermore, a systematic review of the literature on the green transition reveals that there is a positive, but relatively small impact from the green transition on net employment and a negative impact on income distribution<sup>19</sup> (Other studies show a trade-off between GHG emission reduction and increases in income inequality and

unemployment<sup>20</sup>. It is also worth mentioning that new jobs created as a result of the green transition tend to require higher skills, education, and job training than conventional jobs<sup>21</sup>). Our results are in line with such findings, indicating a positive but relatively small impact of green transitions on the green labor share. In contrast, we show that the green transition is mainly driven by capital transfers and green investment decisions.

Another key factor in achieving green growth is technological change driven by R&D investment in physical and human capital productivity and the interactions among the factors controlling such investment decisions<sup>22</sup>. Human capital development has been shown to strengthen R&D capacity<sup>23</sup>, while technological progress and education can increase labor productivity<sup>24</sup>. Therefore, R&D investment can be seen as an engine of economic growth and a facilitator of the green transition. In our model, we investigate the critical role of R&D investment allocation decisions in determining the speed and intensity of the green transition and their broader implications for decarbonization. We show that achieving the green transition requires early R&D investment in green sector productivity, with a higher share of such investment directed to enhancing capital productivity as compared to labor productivity.

Integrated assessment models of climate and the economy (IAMs) are widely used for analyzing climate change policies and assessing their dynamic costs and benefits. They are built on general equilibrium analysis which aims at capturing the essential dynamics underlying economic activities from production to consumption. These models can be as aggregated and global as the Dynamic Integrated model of Climate and Economy (DICE) model<sup>25</sup> or disaggregated and detailed along different regional (e.g., RICE and RICE50+ models<sup>26</sup>), sectoral (e.g., IMAGE model<sup>27</sup>), and technological (e.g., WITCH<sup>28</sup> and MIND<sup>29</sup> models) dimensions. Regardless of their level of aggregation, one of the key premises of IAMs is that the decision makers such as producers, consumers, and governments, or the central planner in centralized models, are rational welfare-, utility- or profit-maximizers<sup>30</sup>. These models provide a powerful tool in analyzing and optimizing climate change policies, assessing their long-term socio-economic and climate impacts, and tracing the mechanisms through which model variables and parameters interact<sup>31</sup>. Nevertheless, there are many critics of IAMs. Compared to input-output models<sup>32</sup>, IAMs in general place less emphasis on material and natural resource use and instead, provide more details about technological change. Furthermore, input-output analyses with detailed sectoral and labor market disaggregations, despite often lacking economy-climate feedback loops, can provide valuable insights into how green growth policies can achieve more equitable outcomes<sup>20</sup>. What often makes IAMs a preferred choice for policy analysis is their ability to couple climate change dynamics with macroeconomic processes in order to assess the trade-offs between abatement efforts and the economic impacts of climate change. An alternative approach is offered by IAMs built on agent-based macroeconomic frameworks<sup>33</sup>. While these provide a valuable alternative and complement to conventional IAMs, they typically do not allow for the derivation of optimal policies. We believe that adopting a simple IAM framework for the purpose of analyzing green transition mechanisms and investigating the trade-offs between transition pathways and optimal mitigation efforts would be more appropriate and useful in this context.

A key feature of IAMs is how they model technological change through targeted R&D investment, which determines the rate of reduction in abatement costs and facilitates the green transition<sup>34</sup>. Despite its importance, some of the most prominent IAMs are equipped with a limited or no endogenous mechanism to account for investment in capital and labor productivity, as well as the

interplay between R&D investment, technological change, education, and productivity<sup>35,36</sup>. For example, DICE has been widely used by the U.S. government to estimate the social cost of carbon<sup>37</sup>. One of the key assumptions of this model is that technological change follows an exogenous path which not only defines the economic growth trajectory but also reductions in the marginal cost of abating CO<sub>2</sub> emissions which is the key driver behind the main findings of the DICE model<sup>38</sup>. There have been several attempts to address this limitation by introducing endogenous technical change in a theoretical framework<sup>39</sup> or by including induced innovation in the energy sector in the DICE model<sup>40</sup> or in the RICE model, the regional version of DICE<sup>41</sup>.

Other IAMs such as the WITCH model<sup>28</sup> have an explicit module of technological change and innovation diffusion through R&D investment and learning-by-doing<sup>42</sup>. In the MIND model<sup>29</sup>, technological change is endogenized in two parallel fashions: R&D investments, which affect labor productivity and energy efficiency, and learning-by-doing, which affects the cost of renewable energy investments. The results show that these features can reduce abatement costs substantially. They also underline the importance of learning and inertia, which result in smoother abatement with substantially higher early investment efforts<sup>43</sup>. We build on these studies, and apply an endogenous model of abatement cost which depends on productivity growth induced by R&D investment. However, there is no clear best approach emerging from the literature for modeling endogenous technological change<sup>34</sup>.

Finally, while a growing body of literature studies technological change through R&D investment<sup>44</sup>, there has been less effort to account for endogenized human capital development and labor productivity in IAM frameworks. Here, we aim to fill this gap by decomposing the DICE model into two economic sectors and (a) endogenizing the effect of learning-by-doing on abatement cost, (b) endogenizing the effect of R&D investment on capital productivity, and (c) endogenizing the effect of R&D investment on labor productivity. The results of these improvements to the original DICE model highlight a distinct but less-discussed transition mechanism: early R&D investment in green capital productivity coupled with a steady flow of capital from the brown to the green sector guarantees the growth of the green sector. On the other hand, labor productivity growth and labor transfers play a less prominent role in shaping the green transition. The overall pattern of the results is shown to be robust to changes in transfer cost.

## Results

**Modeling the green transition.** As in the 2016 version of DICE, our model is a finite horizon dynamic model with 60 time periods (300 years). It includes a representative agent model of the economy with endogenous technological growth. We assume a two-sector economy including green and brown industries. The transition to a green economy is modeled as a growing share of green output in the composite final consumption good.

In each period (5 years), the central planner decides on how to divide an existing capital stock and labor force between the two economic sectors through transfers. Capital (We have not included natural capital in our model. Some studies have shown that considering the use and non-use value of natural capital can have large implications for climate policy<sup>45,46</sup>) and labor are the inputs of the aggregate production function in each sector. The productivity of capital and labor is determined by allocating a share of total R&D investment to each factor in each sector. Similarly to the original DICE model, the abatement rate is another decision variable, which controls the amount of carbon emissions in both sectors (As discussed in ‘Methods’, we assume

**Table 1 Three transition pathways and the Baseline pathway.**

Pathway	Shape	Green consumption share		
		2010	2050	2100
Baseline	—	20%	20%	20%
Linear	/	20%	49%	90%
Delayed	—/	20%	20%	90%
Fast	—/	20%	90%	90%

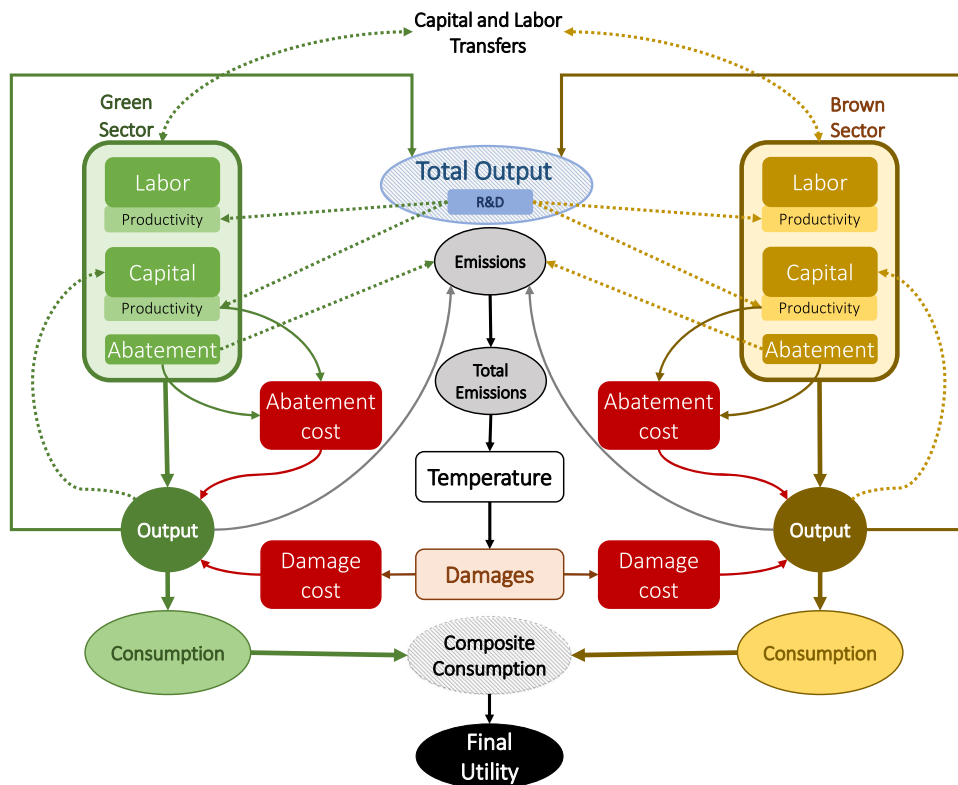
that economic activities in the green sector have a lower emission intensity than those in the brown sector). Furthermore, the marginal abatement cost declines endogenously over time as capital and labor productivity increase through R&D investment.

Emissions accumulate in the atmosphere over time and a portion of the atmospheric carbon stock sinks into the ocean. Radiative forcing - the difference between incoming short-wave radiation and outgoing long-wave energy (heat) - is a function of the atmospheric carbon stock, while global temperature is a function of radiative forcing and past temperatures. The economic and climate models are linked through a damage function. An increase in the global mean temperature reduces net economic output in each sector through sector-specific damage functions. Damage functions such as the one used in the DICE model are intended to represent aggregate climate change damages. Alternatively, one can account for the effects of temperature on different parts of economic production separately<sup>47</sup>. This includes climate change impacts on population dynamics<sup>48</sup>, labor markets<sup>49</sup>, as well as capital stocks and financial systems<sup>50,51</sup>. In order to be able to compare our results with the benchmark provided by the DICE model, we keep the sectoral damage functions similar to the aggregate one used in the DICE model. These damages can be avoided by (a) fostering the green transition through the expansion of the green sector and allocating a greater share of economic output to low-carbon green products, and (b) increasing abatement measures to reduce emissions from economic activities in both sectors. However, in our modeling framework, the first mechanism is an exogenous assumption (represented by the assumed transition pathways), while the second mechanism is a decision variable (see ‘Methods’ for a detailed description of the model, equations, and the calibration).

We analyze the green transition through 3 representative pathways and compare them to the Baseline pathway with a constant share of green output in the composite final consumption good. Table 1 presents these 3 transition pathways along with the Baseline pathway and their characteristics (see ‘Methods’ for more detailed descriptions of these transition pathways).

The model’s central planner aims to generate the maximum utility from composite consumption over the modeling time horizon given a fixed discount rate. As a result of this dynamic optimization, at each time period one can calculate the optimal abatement rate in each sector, the optimal share of output allocated to capital formation in the next period in each sector, the optimal share of capital and labor transferred between the two sectors, and the optimal share of R&D invested in capital and labor productivity in each sector.

Figure 1 shows a schematic diagram of the modified DICE model (see ‘Methods’ for details). It is worth mentioning that, following the original DICE model, the proposed framework does not include material resources dynamics. Therefore, the results presented here should be treated with caution as they do not



**Fig. 1 Schematic overview of the 2-sector DICE model.** Continuous lines depict relationships between variables while the dashed lines represent the 11 decision variables defining the action space.

consider issues pertaining to material decoupling in the green sector.

**Assessment of transition pathways.** In this section, we present the results of three scenarios of future green growth (i.e., three green transition pathways) as described in Table 1 and shown in Fig. 2a. The first set, labeled as Baseline, indicates a case where the share of the green good in total consumption is kept at its current level of about 20% until the end of the century. In the Linear case, this share increases constantly to reach 90% by 2100. In the Delayed case, on the other hand, green growth is kept at zero during the first half of the century, but it picks up speed linearly in the second half until it reaches 90% by 2100. Finally, in the Fast case, the consumption share of the green sector grows fast initially to reach 90% by 2050 and subsequently remains at that level until 2100. It is important to note that green transition pathways are green growth trajectories which are concerned with the share of green output in the composite final consumption good. They do not necessarily translate into climate objectives such as the net-zero targets, as the climate implications of each pathway depend not only on the growth of the green sector but also on the stringency of abatement efforts.

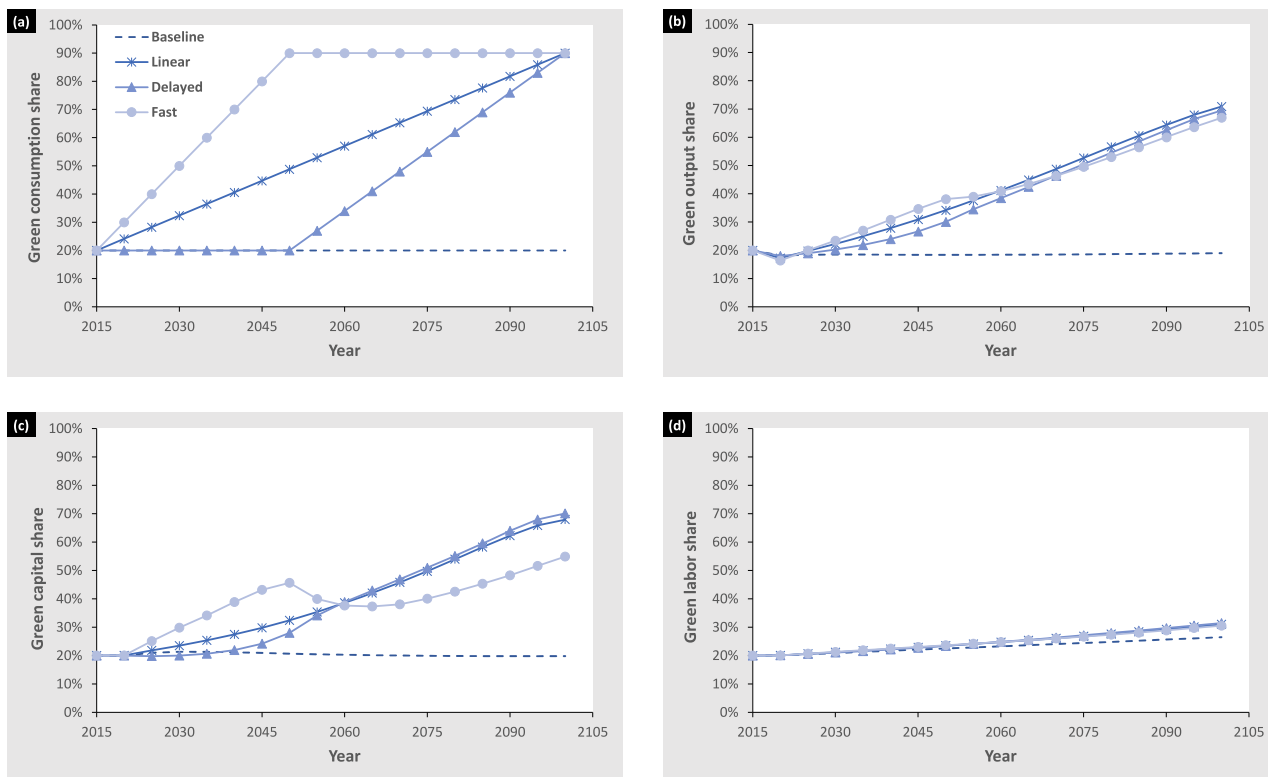
Figure 2b shows the share of green output in total output under each transition path. Comparing different pathways for green output growth in this panel reveals that they all share a similar increasing trend starting from 20% in 2015 and growing slowly up to about 70% in 2100. The difference between output growth under different pathways, especially between the Delayed and Fast pathways is similar to but less profound than those reported in Fig. 2a. This is chiefly due to two factors: a modeling assumption and an optimization result. While the green and brown outputs are linearly combined to generate total output, the final consumption good is a constant elasticity of substitution (CES) function of green and brown output, with their shares

following the trends shown in Fig. 2a. On the other hand, the magnitude of (green and brown) output which is consumed is derived from production and what is saved and invested in capital formation in the next period. Therefore, the choice of saving rate (i.e., the portion of output which is not consumed but invested in capital formation) can also affect the transformation of output into consumption patterns.

Transitioning to a green economy requires the expansion of green capital and green labor markets. Figure 2c, d, shows the shares of capital and labor inputs dedicated to the green sector. While the labor share grows slowly and more homogeneously across the pathways, the green capital share follows the consumption patterns of Fig. 2a. As noted above, this again reinforces our conjecture that capital formation dynamics (i.e., capital formation, accumulation, and transfer) are the main drivers of the green transition.

The green transition will also require a substantial decarbonization of the economy, especially in the brown sector. Figure 3a, b shows the optimal abatement rates under the three pathways compared to the Baseline case for the green and brown sectors, respectively. By definition, the emission intensity of the green output is much lower than the brown sector. Nevertheless, both sectors are required to undergo varying degrees of decarbonization depending on the pathways. In both sectors, however, the Fast pathway entails higher abatement rates. This difference is more pronounced in the brown sector where under the Fast pathway, the abatement rate reaches about 70% by the end of the century.

Saving rates, by contrast, demonstrate smaller but nevertheless noticeable fluctuations across the pathways in both sectors. Most notable is the optimal saving rate behavior under the Delayed pathway in the green sector. In this case, the saving rate increases in the first half of the century when the green transition is stalled, in anticipation of the rapid expansion of green consumption in



**Fig. 2 Green growth transition pathways and their consequences.** **a** Share of the green consumption good in composite consumption, **(b)** Share of green output in total output, **(c)** share of green capital in total capital input, and **(d)** share of green labor in total labor input.

the second half of the century. Another interesting behavior can be observed under the Fast pathway in the brown sector, where falling saving rates imply that much of the brown capital has already been transferred to the green sector. This is indeed a core feature of our model, which allows for the transfer of production factors (i.e., capital and labor) from one sector to another at a cost. The optimal transfers of capital and labor between the two sectors are demonstrated in Fig. 4.

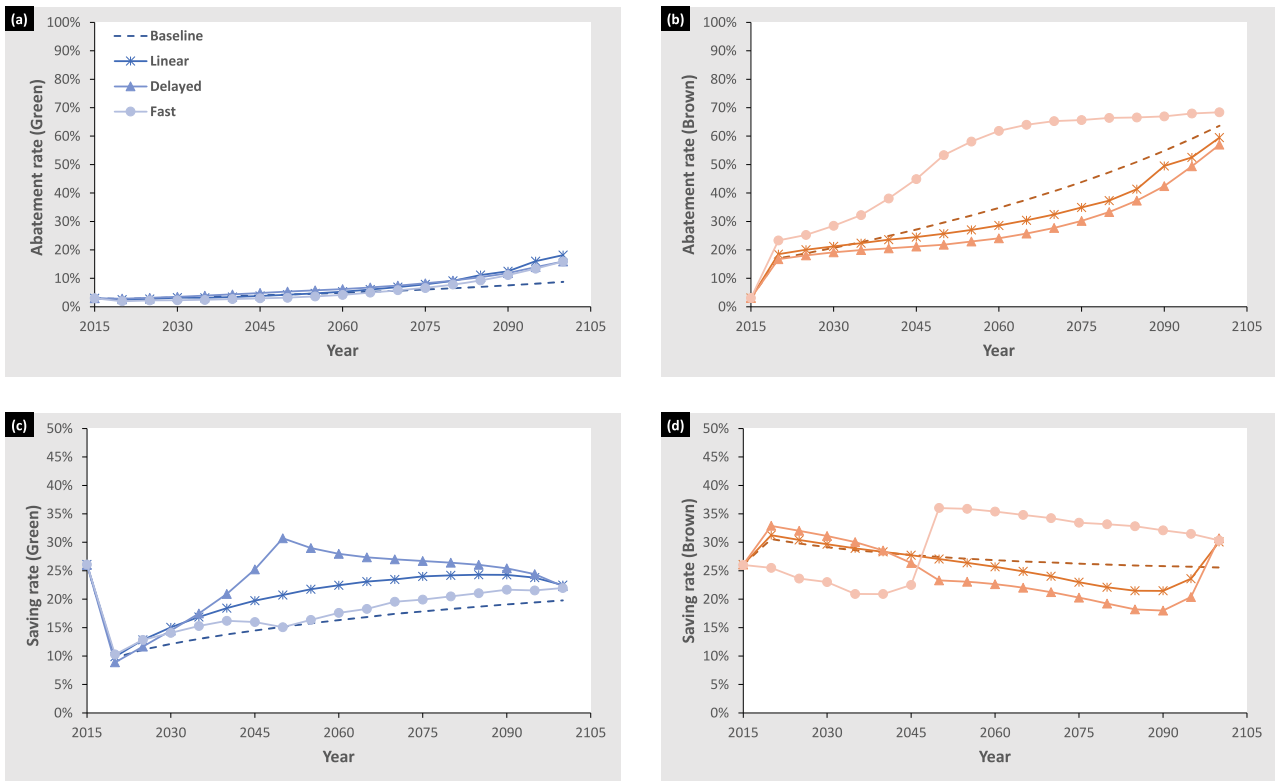
As shown in Fig. 4a, c, there is no transfer of capital or labor from the green to the brown sector. On the contrary, green transitioning under any pathway, and even the Baseline case without a transition requires some transfer of capital and labor from the brown to the green sector. Figure 4b shows the capital transfer from the brown to the green sector. While the capital transfer is initially the highest under the Fast pathway, it decreases towards the end of the century. This is due to the fact that after initial rapid growth of the green sector, the green sector stabilizes in the second half of the century, reducing its dependency on new capital transfers from the brown sector. The decrease in capital transfers under the Delayed pathway however, is linked to rising saving rates in the green sector which makes it easier for the green sector to accumulate capital endogenously while reducing its dependency on acquired capital from the brown sector. The labor transfer patterns in Fig. 4d, on the other hand, appear to follow the overall patterns of the pathways; the Fast pathway requires more labor transfers in the first few decades of the century while the transfers are higher in the second half of the century under the Delayed pathway. Transfer costs (as a share of total sectoral output) along with abatement and climate damage costs are presented in Supplementary Fig. 1, while sectoral economic outputs (gross and net) are shown in Supplementary Fig. 2.

Although the combination of transfers and saving rate results can provide information about the underlying mechanisms

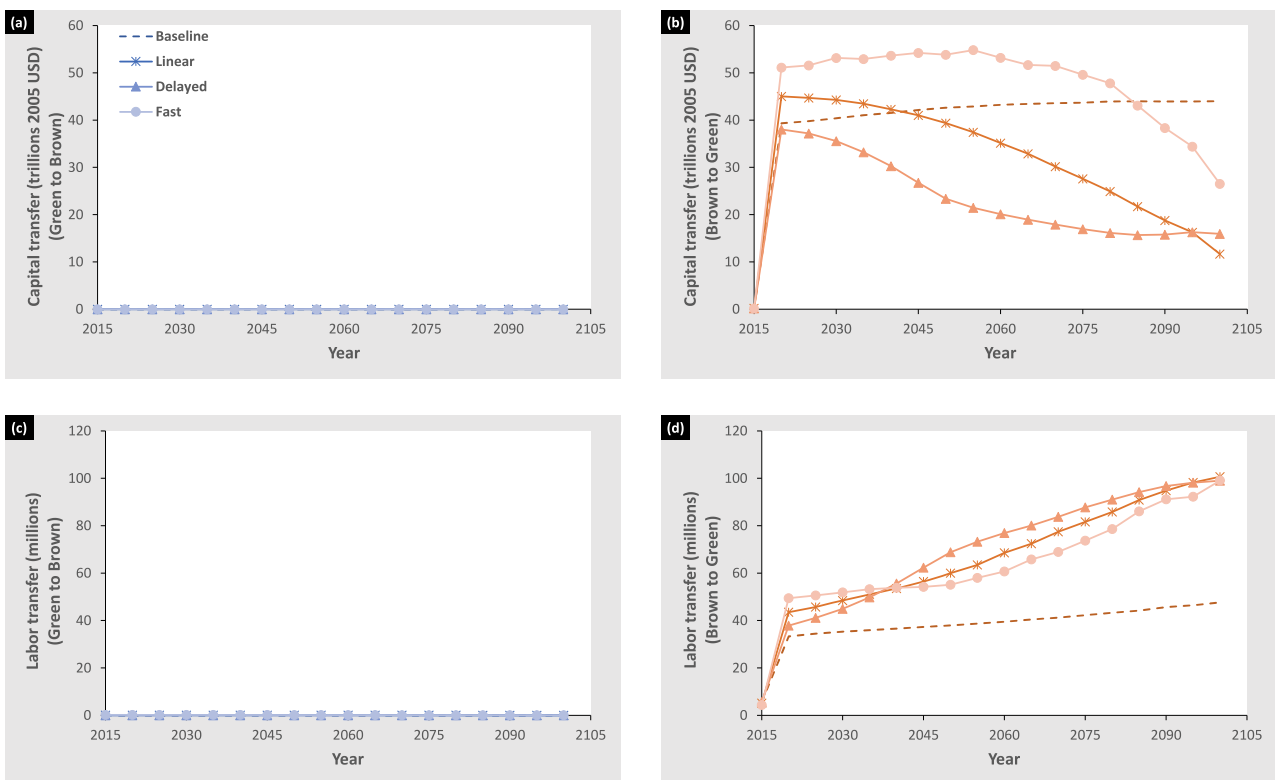
driving the green transition in each pathway, their contribution is incomplete without considering the central role of productivity growth and R&D investments which makes the transition possible. Figure 5 depicts the optimal allocation of R&D output to capital and labor productivity in each sector. As shown in Fig 5a, c, all transition pathways, regardless of their speed, require a full allocation of R&D output to green sector productivity. The only exception is observed during the early stages of the Delayed pathway where some R&D output is allocated to the brown sector's capital and labor productivity (Fig. 5b, d). These allocations, however, are short-lived with a declining trend which goes to zero by 2040. As a result, the green sector enjoys a boost in productivity which helps it achieve the 90% targeted share of total consumption by the end of the century. As shown in Supplementary Fig. 3, the result of heavy R&D investment in the green sector is (a) larger productivity of capital and labor in this sector compared to the brown sector, and (b) higher productivity of green capital than green labor. The combination of these factors, helps increase the share of green output in accordance with transition pathways.

The magnitude of transfer flows depends not only on the policy forces driving each pathway, but also on the unit cost of transferring capital and labor between the two sectors. Supplementary Note 1 describes a sensitivity analysis of transfer costs. As expected, lowering the transfer cost of a production factor (see Supplementary Fig. 4) facilitates the transfer of larger quantities of it from the brown to the green sector. As shown in Supplementary Fig. 5, lowering labor transfer cost, in particular, not only increases labor transfers from the brown to the green sector, but also reduces the need for capital transfer to the point that no capital will move from the brown to the green sector by the end of the century. Despite the adverse effects of lowering transfer cost for one factor on the other factor's transfer quantities, the overall transfer patterns and optimal saving rates

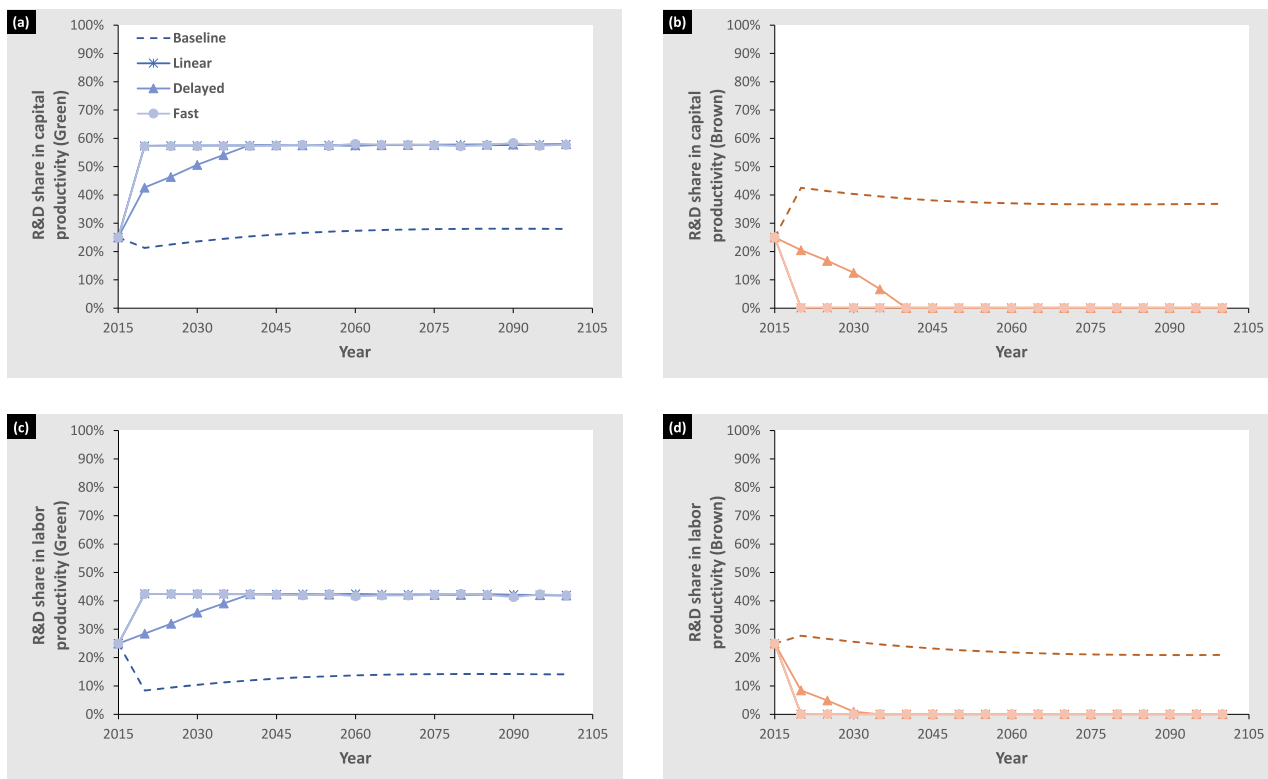




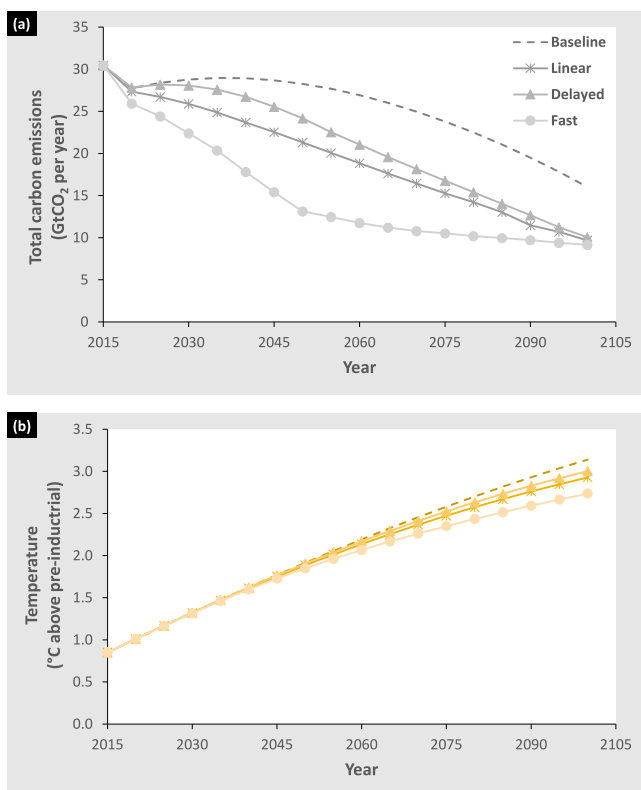
**Fig. 3 Key drivers of the transition pathways.** **a** Abatement rate in the green sector, **b** abatement rate in the brown sector, **c** saving rate in the green sector, and **d** saving rate in the brown sector.



**Fig. 4 Capital and labor transfers under different transition pathways.** **a** Capital transfers from the green to the brown sector, **b** capital transfers from the brown to the green sector, **c** labor transfers from the green to the brown sector, and **d** labor transfers from the brown to the green sector.



**Fig. 5 Share of R& D allocated to each sector. a** Share of R& D allocated to capital productivity in the green sector, **(b)** Share of R& D allocated to capital productivity in the brown sector, **(c)** Share of R& D allocated to labor productivity in the green sector, and **(d)** Share of R& D allocated to labor productivity in the brown sector.



**Fig. 6 Climate indicators in the transition cases. a** Total carbon emissions, and **(b)** atmospheric temperature change compared to pre-industrial levels.

(Supplementary Fig. 6) across different transfer cost scenarios remain unchanged.

Finally, we can compare the transition pathways in terms of their broader impact on climate change indicators. Figure 6a displays total carbon emissions. Early investment in the green sector under the Fast pathway manifests itself in lower levels of carbon emissions which stabilize in the second half of the century. After an initial upward trajectory, emissions under the Delayed pathway follow a decreasing trend throughout the rest of the century. A similar trajectory (but without the initial rise) can be observed under the Linear pathway.

The overall impact of the different emission trajectories on atmospheric temperature change is less profound, but nevertheless important, as shown in Fig. 6b. The end-of-century atmospheric temperature change reaches 3.1 °C in the Delayed case while it stays just below 2.7 °C in the Fast transition case.

**Conclusion**

In this paper, we develop an IAM framework to study different green transition pathways (Linear, Delayed, and Fast) and compare them to a Baseline case with no green transition. We decompose the economy into two sectors, namely green and brown, which respectively represent renewable-based and fossil fuel-based economic activities. We investigate the implications of each transition pathway for decarbonization efforts in terms of R&D investment in productivity improvements, capital and labor market transfers, and endogenous technological change.

The results of our analysis highlight some important policy insights for the green transition. First, comparing the trends in labor and capital markets, the results suggest that the main burden of the green transition lies on capital formation, accumulation, and transfer. While the green sector’s labor input share

increases modestly in all pathways, its capital input share grows dramatically and almost triples by the end of the century. However, it is important to note that there are preexisting modeling assumptions and biases that may have contributed to such outcomes. For example, the specific choice of the production function with a higher capital share in the original DICE model underscores the role of capital in the green transition which translates into an increasing trend of saving and endogenous investment in the green sector.

Second, transition pathways appear to rely on different mechanisms to achieve their targets. Under the Fast transition pathway, the rapid growth of the green sector in the first half of the century is mainly accomplished through large transfers of capital from the brown to the green sector. In the Delayed transition pathway however, green capital is accumulated through increased saving rates in the green sector in the first half of the century and is maintained at a high level during the rapid expansion of the green sector throughout the second half of the century. Capital transfer from the brown to the green sector in this pathway, on the other hand, reduces over time, indicating a higher reliance on endogenous capital formation rather than converted capital acquisition. This can further be confirmed by considering the R&D allocations shown in Fig. 5, where the R&D investment share in the green sector is low at the beginning, justifying the need to initially import some capital from the brown sector. As investment in R&D increases over the first few decades under the Delayed transition pathway, green capital becomes more productive, reducing the need for transferring capital from the less productive brown sector.

This leads us to our third finding, which concerns the transition speed. While the abatement rate in the green sector grows steadily but slowly, decarbonization of the brown sector follows the underlying trajectory of the transition pathways and reaches its highest peak under the Fast transition pathway. This is an interesting consequence of our earlier conjectures, expressed above. The Fast transition pathway requires massive transfers of capital from the brown to the green sector in a short period of time, before the green sector can grow endogenously and sustainably. In other words, the Fast transition implies, quite paradoxically, heavy reliance on the brown sector. As a result and to limit the consequences of relying on the dirty sector, abatement in the brown sector needs to increase rapidly under the Fast transition pathway to limit potential climate change damages. Consequently, the rapid growth of the abatement rate in the brown sector leads to a sharp decline in total carbon emissions and a 0.5 °C reduction in global mean temperature change compared to the Baseline case with a fixed share of green consumption.

Finally, it is worth mentioning that the Linear transition pathway lies somewhere between the Fast and the Delayed transition pathways. As a result, while capital transfers from the brown sector decline gradually, the saving rate of the green sector increases steadily, paving the way for a more sustainable and endogenous way to create and accumulate capital in the green sector. Nevertheless, even the linear growth of the green consumption share still requires full allocation of R&D investment to increase the productivity of capital and labor in this sector, similar to the other two transition pathways. This highlights an important fact about the green transition: regardless of the speed of the transition, greening of the economy requires not only a substantial transfer of resources, especially capital, from the brown to the green sector, but also a full allocation of R&D resources to enhance green capital and green labor productivity.

Besides transfer costs and R&D investment expenditures, a sustainable transition, in reality, would also require broad political support and public acceptance at different levels of society. The model presented in this paper does not distinguish between different skill levels of the workforce, nor does it consider structural differences between the two sectors. Therefore, investigating issues at the intersection of climate change and development such as unemployment, inequality, justice, and up-skilling is beyond the scope of the current paper. A more detailed analysis of abatement options and energy transition methods as well as disaggregated climate change impacts on different parts of the production system would provide a better understanding of the transition risks and their broader implications for the economy. Another limitation of our model as well as the original DICE framework is the exclusion of natural resources from the analysis. This shortcoming should be taken seriously and addressed adequately in future modeling developments. Nevertheless, we hope that the 2-sector framework presented in this paper can be a starting point for future research on the interaction between green transition, human capital development, and endogenous technical change. We also acknowledge the fact that there are deep uncertainties in the climate and economic systems that require careful analysis of key parameters and the sensitivity of the main results to their variations.

## Methods

**Summary of Modifications to DICE.** Here we briefly summarize our modifications to DICE. The model's time horizon spans over 250 years starting from the year 2015 with 5-year time steps. In this paper we report the truncated results up until the year 2100. Therefore, we assume that the time horizon is  $t = \{0, \dots, 17\}$  corresponding to the years from 2015 to 2100 in 5-year increments.

- **Economic sectors**

We divide the economy into two sectors (brown sector, and green sector) with each having a designated stock of labor and capital and each factor having a sector-specific productivity. We deploy a two-factor Cobb-Douglas production function to calculate the output of each sector. Total output is calculated as the sum of sectoral outputs.

- **Labor market**

As in the original DICE model, there is only one type of labor input to the production function. We further distinguish between labor working in green and brown sectors. The division of labor between green and brown sector is controlled through the labor transfer mechanism which is a decision variable determined during the optimization.

- **Capital market**

Similarly, capital transfer decision variables are introduced to the model to regulate the allocation of capital to each sector. We assume that the depreciation rate is fixed for capital in both sectors. Sectoral saving rates are also considered as part of the decision variables.

- **Productivity**

We endogenize productivity growth by modeling R&D output allocation dynamics. R&D output is generated from the fixed investment of 2% of total output in every period. This R&D output is then allocated to each sector's capital and labor productivity using new decision variables representing the allocation share to capital and labor in each sector. As the R&D output share allocated to capital and labor productivity improvements in one sector



increases, overall output will grow faster in that sector subsequently.

We model DICE similar to a Markov decision process but without uncertainty. This setup includes a state space, an action space, a transition function, and a reward function.

• State Space

The first modification to the DICE model is to replace its single sector economic model with a 2-sector model. Each sector has its own stocks of capital and labor. Therefore, the global climate-economy system can be defined as a state with 13 continuous variables comprising 5 climate variables and 6 economic variables. Among the list of climate variables,  $T_t^{at}$  denotes atmospheric temperature (degrees Celsius above the pre-industrial level),  $T_t^{oc}$  is the ocean temperature (degrees Celsius above the pre-industrial level),  $M_t^{at}$  is the atmospheric concentration of carbon (Gigatons of Carbon, GtC),  $M_t^{up}$  is the concentration in upper ocean layers (GtC), and  $M_t^{lo}$  is the concentration in deep ocean layers (GtC). Among the list of economic variables,  $A_t^b$  and  $A_t^g$  denote the productivity of capital in the brown and green sectors respectively,  $B_t^b$  and  $B_t^g$  are the productivity of labor in the brown and green sectors respectively,  $K_t^b$  and  $K_t^g$  are the capital stocks (trillions of 2010 USD) in the brown and green sectors respectively, and finally,  $L_t^b$  and  $L_t^g$  are the labor stocks (millions of people) in the brown and green sectors respectively. Therefore, we can define the state space as  $STATE_t = \{A_t^b, A_t^g, B_t^b, B_t^g, K_t^b, K_t^g, L_t^b, L_t^g, T_t^{at}, T_t^{oc}, M_t^{at}, M_t^{up}, M_t^{lo}\}$ .

• Action Space

At each time step, the central planner decides the levels of the following variables: abatement rate in each sector ( $a_t^b$  and  $a_t^g$ ), saving rate in each sector ( $s_t^b$  and  $s_t^g$ ), capital transfer rates indicating the share of capital transferred from one sector to another ( $\kappa_t^b$  and  $\kappa_t^g$ ), labor transfer rates indicating the share of labor transferred from one sector to another ( $\lambda_t^b$  and  $\lambda_t^g$ ), R&D output allocation to capital productivity ( $r_t$ , with the corresponding share allocated to labor being given by  $(1 - r_t)$ ), each sector's share of the R&D allocation to capital productivity ( $\rho_t^b$  and  $\rho_t^g$ ), each sector's share of the R&D allocation to labor productivity ( $\eta_t^b$  and  $\eta_t^g$ ). Note that  $\rho_t^g = 1 - \rho_t^b$  and  $\eta_t^g = 1 - \eta_t^b$ . Therefore the action space is defined as  $ACTION_t = \{a_t^b, a_t^g, s_t^b, s_t^g, \kappa_t^b, \kappa_t^g, \lambda_t^b, \lambda_t^g, r_t, \rho_t^b, \eta_t^b\}$  where every member belongs to the interval  $[0, 1]$ .

• Transition Functions

The gross output of sector  $i \in \{b, g\}$  is calculated from the given level of net capital  $K_t^i$ , productivity of capital  $A_t^i$ , net labor  $L_t^i$ , and productivity of labor  $B_t^i$ .

$$\bar{Y}_t^i = (A_t^i \times K_t^i)^\theta \times (B_t^i \times L_t^i)^{1-\theta}, \quad i \in \{b, g\} \quad (1)$$

where  $\theta^i$  is the output elasticity of capital. Net capital and labor in sector  $i$  are calculated from the gross values ( $\bar{K}_t^i$  and  $\bar{L}_t^i$ ) net of the transfers to and from sector  $j$ :

$$K_t^i = \bar{K}_t^i - \kappa_t^i \times \bar{K}_t^i + \kappa_t^j \times \bar{K}_t^j, \quad i, j \in \{b, g\} \quad (2)$$

$$L_t^i = \bar{L}_t^i - \lambda_t^i \times \bar{L}_t^i + \lambda_t^j \times \bar{L}_t^j, \quad i, j \in \{b, g\} \quad (3)$$

Capital transfer costs ( $\Phi_t^i$ ) and labor transfer costs ( $\Omega_t^i$ ) are assumed to have a polynomial form:

$$\Psi_t^i = \eta_K \times (\kappa_t^i)^{\bar{\eta}_K}, \quad i, j \in \{b, g\} \quad (4)$$

$$\Omega_t^i = \eta_L \times (\lambda_t^i)^{\bar{\eta}_L}, \quad i, j \in \{b, g\} \quad (5)$$

where  $\eta_K$  and  $\eta_L$  are the transfer cost scaling factors, and  $\bar{\eta}_K$  and  $\bar{\eta}_L$  are the transfer cost exponents. As in the original DICE model, we use exogenous population growth projections to obtain the size of the overall labor force in a period:

$$\bar{L}_{t+1}^i = \bar{L}_t^i \times \frac{L_{t+1}^i}{L_t^i}, \quad i \in \{b, g\} \quad (6)$$

where  $L_t^i$  is the exogenous population level at time  $t$  from the original DICE model. Total output is calculated as the sum of sectoral outputs, and R&D output ( $R_t$ ) is a fixed share ( $d$ ) of this total output:

$$\bar{Y}_t = \sum_i \bar{Y}_t^i, \quad i \in \{b, g\} \quad (7)$$

$$R_t = d \times \bar{Y}_t. \quad (8)$$

Capital and labor productivity in each sector evolve through R&D output share allocation:

$$A_{t+1}^i = (1 + \omega_A^i \times r_t \times \rho_t^i)^{\zeta_A^i} \times A_t^i, \quad i \in \{b, g\} \quad (9)$$

$$B_{t+1}^i = (1 + \omega_B^i \times (1 - r_t) \times \eta_t^i)^{\zeta_B^i} \times B_t^i, \quad i \in \{b, g\} \quad (10)$$

where  $\omega_A^i$  and  $\omega_B^i$  are scaling factors, and  $\zeta_A^i$  and  $\zeta_B^i$  are exponents of the productivity growth functions. Beside improving the productivity of capital and labor through R&D investment, in this model we depict improvements in the abatement cost factor  $\Delta_t^i$  through learning-by-doing. The functional form of abatement cost is similar to the original DICE model:

$$\Delta_t^i = \gamma_t \times (a_t^i)^{\bar{\gamma}}, \quad i \in \{b, g\} \quad (11)$$

$$\gamma_t = \gamma_0 \times \left( \frac{A_t^b + A_t^g + B_t^b + B_t^g}{A_0^b + A_0^g + B_0^b + B_0^g} \right)^{-\nu} \quad (12)$$

where  $\gamma_0$  is the abatement cost coefficient,  $\bar{\gamma}$  is the abatement cost exponent, and  $\nu$  is the exponent of the learning curve. Climate change damage cost in sector  $i$  depends on the atmospheric temperature change ( $T_t^{at}$ ):

$$D_t^i = \xi_1^i \times T_t^{at} + \xi_2^i \times (T_t^{at})^2, \quad i \in \{b, g\} \quad (13)$$

where parameters  $\xi_1^i$  and  $\xi_2^i$  are the damage cost coefficients specific for sector  $i$ . The net output of each sector,  $Y_t^i$ , is calculated after subtracting transfer costs ( $\Psi_t^i$  and  $\Omega_t^i$ ), abatement cost ( $\Delta_t^i$ ), and climate damage costs ( $D_t^i$ ):

$$Y_t^i = \bar{Y}_t^i - \Phi_t^i - \Omega_t^i - D_t^i \times \bar{Y}_t^i - \Delta_t^i \times \bar{Y}_t^i, \quad i \in \{b, g\} \quad (14)$$

Total consumption in each sector ( $C_t^i$ ) is calculated after subtracting saving for investment in future capital:

$$C_t^i = (1 - s_t^i) \times Y_t^i, \quad i \in \{b, g\} \quad (15)$$

$$K_{t+1}^i = (1 - \delta) \times K_t^i + s_t^i \times Y_t^i, \quad i \in \{b, g\} \quad (16)$$

where  $\delta$  is the capital depreciation rate and  $s_t^i$  is the saving rate in sector  $i$ . Finally, composite consumption is obtained as a CES function of green and brown consumption:

$$C_t = \left[ \alpha_t \times (C_t^b)^{\frac{\epsilon-1}{\epsilon}} + (1 - \alpha_t) \times (C_t^g)^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} \quad (17)$$

where  $\alpha_t$  is the share of brown output in the composite final consumption good, and  $\epsilon$  is the elasticity of substitution between brown and green consumption.

We assume that initially, the production of one unit of green output emits  $\alpha_0$  times less than the emissions arising from the production of one unit of brown output:

$$\sigma_0^g = (1 - \alpha_0) \times \sigma_0^b \tag{18}$$

Total carbon emissions ( $E_t$ ) therefore consist of sectoral emissions ( $E_t^i$ ) post-abatement,  $a_t^i$ , as well as exogenous sources such as land use change ( $E_t^{exg}$ ):

$$E_t^i = \sigma_t^i \times \bar{Y}_t^i, \quad i \in \{b, g\} \tag{19}$$

$$E_t = \sum_i (1 - a_t^i) \times E_t^i + E_t^{exg}, \quad i \in \{b, g\} \tag{20}$$

where  $\sigma_t^i$  is the carbon intensity of output in each sector, which declines over time according to an exogenous function similar to the original DICE model.

$$\sigma_{t+1}^i = \sigma_t^i \times e^{g\sigma_t^i \times t} \tag{21}$$

$$g\sigma_{t+1}^i = g\sigma_t^i \times (1 + d\sigma^i)^t \tag{22}$$

where  $g\sigma_t^i$  is the growth rate of  $\sigma_t^i$  and  $d\sigma^i$  is the decline rate of decarbonization. The atmospheric and oceanic carbon concentrations in the  $t + 1$  are given by:

$$M_{t+1}^{at} = E_t + (1 - \phi_{12}) \times M_t^{at} + \phi_{21} \times M_t^{up} \tag{23}$$

$$M_{t+1}^{up} = \phi_{12} \times M_t^{at} + \phi_{22} \times M_t^{up} + \phi_{32} \times M_t^{lo} \tag{24}$$

$$M_{t+1}^{lo} = \phi_{23} \times M_t^{up} + \phi_{33} \times M_t^{lo} \tag{25}$$

where  $\phi_{12} \dots \phi_{33}$  are carbon cycle transition coefficients. The equations giving the temperature anomalies in period  $t + 1$  are:

$$T_{t+1}^{at} = T_t^{at} + \tau_1 \times \{F_{t+1} - \tau_2 T_t^{at} - \tau_3 \times \{T_t^{at} - T_t^{lo}\}\} \tag{26}$$

$$T_{t+1}^{lo} = T_t^{lo} + \tau_4 \times \{T_t^{at} - T_t^{lo}\} \tag{27}$$

$$F_{t+1} = \tau_2 \times \log_2 (M_t^{at} / M_0^{at}) + Fex_t \tag{28}$$

where  $\tau_1, \dots, \tau_4$  are temperature coefficients and  $F_{t+1}$  is the radiative forcing, where  $Fex_t$  is exogenous forcing due to anthropogenic emissions of GHGs other than  $CO_2$  (assumed exogenous in DICE).

• Reward Function

The reward is calculated as the social utility of consumption at each time step:

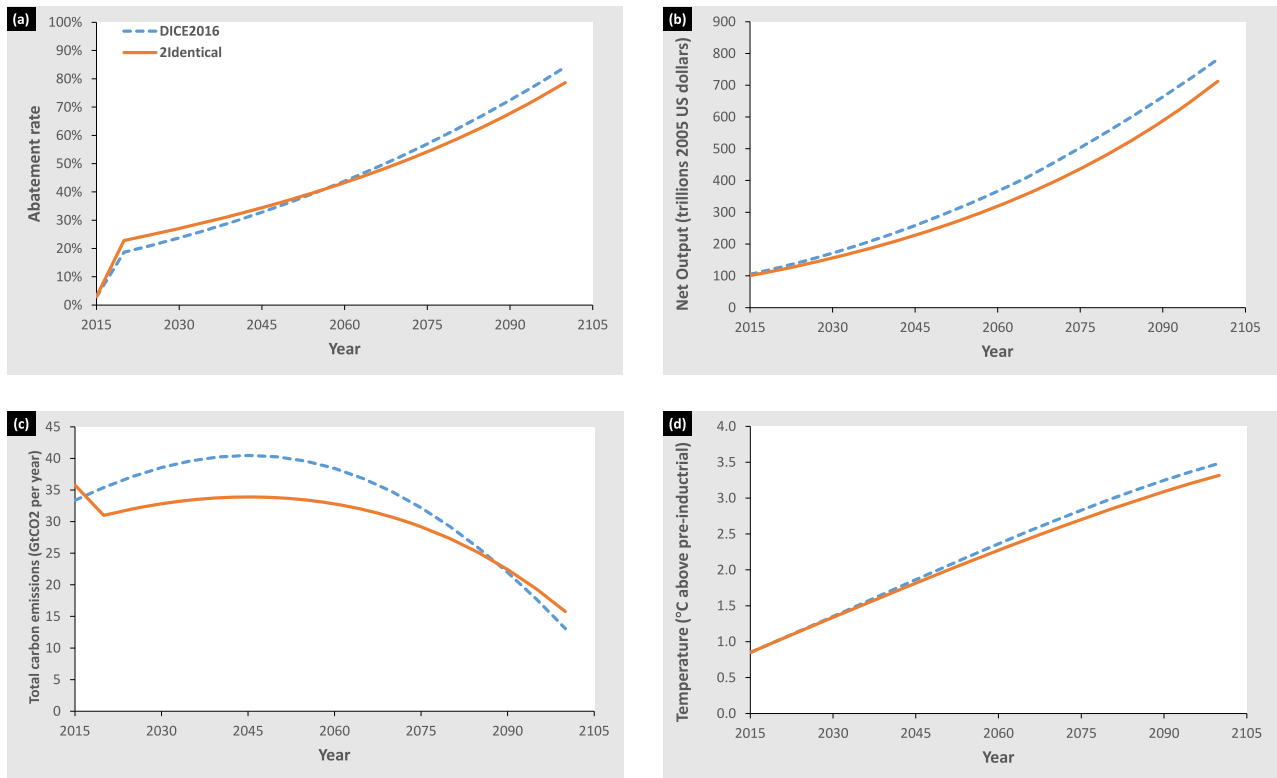
$$U_t = L_t \times \left[ \frac{\left( \frac{C_t}{L_t} \times 1000 \right)^{1-\psi} - 1}{1 - \psi} - 1 \right] \tag{29}$$

where  $\psi$  is the elasticity of marginal utility of consumption and  $L_t$  is the exogenous total population coming from the original DICE model. The objective is to maximize the sum of discounted expected social utilities over the modeling horizon:

$$\max \sum_{t=0}^T \pi^t U_t \tag{30}$$

where  $\pi$  is the discount factor.

**Calibration of parameters in the modified DICE model.** We calibrate the model parameters in order to generate results



**Fig. 7 Calibration of the baseline model with two identical sectors based on DICE2016. a** Abatement rate in percentage, **(b)** net output, **(c)** net carbon emissions, and **(d)** atmospheric temperature change compared to pre-industrial levels.

**Table 2 Key parameters of the 2-sector modified DICE model.**

Parameter	Description	Value
$\theta^j$	output elasticity of capital (both sectors)	0.3
$\eta_K$	capital transfer cost scaling factor	0.001
$\eta_L$	labor transfer cost scaling factor	0.001
$\bar{\eta}_K$	capital transfer cost exponent	2
$\bar{\eta}_L$	labor transfer cost exponent	2
$d$	R&D share of output	0.02
$\alpha_0$	initial share of brown output in final consumption	0.8
$\epsilon$	elasticity of substitution between consumption goods	0.5
$\gamma_0$	abatement cost coefficient	0.1
$\bar{\gamma}$	abatement cost exponent	2.5
$\omega_A^j$	capital productivity scaling factor (both sectors)	$0.5/\alpha_0$
$\omega_B^j$	labor productivity scaling factor (both sectors)	$0.5/\alpha_0$
$\zeta_A^j$	capital productivity exponent (both sectors)	0.5
$\zeta_B^j$	labor productivity exponent (both sectors)	0.2
$\zeta_1^j$	climate change damage cost scaling factor (both sectors)	0.00236
$\zeta_2^j$	climate change damage cost exponent (both sectors)	2
$\nu$	learning rate exponent	0.85
$\delta$	capital depreciation rate	0.1
$\sigma_0^b$	initial carbon intensity of brown output	0.340
$g\sigma_0$	initial growth of $\sigma$	-0.0152
$d\sigma$	decline rate of decarbonization	-0.001

which are comparable to those arising from the original DICE model. First, we develop a baseline model with two identical sectors (i.e., also assuming that both sectors have the same initial emission intensity of output ( $\sigma_0^g = \sigma_0^b = 0.340$ ) instead of Eq. (18)). Each sector is responsible for half of the economic output and, consequently, half of the endogenous emissions. The results of this calibration are presented in Fig. 7.

Beginning from these calibration results, we set the values for the additional parameters in the model. Table 2 lists the key parameters of the model and their values.

**Green transition pathways.** The transition speed to a green economy is controlled by setting a pathway for the share of the brown good in total composite consumption ( $\alpha_t$ ) in Eq. (17). We define the four pathways Baseline, Linear, Delayed, and Fast as follows:

- **Baseline pathway**

In this case, the share of green output in composite consumption remains at 20% until 2100:

$$\alpha_t = 0.80, \quad t = \{0, \dots, 17\} \quad (31)$$

- **Linear pathway**

In this case, the share of green output in composite consumption increases from the initial value of 20% in year 2015 to 90% by 2100 in a linear fashion. This translates into a 0.8% annual decrease (or 4.1% decline over every 5-year time step) in the share of brown output:

$$\alpha_t = 0.80 - 0.041 \times t, \quad t = \{0, \dots, 17\} \quad (32)$$

- **Delayed pathway**

In this case, the share of green output in composite consumption remains at 20% until 2050 and then rapidly increases to reach 90% by 2100. This translates into a fixed share of brown output until 2050, followed by a 7% decline

over every 5-year time step until 2100:

$$\alpha_t = 0.80 \times t, \quad t = \{0, \dots, 7\} \quad (33)$$

$$\alpha_t = 0.80 - 0.07 \times (t - 7), \quad t = \{8, \dots, 17\}$$

- **Fast pathway**

In this case, the share of green output in composite consumption grows fast up to 90% until 2050 and then remains at 90% until 2100. This translates into a 10% decline of the brown output share over every 5-year time step until 2050, followed by a fixed share of 10% until 2100:

$$\alpha_t = 0.80 - 0.1 \times t, \quad t = \{0, \dots, 7\} \quad (34)$$

$$\alpha_t = 0.10, \quad t = \{8, \dots, 17\}$$

**Data availability**

We do not analyze or generate any datasets, because our work proceeds within a theoretical and mathematical approach. Model outputs are publicly available<sup>52</sup>.

**Code availability**

All codes used in this paper are publicly available<sup>52</sup>.

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## Author contributions

S.S. designed the study and led the writing of the paper. S.S. and S.R. contributed data and analysis. S.S., S.R., E.R., and M.C. contributed to the development of the model. All authors contributed to the editing and discussion of the paper.

## Competing interests

The authors declare no competing interests.

## Additional information

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**Correspondence** and requests for materials should be addressed to Soheil Shayegh.

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