The Impact of Sustainable Innovation Finance on Global Climate Goals

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Abstract

This paper investigates the impact of financial frictions on sustainable economic growth in the global economy. We present a model of endogenous directed technical change including a public and private financial sector, allowing for an endogenous financing decision in terms of internal and different external financing of technical change. Capturing the dynamics between the 'global North', i.e., the developed economies, and the 'global South', i.e., the developing economies, we allow for technological development to occur through innovation or imitation, hence, capturing technology diffusion processes in the global economy.

Our findings substantiate the way in which the presence of financing costs and frictions in the financial markets—which are elevated with regards to sustainable innovation and in the developing world—cause the global economy to converge towards a non-sustainable growth path in the absence of policy intervention. This development can be addressed partially, but not fully, by sustainable public investment. However, to steer the economy to a fully sustainable growth path, an additional regulation or incentivization of private investors is necessary. Alternatively, a sufficiently high carbon price can be set, however, other than in the current reality, this carbon price would have to cover a large share of global emissions.

List of abbreviations

BEV	Battery electric vehicle
BGP	Balanced growth path
CAPEX	Capital expenditure
CCUS	Carbon capture, utilization, and storage
CES	Constant elasticity of substitution
CRRA	Constant relative risk aversion
ECB	European Central Bank
ESG	environmental, social and governance
E1	Economies 1 ('Global North')
E2	Economies 2 ('Global South')
FI	Financial intermediaries
FOC	First-order condition
GDP	Gross domestic product
G7	Group of Seven
HH	Household
ODE	Ordinary differential equation
PF	Production Function
PPP	Public-private partnerships
ROI	Return on investment
R&D	Research and development
RES	Renewable energy sources
ROW	Rest of the World
SM	Supplementary material
VC	Venture capital

1 Introduction

For the achievement of climate goals, a development of low-carbon technologies plays a key role. This is especially, if the transition to a sustainable economy is supposed to not take place at the expense of economic performance[3] (e.g., IEA, 2021a for the energy sector). The achievement of climate goals is a global effort, and technological developments must take place across both developed and developing economies[4]. Both the innovation and the diffusion of cutting-edge technologies require considerable investment volumes (cf., e.g., Pollitt & Mercure, 2018; BCG, 2021). However, in both developed and developing economies, financial constraints such as limitations in cash availability and constrained access to external financing options such as private and public equity and debt impose severe challenges to raising sufficient capital for investments. The current macroeconomic environment characterized by increasing inflation and rising interest rates further aggravates the constraints (IMF, 2014; 2020; 2021; Sinn, 2021). While this holds true for the financing of any kind of investment, the financing of innovation faces additional challenges. Outcomes of research and development (R&D) are uncertain by nature, and information asymmetries often increase the uncertainty for potential financial investors (Kerr and Nanda, 2015; Hahn et al., 2019). Also, innovators are often young, small, and technology-intensive firms with, hence, unfavorable risk profiles, for instance lacking any substantial collateral (cf., Hall and Lerner, 2010; Ascani et al., 2020).

These challenges are aggravated in the sustainable innovation space. To underpin this, it is worthwhile to illuminate more closely the nature of the required technology to be subject to innovation, the actors involved in the innovation processes, as well as the potentially available financing vehicles and financiers. The most GHG-intensive sectors are the energy industry, the buildings sector, the transport sector, as well as the aggregate remaining industry, followed by other emitting sectors such as agriculture[5] (e.g., BCG, 2021). All these sectors are infrastructure-

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[3] Currently measured in growth targets. A discussion of an adjustment of growth targets by alternative metrics exists, see literature related to non-growth economics, e.g., Daly (1973), Raworth (2017).

[4] This generally holds true if all climate targets are supposed to be reached. The question of the distribution of effort and costs, in particular between the industrialized, developed economies (often referred to as 'Global North') and the less industrialized, developing economies (often referred to as 'global South') is controversial (e.g., Shue, 1993; Caney, 2010).

[5] Depending on the economic structure of different countries, the size and the emission intensities of these emitting sectors can vary. For instance, in developing economies, where agriculture represents a large part of economic output, the shares of total GHG emissions emitted by this sector are generally higher than in developed economies, where agriculture represents a smaller part of economic output.

heavy[6], and within all these sectors, a reduction of greenhouse gas (GHG) emissions requires a replacement or improvement of the legacy infrastructure. For instance, in the energy industry, fossil energy power plants need to be replaced by power plants based on renewable energy sources (RES), and the electricity grid needs to be modified in a way that it serves the RES-based system (cf. Schreiner and Madlener, 2021; 2022). In the transport sector, alternative drive technologies such as battery electric vehicles (BEV) can reduce GHG emissions, entailing the need for an according charging infrastructure, and production and recycling facilities for batteries. In the manufacturing industry, for instance, more energy-efficient machine parks, or carbon capture, utilization, and storage (CCUS) facilities can be installed. All these examples highlight that investments in innovation in sustainable technologies are characterized by high capital expenditure (CAPEX) intensities. Furthermore, investments related to infrastructure are usually characterized by comparably small expected returns. In the case of infrastructure investments based on mature technologies, these small expected returns come along with low-risk profiles of the investments, which make them attractive investment options for investors looking for low-risk-low-return profiles such as institutional investors (cf., e.g., Della Croce and Yermo, 2013; OECD, 2021). When considering investments into innovative sustainable infrastructure, however, both the expected returns and the risk profiles are often less attractive. Unless environmental externalities are fully internalized[7], investment decisions into sustainable innovation can be motivated by non-monetary goals and thus, investment decisions are not necessarily based on a return on investment (ROI) approach in monetary terms. Hence, revenues tend to be smaller, while risk is elevated, especially given policy uncertainty regarding green premia, and increasing merchandising risk. Besides, path dependencies and lock-in effects can make innovation in the sustainable space the less attractive investment option (cf., Awerbuch, 2000; Mazzucato, 2013, 2018; Yu et al., 2021). Due to the nature of sustainable innovation being infrastructure-heavy, as well as due to the global nature of the sustainability transition, actors involved in the sustainable innovation process stem from both the public and the private sectors, and they involve economies across the globe. Sustainable innovation is, hence, an effort requiring both public-private and transnational cooperation (cf., e.g., Dechezleprêtre and Sato, 2017; He and Tian, 2018; Owen et al., 2018; D'Orazio and Valente, 2019). These characteristics impact the attractiveness of the

[6] Often including critical infrastructure. We deploy a broad definition of infrastructure, involving not only infrastructure facilities, which are subject to market failures such as network effects such as the electricity grid, but also any form of CAPEX-heavy facilities, such as power plants.

[7] Either by pricing environmental externalities adequately, for instance by setting a carbon price, or caused by buying decisions which reflect a willingness to pay a sustainability premium.

sustainable investment options to different financiers in different ways[8]. In general, however, the outlined financing challenges of sustainable innovation can be expected to lead to considerable underinvestment and a constrained development of sustainable technologies (cf., e.g., Mercure et al., 2019). Improving financing conditions for sustainable innovation is, hence, an indispensable lever to successfully achieve climate policy and sustainable development goals.

Despite its vital role, not much research exists regarding the way in which the financing of sustainable innovation impacts the achievement of global climate policy and sustainable development goals, which inefficiencies regarding sustainable innovation arise from financing constraints, and which measures can be taken to address these inefficiencies.

This paper attempts to contribute to filling this lacuna by incorporating financing decisions in an environment of imperfect capital markets into a model of directed technical change based on innovation and imitation activities in developed and developing countries.

We find that in the absence of financing costs and financing frictions, the economy converges to a partially sustainable state, with the level of sustainability being positively influenceable by adequate policy intervention, such as an adequately high carbon price. However, the presence of financing costs and frictions in the financial markets, which are elevated with regards to RES-related innovation and in the developing world, causes the global economy to converge towards a non-sustainable growth path. This development can be addressed partially, but not fully, by sustainable public investment. However, to steer the economy to a fully sustainable growth path, an additional regulation or incentivization of private investors is necessary. Alternatively, a sufficiently high carbon price can be set, however, other than in the current reality, this carbon price would have to cover a large share of global emissions, both in terms of sectoral coverage and the economies participating in such an approach.

2 The Current State of the Research and our Contribution

Our paper builds upon and contributes to different strands of literature related to (A) endogenous growth and innovation, (B) innovation finance and capital structure decisions, and (C) literature assessing how the decision-making and dynamics in the financial economy assessed

[8] External financing can, for instance, be provided by private actors such as private banks, equity funds including venture capital (VC) funds, and corporates, or public intermediaries such central banks, development banks or governments. Different groups of investors have different preferences depending on the characteristics of sustainable innovation itself or the characteristics of the innovator. Different forms of financing are, due to their distinct characteristics, better or less well suited for the financing, given the distinct characteristics in the green and non-sustainable spaces and the different investment environments in developed and developing economies.

in the latter literature strand impact the dynamics of the real economy assessed in the former literature strand. Contributions in all three fields have emerged irrelated to sustainability considerations, but with the increasing relevance of the sustainable and green developments, many contributions have enhanced the fields by adding a sustainability perspective. In relation to our paper, hence, sustainability-irrelated contributions often provide the theoretical foundations, which then have been further adjusted and developed, while the fundamental insights are still relevant as a basis for our research. Table 1 provides an overview of the three related literature strands and sub-strands, as well as a brief description in the spaces irrelated and related to sustainability. The grey highlighted field points to the field of our contribution.

Table 1: Strands of Related Literature

Literature Strand	Sub-strand	(I) Sustainability-irrelated	(II) Sustainability-related
(A) Real economy: Endogenous growth and innovation	(A.1) Growth, innovation, and technological diffusion	Endogenous innovation and technology diffusion as explanation for growth	Green growth models, incorporating environmental externalities
	(A.2) Directed technical change	Direction of technological change based on path dependencies and lock-in effects	Models of directed technical change including 'clean' and 'dirty' sectors
	(A.3) Climate policy models & sector-specific models	N.a., as rooted in the sustainability-related space	Climate models to assess the impact of environmental policies or sector-specific models to assess, e.g., aspects of the energy transition
(B) Financial economy: Innovation finance and optimal capital structure	(B.1) Optimal capital structure decisions and private innovation financing	Explanations for the capital structure decisions of corporates, i.e., the choice between debt, equity, and other financing options	Considerations re. adequate financing of sustainable innovation, often in the context of the energy transition
	(B.2) Public-private innovation finance	The role of the public sector (i.e., governments) in innovation and innovation finance	Financing innovation with non-profit goals, e.g., 'Mission-oriented' R&D, public-private partnerships, innovative financing instruments
(C) Real and financial economy: Impact of financing on real economy	(C.1) Finance in innovation and technological diffusion & in the energy transition	The impact of dynamics in the financial sector on real economy outcomes, e.g., re. innovation volumes and direction	• The impact of dynamics in the financial sector on green growth & the achievement of climate goals • Sector-specific models incorporating the financial economy, e.g., E3 models incorporating a financial sector

Note: Our contribution located in the grey highlighted field.

In the following, we provide a description of seminal contributions in the field. A summary of the contributions can be found in the Appendix A.

2.1 Real Economy: Endogenous Growth and Innovation (A)

Endogenous growth theories emerged in the late 20th century as an alternative to the neoclassical growth models, emphasizing the role of innovation and technology in long-term economic growth. Other than in the neoclassical growth models, in which growth is exogenous, growth is driven by endogenous factors, such as human capital accumulation, knowledge spillovers, or R&D activities, rather than just exogenous factors like population growth or capital accumulation (cf., Novales et al., 2022). Within the field of endogenous growth theories, growth models focusing on the role of knowledge and innovation provide the background for our considerations. While their origin is not related to sustainability considerations, endogenous growth theories based on innovation have been adjusted and developed to reflect sustainability considerations.

2.1.1 Growth, Innovation, and Technological Diffusion (A.1)

Amongst the growth models focusing on innovation, our research builds upon the class of models in which innovation is reflected as an increasing number of producer products, i.e., product variants, and growth is caused by spillover effects. The approach roots back to the Romer model (Romer, 1986; 1987; 1990), which explains growth within a one-country, one-sector economy, in which a representative producer of a final good deploys an increasing number of intermediate input varieties. The increase in varieties—which can also be interpreted as knowledge accumulation[9]—has an effect of an increase in the overall economic efficiency, which is comparable to the effect of an increase in total factor productivity (TFP). Subsequent approaches have refined the theory. A seminal contribution stems from Barro and Sala-i-Martin (1997), which adds a technology diffusion process to the model. The model establishes the concept of a leader country, in which—as in the Romer model—new product variants emerge through innovation, and a follower country, which copies existing product varieties from the leader country. By doing so, the model allows to capture dynamics between developed and developing economies.

Building upon the insights from the endogenous growth models, multiple approaches have been taken to reflect sustainability considerations in endogenous growth models. Seminal contributions in the field stems from Nordhaus (1994, 2013). The DICE (Dynamic Integrated Climate-Economy) model, developed by William Nordhaus, is an integrated assessment model that combines economic growth and climate change dynamics. It focuses on the interplay between economic activity, greenhouse gas emissions, and the resulting impacts of climate change and is

[9] As compared to other growth models based on product variants such as the one established by Aghion and Howitt (1992), which is based on creative destruction, meaning that, other than in the Romer model, with the emergence of a new product variant, the established variant becomes obsolete. Other contributions such as Acemoglu and Cao (2015) have merged the two approaches, and included different aspects, such as the role of institutions and policy interventions, the role of technology markets (Peretto, 1998; Akcigit et al., 2016; 2018) or the role of patents (Grossman and Lai, 2004; Zeira, 2011; Aghion et al., 2015).

designed to estimate the optimal path of carbon emissions and climate policy by considering the costs and benefits of reducing emissions. While the original DICE model did not include endogenous growth, developments of the model do (cf. e.g., Goulder and Mathai, 2000). Furthermore, other approaches exist. Popp (2002; 2004; 2006), explore the relationship between energy use and prices, technological change, and economic growth, Brock and Taylor (2010) integrate environmental factors into the traditional Solow growth model, examining the impact of natural resource constraints and environmental quality on long-term economic growth, and Van der Ploeg and Withagen (2012) investigate the role of natural resources in economic growth in a growth model based on learning-by-doing, where productivity improvements occur as a result of accumulated experience in the extraction and use of natural resources.

2.1.2 Directed Technical Change (A.2)

A particular type of endogenous growth models develops the concept of directed technical change, which emphasizes that 'innovation does not only have a size, but also a direction' (Acemoglu et al., 2012). The idea of directed technical change has been introduced by Acemoglu (1998, 2002), who studies how the direction of technological progress—shown on the example of a two-sector model—can be influenced by relative factor prices and by market sizes. Doing so, the paper conceptualized path dependencies and lock-in effects affecting the type of innovation occurring in an economy.

The idea of directed technical change has been applied to questions around optimal policy intervention regarding the achievement of climate goals, which had been previously treated, *inter alia*, by means of the sustainability-related growth models introduced above. Acemoglu et al. (2012) apply the concept of directed technical change towards one of two sectors to the case of a 'clean' and a 'dirty' sector, the direction of the change following the same mechanisms as in their previous, sustainability-irrelated work. Other than in Acemoglu (2002), however, the endogenous growth mechanism is not based on the emergence of product variants, but on an increasing factor productivity in the intermediate goods production function (PF). The model of 'Directed Technological Change and the Environment' is complemented by the accumulation of GHG emissions, which impose disutility on households (HH), and which, eventually, lead to an environmental collapse, after the accumulated emissions have reached a 'tipping point'. The conclusion of the work is that immediate and decisive intervention is necessary to break path dependencies and set the world economy on a path of 'clean' innovation.

2.1.3 Climate Policy Models and Sector-specific Models (A.3)

Apart from the originally sustainability-irrelated macroeconomic growth models incorporating sustainability, various other approaches investigating the role of sustainability in economic developments exist. One type of approach are energy and environmental models, in which some form of endogenous technical change has been incorporated, such as in Grubb et al. (2002), Gillingham et al. (2008) and Goulder et al. (2016). These approaches take different economic models, such as equilibrium models or sector-specific partial equilibrium models and build in some form of endogenous technical change.

2.2 Financial Economy: Innovation Finance and Optimal Capital Structure (B)

Shedding light on the financing of sustainable innovation builds upon two broad strands of literature, which deal with innovation financing of private actors such as corporates or entrepreneurs, as well as their decision-making regarding their optimal capital structure on the one hand, and innovation finance involving public-private cooperation on the other.

2.2.1 Optimal Capital Structure Decisions and Private Innovation Financing

Contributions re. optimal capital structure decisions seek to find explanations for the capital structure decision of private companies, i.e., their selection and composition of different internal and external financing instruments such as cash, debt, or equity. Thus, contributions in the field are not solely related to innovation financing, but rather cover capital structure decisions for all kinds of investments including the financing of innovation (Straebulaev and Whited, 2012).

With their seminal work ‘The Cost of Capital, Corporation Finance, and the Theory of Investment’, Modigliani and Miller (1958) established the Modigliani-Miller Theorem which postulates that under the assumption of perfect capital markets, the firm value is unaffected by its capital structure, and the financing decision is irrelevant. However, empirical evidence suggests that many capital market imperfections in the form of financial frictions incl financing frictions[10] exist. Hence, manifold approaches have been developed, adducing different forms of capital

[10] Financial frictions usually refer to a broader range of imperfections of financial markets incl. financial intermediaries. They include financing frictions, referring to the barriers or difficulties that companies face in obtaining external financing arising due to a variety of factors, such as asymmetric information between lenders and borrowers, transaction costs, or legal and regulatory restrictions. Beyond this, financial frictions also encompass a broader set of issues related to financial market imperfections such as market incompleteness, agency problems, and externalities (Gertler and Kiyotaki, 2010).

market imperfections as an explanation for firms' capital structure decision. These approaches include the trade-off theory, the pecking order theory, and the market timing theory, which have been applied specifically to innovation financing. The trade-off theory posits that firms choose a mix of debt and equity that balances the tax advantages of debt with the costs of financial distress, which may arise if a firm cannot meet its debt obligations and is forced to default or restructure its debt. This theory suggests that firms with stable cash flows and tangible assets, such as property and equipment, are more likely to use debt financing to fund innovation, while firms with less stable cash flows and intangible assets, such as intellectual property, are more likely to use equity financing (Kraus and Litzenberger, 1973; Scott, 1976; Miller, 1977; Fama and French, 2002). The pecking order theory proposes that firms prefer internal financing, such as retained earnings, to external financing, such as debt and equity, to fund innovation; and equity over debt financing[11] (Brown et al., 2009; 2015). This is because internal financing does not require firms to give up control or incur transaction costs, mainly caused by information asymmetries and moral hazard (Donaldson, 1961; Myers and Maljuf, 1984). The market timing theory suggests that firms may time their issuance of debt and equity to take advantage of market conditions. It proposes that firms will issue equity when their stock prices are high, and debt when their stock prices are low, to maximize their financing flexibility and minimize their cost of capital. In the context of financing innovation, the market timing theory suggests that firms may be more likely to issue equity to fund high-risk, high-reward projects, and debt to fund lower-risk projects with more predictable cash flows (Baker and Wurgler, 2002; Lynadres, 2007; Baker and Martin, 2011). These theoretical approaches have been widely reflected in approaches to financial modelling (for an overview see Streabulaev and Whited, 2012). Furthermore, other determinants of the optimal capital structure choice such as different macroeconomic conditions, e.g., in developed vs. developing economies have been analyzed for instance by Korajczyk and Levy (2002), or Booth et al. (2001). Kerr and Nanda (2015) provide a literature re. the latter aspect.

In the context of sustainable finance and sustainable innovation finance, apart from these general factors, there are other, more particular factors impacting the capital structure decision one the one hand, and the financing availability and costs on the other (Haqiqi and Mirian, 2015). Helms et al. (2015), for instance, emphasize the difference in both the investment characteristics

[11] This hypothesis is also controversially discussed: depending on the nature of the investment, equity financing can be preferrable, since, firstly, it does not require a collateral, and, secondly, unlike providers of debt, equity investors share in the upside of the investment. This can make external equity cheaper and more favorable than external debt (Brown, et al., 2009; 2015).

and the investor base of RES vs. fossil energy infrastructure, as well as frictions arising from a limited access to knowledge and human resources and information asymmetries. Noally and Smeets (2016) particularly shed light the effects of the usually smaller firms investing in the sustainable innovation space. Egli et al. (2022) emphasize the relatively higher impact of the cost of capital—which can change over time, e.g., due to changing interest rates (Schmitt et al., 2019)—on RES-related investments, compared to rather high operational expenditure (OPEX) technologies in the fossil space (see also Steffen, 2020; Polzin et al., 2021; Steffen and Waidelich, 2022) and Ameli et al. (2021) for a perspective involving developing economies. BCG (2023) provide a more applied approach and outline different risk-related financing frictions of sustainable technologies, such as elevated technology and merchandising risk accompanied by information asymmetries and leading to prohibitively high risk premia, making many sustainable technology projects unbankable.

2.2.2 Public-private Innovation Finance (B.2)

Financing involving private actors such as private corporates and public stakeholders such as governments and development banks is another area of interest in capital structure decisions. In this context, firms may seek financing from both private and public sources, each of which may have different objectives and expectations for the use of funds. Several theories have emerged to explain how firms choose to finance their operations and growth initiatives in this complex environment, including the agency theory, the stakeholder theory, and the signaling theory (cf. e.g., Jensen and Meckling, 1976; Freeman, 1984).

Regarding sustainable innovation finance, public private approaches are often seen as the means to close investment gaps, as well as to allocate risks in a more efficient manner (cf., e.g., OECD, 2017; 2020). In this context, *inter alia* OECD (2019) investigate the role of alternative financing vehicles in sustainable finance, including, for instance, public-private partnerships (PPP). Regarding more specific characteristics and criteria for an efficient setup and design of such alternative vehicles, different streams of specialized in-depth research exist. For instance, regarding PPPs, Roumboutsos and Saussier (2014) investigate which type of PPP contract most efficiently incentivizes public-private innovation. Aghion et al. (2013) more generally investigate the effects of institutional ownership on innovation.

2.3 Real and Financial Economy: Impact of Financing on Real Economy (C)

2.3.1 Finance in Endogenous Growth and Innovation (C.1)

In recent years, the incorporation of financial frictions in macroeconomic growth models has emerged as a crucial area of research in the field of macroeconomics. The seminal works of Bernanke and Gertler (1989) and Kiyotaki and Moore (1997) laid the foundation for the study of credit market imperfections and their impact on macroeconomic outcomes. To explore the importance of financial frictions in business cycle dynamics, Christiano, Motto, and Rostagno (2003) and Bernanke, Gertler, and Gilchrist (1999) developed dynamic stochastic general equilibrium (DSGE) models that incorporate financial frictions and demonstrated their significance in explaining economic fluctuations. Gertler and Kiyotaki (2010) provide further insights into the role of financial intermediaries (FI) in transmitting shocks to the real economy. Another line of research has focused on the role of financial frictions in shaping long-term economic growth. Aghion, et al. (2005) and Levine (2005) have shown how financial frictions can hinder the efficient allocation of resources and impede technological progress, ultimately affecting growth prospects. More recently, Midrigan and Xu (2014), Mendoza and Quadrini (2018) and Elenev et al. (2020) have explored the implications of financial frictions for international trade and capital flows, highlighting the interdependence between financial markets and macroeconomic growth across countries. On the development economics side, for instance Brunnschweiler (2010) explore the relation between financial development and real economic development.

Regarding the impact of financing sustainable innovation, the role of finance has been considerably underestimated (Mercure et al., 2019). De Haas and Popov (2022)—providing some empirical insights re. the relationship between finance and green growth—point to the limited understanding of the relation between regular finance and the environment and emphasize that to date, no rigorous evidence exists on how finance effects industrial pollution as economies grow and its relevance for a large scale decarbonization transition and its impact on the macroeconomy. For instance, only few of the current E3 models have representations of a stylized financial sector, (e.g., as in GEA, 2012; IPCC, 2014b; Kriegler et al., 2014; Pollitt & Mercure, 2018). Besides these energy-specific approaches, some empirical evidence exists regarding the way in which sustainable innovation finance and the type of financiers impact the type of innovation. Ghisetti et al. (2015) and Noally and Smeets (2016) qualitatively describe the role of financing constraints for directed technical change from fossil fuel to renewable innovation. Mazzucato (2013, 2018) and Mazzucato and Semieniuk (2018) describe the impact of the type of finance on direction of innovation, mainly making a distinction between public and private finance, and give recommendations regarding how to regulate the financial sector to better serve public goals based on an empirical study of the preferences and investment patterns of different public and private financiers regarding sustainable vs. non-sustainable investments. Furthermore, and referring to the impact of the European Central Bank (ECB) as financier for sustainable innovation, Papoutsi et al. (2022) present an assessment of the impact of quantitative easing on sustainable developments in the economy. The analyses provided in the following contribute to this strand of literature, providing an approach to conceptualize the way in which dynamics in the financial sector impact sustainable vs. non-sustainable innovation.

3 The Model

3.1 Summarizing model description

We present a continuous-time model of endogenous directed technical change in a RES-based and a fossil-based sector, with endogenous decisions for innovation finance in both sectors.

The model considers two types of global economies, the leader countries, representing the global North, and the follower countries, representing the global South, denoted with the subscripts $i = 1,2$. In both economies, growth is achieved through the emergence of new varieties of intermediate goods, N_i, which can be created through either innovation, if the product variety has not existed in either of the economies previously, or through imitation, if the product variety has already existed within the respectively other economy. These dynamics are comparable to the growth model based on endogenous innovation presented by Barro and Sala-i-Martin (1997). Within each economy, a RES-based and a fossil-based type of intermediate goods exist, denoted with the subscripts $k = r, f$. RES-based intermediate goods represent all intermediate goods, which are produced by means of “clean” energies and technologies, and which we assume to be carbon neutral. Fossil-based intermediate goods represent all intermediate goods, which are produced by means of “dirty”, GHG-emitting energies and technologies. This conceptualization is comparable to the model of the environment and directed technical change presented by Acemoglu et al. (2012).

Intermediate goods producers in both economies and in both sectors cannot finance costly innovation and imitation activities fully internally[12] but are also dependent on external financing

[12] With reference to the pecking order theory, and resonating that innovation has intrinsic properties that make it difficult to finance externally, we assume that the preference of intermediate goods producers is to finance innovation internally to the largest extent possible (cf., Noally and Smeets, 2016).

options. Based on insights from theories of the optimal capital structure of investments, intermediate goods producers can decide between different debt and equity financing options, as they seek to maximize their firm value and minimize their innovation and imitation costs including their financing costs. Financing options are provided by two types of financial intermediaries. Private financial intermediaries such as lender banks, credit funds or equity funds including venture capital (VC) funds offer private debt and equity, seeking to maximize their shareholders' revenues. Public financial intermediaries subsume public institutions such as governments and development banks and offer public debt and public financing options with equity characteristics, such as project participations or availability-based public-private partnerships (PPP). Other than private financial intermediaries, public financial intermediaries do not seek to maximize shareholder revenues, but to maximize stakeholder benefits by efficiently—i.e., at the optimal cost-benefit ratio—supporting non-financial goals such as GHG reductions.

3.2 The Households

We consider an infinite-horizon continuous-time economy, admitting Ramsey-type households (HH) with the standard constant relative risk aversion (CRRA) preference,

$$U_i = \int_0^\infty e^{-\rho t} \frac{C_i^{1-\theta} - 1}{1-\theta} dt \, , \tag{1}$$

with HH utility U_i, a constant rate of time preference $\rho > 0$, a constant elasticity of the marginal utility of consumption[13] $\theta > 0$, and consumption C_t. The HH supply labor inelastically, which yields competitive wages denoted by w_k with $k = r, f$. We assume the number of HH members, i.e., the population, to be constant over time, but allow them to differ between the leader and the follower economies.

3.3 The Final Goods Sector

There is one consumption good in each economy, consisting of two types of final goods. $Y_{r,i}$ denotes the final good which is produced from RES-based intermediate inputs, $Y_{f,i}$ the final good produced from fossil-based intermediate inputs. $Y_{r,i}$ and $Y_{f,i}$ are imperfect substitutes with a constant elasticity of substitution (CES),

$$Y_i = \left[\gamma Y_{r,i}^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma) Y_{f,i}^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{2}$$

[13] The inter-temporal elasticity of substitution is then the reciprocal value $1/\theta$.

with ε being the elasticity of substitution and γ being a distribution parameter determining the importance of the RES-based and fossil-based final goods in the aggregate production of the consumption good. The RES-based and fossil-based types of final goods are produced competitively according to the Cobb-Douglas type production functions

$$Y_{r,i} = A_{r,i} \frac{1}{1-\beta} \int_0^{N_{r,i}} \left(x_{r,ij}\right)^{1-\beta} dj \, {L_{r,i}}^{\beta} \tag{3}$$

and

$$Y_{f,i} = A_{f,i} \frac{1}{1-\beta} \vartheta_i \int_0^{N_{f,i}} \left(x_{f,ij}\right)^{1-\beta} dj \, {L_{f,i}}^{\beta} \tag{4}$$

with ϑ_i being the carbon emissions per fossil intermediate input deployed, $A_{k,i}$ being the overall total factor productivity (TFP) of the RES-based and the fossil-based final goods sectors in the economy, $L_{k,i}$ being the labor dedicated to the production of the two types of final goods, and $N_{k,i}$ being the intermediate goods variants. Final goods producers in both sectors take factor prices as given and maximize their profits according to

$$\max_{x_{r,i}, L_{r,i}} (1-\tau_i) p_{r,i} Y_{r,i} - w_{r,i} L_{r,i} - \int_0^{N_{r,i}} \psi_{r,ij} x_{r,ij} dj, \tag{5}$$

and

$$\max_{x_{f,i}, L_{f,i}} \left(1-\tau_{ij}-\tau_i^{CO2}\right) p_{f,t} Y_{f,t} - w_{f,t} L_{f,t} - \int_0^{N_{f,i}} \psi_{f,ij} x_{r,ij} dj \,, \tag{6}$$

with τ_i being the economy's tax rate and $\psi_{r,ij}$ and $\psi_{f,ij}$ being the prices for the intermediate goods[14]. From the profit maximization problem[15], we obtain the iso-elastic demand curves for the intermediate goods

$$x_{r,ij} = \left(\frac{(1-\tau_i) p_{r,i} A_{r,i}}{\psi_{r,i}}\right)^{\frac{1}{\beta}} \; L_{r,i}, \tag{7}$$

and

$$x_{f,ij} = \left(\frac{\vartheta_i \left(1-\tau_i-\tau_i^{CO2}\right) p_{f,i} A_{f,i}}{\psi_{f,i}}\right)^{\frac{1}{\beta}} \; L_{f,i}. \tag{8}$$

The wages in the production of the two outputs are

[14] We assume that each RES-based intermediate good is produced at the same amount, i.e., $x_{k,ij} = X_{k,i}/N_{k,i}$ and is sold to the final goods sector for the same price, i.e., $\psi_{k,ij} = \Psi_{k,i}/N_{k,i}$, with $X_{k,i}$ being the total amount of intermediate goods, and $\Psi_{k,i}$ being price for the total number of variants.

[15] For the derivation, see supplementary material (SM) 1.1.

$$w_{k,i} = \left(1 - \tau_i - \tau_{k,i}^{CO2}\right) A_{k,i} \frac{\beta}{1-\beta} p_{k,i} \left(\int_0^{N_{k,i}} \left(x_{k,ij}\right)^{1-\beta} dj \right) L_{k,i}{}^{\beta-1}, \tag{9}$$

with $\tau_{r,i}^{CO2} = 0$. Following Aghion and Howitt (1992), Acemoglu (2002) and Acemoglu et al. (2012), in equilibrium, the relative prices of the RES-based final goods and the fossil-based final goods, $p_{r,i}/p_{f,i}$, must equal the marginal rate of substitution in demand between the two goods, depending on the relative quantity $Y_{r,i}/Y_{f,i}$ according to

$$p_i \equiv \frac{p_{f,i}}{p_{r,i}} = \frac{1-\gamma}{\gamma} \left(\frac{Y_{f,i}}{Y_{r,i}} \right)^{-\frac{1}{\varepsilon}}, \tag{10}$$

with $\varepsilon > 0$. Choosing the ideal price index of the final good as the numéraire implies

$$\left[\gamma^{\varepsilon} p_{r,i}^{1-\varepsilon} + (1-\gamma)^{\varepsilon} p_{f,i}^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}} = 1, \tag{11}$$

And, thus, reveals the relation of the prices of the RES-based and fossil-based final goods,

$$p_{r,i} = \left(\frac{1-(1-\gamma)^{\varepsilon}}{\gamma^{\varepsilon}} \right)^{\frac{1}{1-\varepsilon}} p_{f,i}. \tag{12}$$

3.4 The Intermediate Goods Sectors

3.4.1 Overall Description of the Intermediate Goods Sectors

As described above, in both economies, intermediate goods producers can either imitate or innovate to the end of developing new varieties of intermediate goods, with the total number of varieties $N_{k,i}$ in each economy being

$$N_i = N_{r,i} + N_{f,i} = N_{r,i}^I + N_{r,i}^C + N_{f,i}^I + N_{f,i}^C, \tag{13}$$

with $N_{k,i}^I$ being the number of innovated goods, and $N_{k,i}^C$ being the number of imitated ("copied") goods. We define the shares of innovated variants in the total variants, $\lambda_{k,i}$, as

$$\lambda_{k,1} \equiv \frac{N_{k,1}^I}{N_{k,1}} = \left(\frac{N_{k,2}}{N_{k,1}} \right)^{\frac{b}{2}}. \tag{14}$$

and

$$\lambda_{k,2} \equiv \frac{N_{k,2}^I}{N_{k,2}} = \left(\frac{N_{k,2}}{N_{k,1}} \right)^{b}, \tag{15}$$

to ensure that $\lambda_{r,2} \leq \lambda_{r,1}$, meaning that the leader countries have a higher proportion of innovated goods as compared to imitated goods. As in Barro and Sala-i-Martin (1997), we assume that the intermediate goods producers act as monopolists supplying their variants of the intermediate good. The profits of an intermediate goods producer can, hence, be written as

$$\pi_{r,ij} = (1-\tau_i)\big(\psi_{r,ij} - \varphi_{r,ij}\big)x_{r,ij}, \tag{16}$$

and

$$\pi_{f,ij} = \big(1-\tau_i-\tau_i^{CO2}\big)\big[\psi_{f,ij} - \varphi_{f,ij}\big]x_{f,ij}. \tag{17}$$

Since the demand curves in eq. (8) and (9) are iso-elastic, the profit-maximizing price of the intermediate goods is a constant markup over marginal cost, $\psi_{r,ij} = \varphi_{r,ij}/(1-\beta)$ and $\psi_{f,ij} = \varphi_{f,ij}/(1-\beta)$. To simplify, we normalize the marginal cost to $\varphi_{r,ij} = 1-\beta$ and $\varphi_{f,ij} = 1-\beta$, resulting in equilibrium prices of intermediate inputs $\psi_{r,ij} = \psi_{f,ij} = 1$.

We, hence, obtain in equilibrium

$$x_{r,ij} = \Big((1-\tau_i)p_{r,i}A_{r,i}\Big)^{\frac{1}{\beta}}\ L_{r,i}, \tag{18}$$

and

$$x_{f,ij} = \Big(\big(1-\tau_i-\tau_i^{CO2}\big)p_{f,i}A_{f,i}\Big)^{\frac{1}{\beta}}\ L_{f,i}, \tag{19}$$

As well as

$$x_{r,i} = \int_0^{N_{r,i}} \big(x_{r,ij}\big)^{1-\beta} dj = \Big((1-\tau_i)p_{r,i}A_{r,i}\Big)^{\frac{1-\beta}{\beta}}\ {L_{r,i}}^{1-\beta} N_{r,i} \tag{20}$$

and

$$x_{f,i} = \int_0^{N_{f,i}} \big(x_{f,ij}\big)^{1-\beta} dj = \Big(\big(1-\tau_i-\tau_i^{CO2}\big)p_{f,i}A_{f,i}\Big)^{\frac{1-\beta}{\beta}}\ {L_{f,i}}^{1-\beta} N_{f,i}. \tag{21}$$

Furthermore, it is

$$Y_{r,i} = \frac{1}{1-\beta} {A_{r,i}}^{\frac{1}{\beta}} \Big((1-\tau_i)p_{r,i}\Big)^{\frac{1-\beta}{\beta}}\ L_{r,i}N_{r,i}, \tag{22}$$

and

$$Y_{f,i} = \frac{1}{1-\beta} {A_{f,i}}^{\frac{1}{\beta}} \Big(\big(1-\tau_i-\tau_i^{CO2}\big)p_{f,i}\Big)^{\frac{1-\beta}{\beta}}\ L_{f,i}N_{f,i}. \tag{23}$$

The profits of the intermediate goods producers from the two sectors are[16]

$$\pi_{r,ij} = \pi_{r,i} = (1-\tau_i)^{\frac{\beta+1}{\beta}} \beta\big(p_{r,i}A_{r,i}\big)^{\frac{1}{\beta}} L_{r,i}, \tag{24}$$

and

[16] It is $\pi_{r,ij} = \pi_{r,i}$, as the growth in $N_{k,i}$ expresses itself as an increase in TFP (cf. eq. (20) and (21)).

$$\pi_{f,ij} = \pi_{f,i} = \left(1 - \tau_i - \tau_i^{CO2}\right)^{\frac{\beta+1}{\beta}} \beta\left(p_{f,i}A_{f,i}\right)^{\frac{1}{\beta}} L_{f,i}. \tag{25}$$

Furthermore, the wages from eq. (9) become with eq. (20) and (21)

$$w_{k,i} = \frac{\beta}{1-\beta}\left(\left(1 - \tau_i - \tau_{k,i}^{CO2}\right)p_{r,i}A_{r,i}\right)^{\frac{1}{\beta}} N_{r,i}, \tag{26}$$

again with $\tau_{r,i}^{CO2} = 0$.

3.4.2 Innovation costs of the intermediate goods sectors

Costs for new variants are the weighted average cost of economy i's costs for innovation and imitation activities to create new variants in the RES- and fossil-based intermediate goods sectors,

$$e_i = e_{r,i} + e_{f,i} = \left(1 - \lambda_{r,i}\right)\upsilon_{r,i} + \lambda_{r,i}\eta_{r,i} + \left(1 - \lambda_{f,i}\right)\upsilon_{f,i} + \lambda_{f,i}\eta_{f,i}, \tag{27}$$

with $\eta_{k,i}$ being the costs of innovation activities, and $\upsilon_{k,i}$ being the costs of imitation, which we define as

$$\upsilon_{k,i} = \eta_{r,i}\left(\frac{N_{r,i}}{N_{r,l}}\right)^{\sigma} \quad i = 1,2; l = 1,2 \neq i. \tag{28}$$

To cover their aggregate costs of innovation and imitation, intermediate goods producers can deploy the cash flows resulting from their profits—i.e., deploy internal finance—and issue different types of securities, with $a_{k,i}^{s}$ being one security of the type $s \in S$, as we will describe in detail in section 3.4.3. The costs of innovation activities consist, hence, of the costs for R&D activities themselves, which are related to any research and development (R&D) activities, $\eta_{k,i}^{R\&D}$, and financing costs, which arise from the acquisition of external capital to finance the innovation activities, $\varphi_{k,i}^{fin}$,

$$\eta_{k,i} = \eta_{k,i}^{R\&D} + \varphi_{k,i}^{fin}, \tag{29}$$

which, with eq. (15), (27) and (28) is

$$e_{k,1} = \left[\left(\frac{N_{k,2}}{N_{k,1}}\right)^{-\sigma} - \left(\frac{N_{k,2}}{N_{k,1}}\right)^{\frac{b}{2}-\sigma} + \left(\frac{N_{k,2}}{N_{k,1}}\right)^{\frac{b}{2}}\right]\left(\eta_{k,1}^{R\&D} + \varphi_{k,1}^{fin}\right), \tag{30}$$

And

$$e_{k,2} = \left[\left(\frac{N_{k,2}}{N_{k,1}}\right)^{\sigma} - \left(\frac{N_{k,2}}{N_{k,1}}\right)^{\sigma+b} + \left(\frac{N_{k,2}}{N_{k,1}}\right)^{b}\right]\left(\eta_{k,2}^{R\&D} + \varphi_{k,2}^{fin}\right), \tag{31}$$

Under the assumption of perfect capital markets, the Modigliani-Miller theorem holds, and financing costs equal the economy wide interest rate, making any financing decision trivial

(Modigliani and Miller, 1958). Then, the present value of the intermediate goods firms' profits can be expressed as

$$V_{k,i}^{I} = V_{k,i}^{C} = V_i = \left(V_{r,i} + V_{f,i}\right) = \left(\pi_{r,i} + \pi_{f,i}\right) \int_{t}^{\infty} e^{-\int_t^s M_i(v) dv} ds, \tag{32}$$

where M_i is the real interest rate in economy i at time v, which is also the cost of a one-period risk-free asset. Assuming free entry into the R&D business, in equilibrium,

$$V_i = e_i \left(\frac{N_2}{N_1}\right) \tag{33}$$

must hold. Substituting eq. (32) in (33) and building the derivative of both sides with regards to t reveals

$$M_i(t) = \frac{\pi_{r,i} + \pi_{f,i}}{e_{r,i} + e_{f,i}} + \frac{\dot{e}_{r,i} + \dot{e}_{f,i}}{e_{r,i} + e_{f,i}} \tag{34}$$

under the assumption of perfect capital markets and, hence, a common interest rate $M_i(t)$ for the RES-based and the fossil-based sector in each economy; with

$$\frac{\dot{e}_{k,1}}{e_{k,1}} = \frac{\dot{\eta}_{k,1}}{\eta_{k,1}} + \frac{\dot{\left(\frac{N_{k,2}}{N_{k,1}}\right)}}{\left(\frac{N_{k,2}}{N_{k,1}}\right)} \frac{\left[-\sigma\left(\frac{N_{k,2}}{N_{k,1}}\right)^{-\sigma} - \left(\frac{b}{2} - \sigma\right)\left(\frac{N_{k,2}}{N_{k,1}}\right)^{\frac{b}{2}-\sigma} + b\left(\frac{N_{k,2}}{N_{k,1}}\right)^{\frac{b}{2}}\right]}{\left(\frac{N_{k,2}}{N_{k,1}}\right)^{-\sigma} - \left(\frac{N_{k,2}}{N_{k,1}}\right)^{\frac{b}{2}-\sigma} + \left(\frac{N_{k,2}}{N_{k,1}}\right)^{\frac{b}{2}}} \tag{35}$$

and

$$\frac{\dot{e}_{k,2}}{e_{k,2}} = \frac{\dot{\eta}_{k,2}}{\eta_{k,2}} + \frac{\dot{\left(\frac{N_{k,2}}{N_{k,1}}\right)}}{\left(\frac{N_{k,2}}{N_{k,1}}\right)} \frac{\left[\sigma\left(\frac{N_{k,2}}{N_{k,1}}\right)^{\sigma} - (\sigma + b)\left(\frac{N_{k,2}}{N_{k,1}}\right)^{\sigma+b} + b\left(\frac{N_{k,2}}{N_{k,1}}\right)^{b}\right]}{\left(\frac{N_{k,2}}{N_{k,1}}\right)^{\sigma} - \left(\frac{N_{k,2}}{N_{k,1}}\right)^{\sigma+b} + \left(\frac{N_{k,2}}{N_{k,1}}\right)^{b}} \tag{36}$$

being the growth rates of the costs for innovation and imitation.

3.4.3 The financing decision of the intermediate goods sectors under financing frictions

Intermediate goods producers seek to minimize their costs of innovation and imitation activities by choosing their optimal capital structure, taking $\eta_{k,i}^{R\&D}$ as given. As mentioned above, we allow for four different types of financing options facing the intermediate goods sectors: private debt, d, and private equity, e, which is provided by aggregate private financial intermediaries subsuming, *inter alia*, lender banks, credit funds or equity funds, as well as public debt, pd, and public financing options with equity characteristics, pe, defining $S = \{d, e, pd, pe\}$. The total overall financing costs consist, hence, of the financing costs for the four different types of capital,

$$\varphi_{k,i}^{fin} = \varphi_{k,i}^{d} + \varphi_{k,i}^{e} + \varphi_{k,i}^{pd} + \varphi_{k,i}^{pe}, \tag{37}$$

with $\varphi_{k,i}^{d}$ being the total costs of private debt, $\varphi_{k,i}^{e}$ being the total costs of private equity, $\varphi_{k,i}^{pd}$ being the total costs of public debt and $\varphi_{k,i}^{pe}$ being the total costs of public financing options with equity characteristics.

Following, e.g., Kraus and Litzenberger (1973) and Van Binsbergen et al. (2010), we describe the total costs of debt as

$$\varphi_{k,i}^{d} = a_{k,i}^{d} \frac{1}{\iota_{k,i}^{d}} \left(1 - \tau_{r,i}^{d}\right) R_{k,i}^{d}\left(a_{k,i}^{d}, a_{k,i}^{pd}\right), \tag{38}$$

with $R_{k,i}^{d}\left(a_{k,i}^{d}, a_{k,i}^{pd}\right)$ being the costs—i.e., interest rates—per debt security issued, and $\iota_{k,i}^{d} \in [0, 1)$ being a parameter describing the efficiency of lending[17]. Following standard assumptions, and based on the rationale that the higher a firm's debt ratio, the higher the risk of bankruptcy, we model the costs per debt security issued to be linearly increasing in the intermediate goods producer's leverage $\lambda_{k,ij}^{d}$, for which we use the definition of the debt-to-EBITDA ratio[18],

$$\lambda_{k,i}^{d} = m_{k,i}^{d} \frac{a_{k,i}^{d} + a_{k,i}^{pd}}{Y_{k,i} p_{k,i}}, \tag{39}$$

with $m_{r,ij}^{d}$ being the proportionality factor. We, hence, obtain

$$R_{k,i}^{d}\left(a_{k,i}^{d}, a_{k,i}^{pd}\right) = m_{k,i}^{d} \frac{a_{k,i}^{d} + a_{k,i}^{pd}}{Y_{k,i} p_{k,i}}, \tag{40}$$

with $R_{k,i}^{Md}$ being the model-endogenous market price for debt. Further, $\tau_{r,i}^{d}$ represents the rate at which interest rates for debt are deducible from corporate taxes (cf., e.g., Modigliani and Miller, 1958; Cordes and Sheffrin, 1983; Kane et al., 1984; Graham, 2002), capturing the tax benefit of debt, with

[17] Cost of debt is also dependent on firm size, which we assume here to equal out since we consider a model of one representative firm per sector and without capital accumulation. When comparing the RES-based and the fossil-based intermediate goods sectors, firm size is often smaller in the RES-based sector, as new players enter the market. This case can be accounted for by setting $m_{r,ij}^{d}$ accordingly. Furthermore, at this point, we do not explicitly build in any costs of financial distress, such as bankruptcy costs (cf., e.g., Scott, 1976; Baker and Martin, 2011), but limit these considerations to the costs for debt increasing in leverage.

[18] We use the debt-to-EBITDA ratio for two reasons. Firstly, our model does not include capital accumulation, so any definition based on a firm's assets or capital would be inappropriate. Secondly, the chosen notation allows for the option to include revenue risks into the model, by making the profit development stochastic, e.g., by means of a Brownian motion.

$$0 \leq \tau_{k,i}^{d} \leq \tau_{k,i} \leq 1. \tag{41}$$

Further, based on, e.g., Kraus and Litzenberger (1973), Scott (1976), Altinkilic and Hansen (2000), and Gomes (2001), we describe the costs of private equity as

$$\varphi_{k,i}^{e} = \varphi_{k,i}^{e,fix} + a_{k,i}^{e} \frac{1}{\iota_{k,i}^{e}} R_{k,i}^{e}\left(a_{k,i}^{d}, a_{k,i}^{pd}\right), \tag{42}$$

with $\varphi_{k,i}^{e,fix}$ being flotation costs, and $R_{k,i}^{e}\left(a_{k,i}^{d}, a_{k,i}^{pd}\right)$ being the costs per equity security issued, which can be described as

$$R_{k,i}^{e}\left(a_{k,i}^{d}, a_{k,i}^{pd}\right) = d_{k,i}\left(Y_{k,i}p_{k,i} - \varphi_{k,i}^{d} - \varphi_{k,i}^{pd}\right), \tag{43}$$

with $d_{k,i}^{e} \in \left(0,1 - d_{k,i}^{pe}\right)$ being the agreed dividend payments expressed as a share of the firm's net profits, i.e., less its costs for issuing other types of securities, and $\iota_{k,ij}^{e} \in (0,1)$ being a market efficiency parameter.

Costs for public debt have the same structure as costs for private debt, and differences are expressed only through the magnitude of the parameters. It is

$$\varphi_{k,i}^{pd} = a_{k,i}^{pd}\left(1 - \tau_{k,i}^{pd}\right) \frac{1}{\iota_{k,i}^{pd}} R_{k,i}^{pd}\left(a_{k,i}^{d}, a_{k,i}^{pd}\right) = a_{k,i}^{pd}\left(1 - \tau_{k,i}^{pd}\right) \frac{1}{\iota_{k,i}^{pd}} \left(m_{k,i}^{pd} \frac{a_{k,i}^{d} + a_{k,i}^{pd}}{Y_{k,i}p_{k,i}}\right), \tag{44}$$

with the parameter definitions being analogous to the parameter definitions re. the costs of private debt.

The cost structure of public equity is

$$\varphi_{k,i}^{pe} = a_{k,i}^{pe} \frac{1}{\iota_{k,i}^{pe}} R_{k,i}^{pe}\left(a_{k,i}^{d}, a_{k,i}^{pd}\right) = a_{k,i}^{pe} \frac{1}{\iota_{k,i}^{pe}} d_{k,i}^{pe}\left(Y_{k,i}p_{k,i} - \varphi_{k,i}^{d} - \varphi_{k,i}^{pd}\right), \tag{45}$$

with the parameter definitions being analogous to the parameter definitions re. the costs of private equity. Compared with the cost structure of private equity, firms do not face any flotation costs related to the issuance of public equity securities.

Given the cost structures of issuing different types of securities as described above, the intermediate goods producers minimize their aggregate innovation and imitation costs at each point in time according to

$$\min_{a_{k,ij}^{d}, a_{k,ij}^{e}, a_{k,ij}^{pd}, a_{k,ij}^{pe}} \varphi_{k,i}^{fin}. \tag{46}$$

The first constraint of the maximization problem describes that at each moment in time, the aggregate intermediate goods producers in each sector need to cover their innovation and imitation costs (eq. (30) and (31)) by means of the cash inflows from their profits and the issuance of securities of the types s, which can be expressed as

$$\left[\left(\frac{N_{k,2}}{N_{k,1}}\right)^{-\sigma} - \left(\frac{N_{k,2}}{N_{k,1}}\right)^{\frac{b}{2}-\sigma} + \left(\frac{N_{k,2}}{N_{k,1}}\right)^{\frac{b}{2}}\right]\left(\eta_{k,i}^{R\&D} + \varphi_{k,ij}^{fin}\right) = Y_{k,i}p_{k,i} + \sum_{s\in S} a_{k,i}^{s} v_{k,i}^{s}. \tag{47}$$

with $v_{k,i}^{s}$ being the market-determined value of one security issued. We assume non-negative interest rates. Furthermore, intermediate goods producers can only issue securities and do not act as financiers on the financial markets. Hence, the second constraint is that the financing costs must be non-negative, i.e.,

$$\varphi_{k,i}^{fin} \geq 0. \tag{48}$$

3.5 The financial sector

As described above, the financial sector consists of private and public financial intermediaries. They both provide their specific financing options competitively to the intermediary goods producers of both sectors under their sector-specific conditions.

3.5.1 Private financial intermediaries

Private intermediaries choose holding a mix of private debt and equity to both intermediate sectors within one economy to maximize their shareholders' value by maximizing the returns of their portfolio Υ_i according to

$$\begin{aligned}\max_{a_{r,i}^{d},a_{r,i}^{e},a_{f,i}^{d},a_{f,i}^{e}} \Upsilon_i = \max_{a_{r,i}^{d},a_{r,i}^{e},a_{f,i}^{d},a_{f,i}^{e}} & \left[R_{f,i}^{d}\left(a_{f,i}^{d}, a_{f,i}^{pd}\right) - v_{f,i}^{d}\right]a_{f,i}^{d} \\ & + \left[R_{f,i}^{e}\left(a_{f,i}^{d}, a_{f,i}^{pe}, a_{f,i}^{pd}\right) - v_{f,i}^{e}\right]a_{f,i}^{e} + \left[R_{r,i}^{d}\left(a_{r,i}^{d}, a_{r,i}^{pd}\right) - v_{r,i}^{d}\right]a_{r,i}^{d} \\ & + \left[R_{r,i}^{e}\left(a_{r,i}^{d}, a_{r,i}^{pe}, a_{r,i}^{pd}\right) - v_{r,i}^{e}\right]a_{r,i}^{e} - h_i\left(a_{f,i}^{d}, a_{f,i}^{e}, a_{r,i}^{d}, a_{r,i}^{e}\right),\end{aligned} \tag{49}$$

with h_i being the per-period holding costs, which we define as being dependent on the quantity of securities held,

$$h_i\left(a_{f,i}^{d}, a_{f,i}^{e}, a_{r,i}^{d}, a_{r,i}^{e}\right) = h_i^{fix} + h_i^{var}\left(a_{f,i}^{d} + a_{f,i}^{e} + a_{r,i}^{d} + a_{r,i}^{e}\right)^{\omega} \tag{50}$$

With h_i^{fix} being the fixed, and h_i^{var} being the variable holding costs, and ω, expressing the type of returns to scale. The private financial intermediaries receive their investable resources from the HH savings S_i. Hence, private financial intermediaries face the constraint

$$a_{f,i}^{d}v_{f,i}^{d} + a_{f,i}^{e}v_{f,i}^{e} + a_{r,i}^{d}v_{r,i}^{d} + a_{r,i}^{e}v_{r,i}^{e} + h_i\left(a_{f,i}^{d}, a_{f,i}^{e}, a_{r,i}^{d}, a_{r,i}^{e}\right) \leq S_i \tag{51}$$

to their shareholder value maximization problem. The magnitude of S_i can be obtained from the HH intertemporal utility maximization based on eq. (1), assuming a standard HH budget constraint. As we assume that due to information asymmetries, HH cannot differentiate between the different investment options, they make their savings decision based on the real interest rate in economy i, M_i. Given this, savings are in each point in time

$$S_i = L_{r,i} w_{r,i} + L_{f,i} w_{f,i} - C_i. \tag{52}$$

3.5.2 Public financial intermediaries

Other than private financial intermediaries, public financial intermediaries do not maximize shareholder value, but are interested in pursuing specific goals. This can—generally and in an ideal world—be broken down to the principle of maximizing stakeholder value, for instance, an achievement of environmental, social and governance (ESG) goals including a reduction of GHG emissions. When considering the overall economy, public financial intermediaries are still bound to market mechanisms, however. Furthermore, a maximization of stakeholder value still implies a maximization of returns on investment, Υ_i^p, as one criterion for public financial intermediaries, and hence, investments into fossil-based intermediate goods are not excluded from the public intermediaries' portfolio[19]. To account for a general stronger preference of public financial intermediaries to invest into securities issued by the RES-based sector, we introduce a valuation parameter, p_i^{CO2}, which can be interpreted as an internal carbon price, the magnitude of which is determined by the individual sustainability goals of an economic actor. These considerations lead to the maximization problem of the public financial intermediaries,

[19] This can be illustrated by the following two examples. The first example refers to the limitations, which public investors face with regards to their investment allocation according to stakeholder maximization criteria. Public health insurances and pension funds, which are highly relevant institutional investors in terms of public investment volumes, pursue the primary goal of investing their funds efficiently and profitably, to the end of adequately ensuring their members' benefits, i.e., the funding of medical services and the payout of pension payments. This is also subject to according regulations in the form of constraints re. the assets institutional investors are allowed to hold. These regulations vary dependent on the country's legislation; however, all inhibit institutional investors from holding high-risk assets (e.g., OECD, 2011) In a secondary instance—and given the limitations their primary goal imposes—they can also pursue other goals with their investments, such as a promotion of clean energy or technologies. The second example illustrates that even if the only goal that public investors pursue is stakeholder maximization, this does not necessarily mean a total exclusion of investments in the fossil sector. Firstly, fossil-based intermediate goods often serve as system-relevant transitional technologies, such as gas power plants in the energy system. Secondly, pursuing different ESG goals can lead to trade-offs. Investing in a fossil-based power plant in a developing country can increase energy access and, thus, contribute to the social ESG dimension, while, coincidingly, increase GHG emissions and, thus, negatively contribute to the environmental ESG dimension.

$$
\begin{aligned}
&\max_{a_{r,i}^{pd},a_{r,i}^{pe}a_{f,i}^{pd},a_{f,i}^{pe}} Y_i^p \\
&\qquad = \max_{a_{r,i}^{pd},a_{r,i}^{pe}a_{f,i}^{pd},a_{f,i}^{pe}} \left[R_{f,i}^{pd}\left(a_{f,i}^{d},a_{f,i}^{pd}\right) - v_{f,i}^{pd} - p_i^{CO2}\right]a_{f,i}^{pd} \\
&\qquad + \left[R_{f,i}^{pe}\left(a_{f,i}^{d},a_{f,i}^{e},a_{f,i}^{pd}\right) - v_{f,i}^{pe} - p_i^{CO2}\right]a_{f,i}^{pe} + \left[R_{r,i}^{pd}\left(a_{r,i}^{d},a_{r,i}^{pd}\right) - v_{r,i}^{pd}\right]a_{r,i}^{pd} \\
&\qquad + \left[R_{r,i}^{pe}\left(a_{r,i}^{d},a_{r,i}^{e},a_{r,i}^{pd}\right) - v_{r,i}^{pe}\right]a_{r,i}^{pe} - h_i^p\left(a_{f,i}^{pd},a_{f,i}^{pe},a_{r,i}^{pd},a_{r,i}^{pe}\right).
\end{aligned}
\tag{53}
$$

Investible funds arise from taxes and social security contributions, T_i, which leads to the constraint to the maximization problem of public financial intermediaries

$$
a_{r,i}^{pd} + a_{r,i}^{pe} + a_{f,i}^{pd} + a_{f,i}^{pe} + h_i^p\left(a_{f,i}^{pd},a_{f,i}^{pe},a_{r,i}^{pd},a_{r,i}^{pe}\right) = \tau_i\left(Y_{r,i}p_{r,i} + Y_{f,i}p_{f,i}\right), \tag{54}
$$

3.6 The relationship between innovation in the RES-based and the fossil sectors

To determine the relation between innovation in the RES-based and the fossil intermediate goods sectors, we revisit the relation between $p_{r,i}$ and $p_{f,i}$. Substituting eq. (22) and (23) into eq. (10) reveals

$$
\frac{p_{f,i}}{p_{r,i}} = \left(\frac{1-\gamma}{\gamma}\right)^{\frac{\beta\varepsilon}{\kappa}} \left(\frac{A_{f,i}}{A_{r,i}}\right)^{-\frac{1}{\kappa}} \left(\frac{\left(1-\tau_i-\tau_i^{CO2}\right)}{(1-\tau_i)}\right)^{-\frac{1-\beta}{\kappa}} \left(\frac{L_{f,i}N_{f,i}}{L_{r,i}N_{r,i}}\right)^{-\frac{\beta}{\kappa}}, \tag{55}
$$

with $\kappa \equiv 1-\beta+\varepsilon\beta$.

3.6.1 The innovation possibilities frontier

The production function for new machine varieties is

$$
\dot{N}_{k,i} = \varsigma_{k,i}e_{k,i}, \tag{56}
$$

with $\varsigma_{k,i}$ is an efficiency parameter, which allows the cost for innovation to differ. In this specification, $\varsigma_{r,i}/\varsigma_{f,i}$ is constant. In the BGP, the prices $p_{r,i}$ and $p_{f,i}$ are constant, and $N_{r,i}$ and $N_{f,i}$ grow at the same rate. The technology market clearing condition is then

$$
\frac{V_{r,i}}{V_{f,i}} = \frac{\varsigma_{f,i}}{\varsigma_{r,i}}, \tag{57}
$$

which, given that the interest rate $M_{r,i} = M_{f,i} = M_i$, simplifies to

$$
\varsigma_{r,i}\pi_{r,i} = \varsigma_{f,i}\pi_{f,i}. \tag{58}
$$

With eq. (16), (17) and (52), it is then

$$N_{f,i} = \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon} \left(\frac{1-\tau_i-\tau_i^{CO2}}{1-\tau_i}\right)^{\frac{\kappa(\beta+1)-1+\beta}{\beta}} \left(\frac{A_{f,i}}{A_{r,i}}\right)^{\frac{\kappa-1}{\beta}} \left(\frac{L_{f,i}}{L_{r,i}}\right)^{1-\kappa} \left(\frac{\varsigma_{f,i}}{\varsigma_{r,i}}\right)^{\kappa} N_{r,i}, \tag{59}$$

and we define

$$N_{f,i} \equiv \xi_i N_{r,i}. \tag{60}$$

Further, in the balanced growth path (BGP), $N_{r,i}$ and $N_{f,i}$ grow at the same rate, i.e., $\dot{N}_{r,i}/N_{r,i} = \dot{N}_{f,i}/N_{f,i}$, and $\xi_i = N_{f,i}/N_{r,i}$ (see Acemoglu, 2002), which leads to the relation $\dot{N}_{f,i} = \xi_i \dot{N}_{r,i}$. Allowing for increasing carbon taxes, however, building the derivatives of both sides of eq. (59) leads to the approximated relation

$$\dot{N}_{f,i} = \dot{N}_{r,i}\xi_i - (\dot{\tau_i^{CO2}}) N_{r,i}\xi_i, \tag{61}$$

3.7 Aggregation

Given eq. (2), the economies' overall budget constraints are

$$Y_i = \left[\gamma Y_{r,i}^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma) Y_{f,i}^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} = C_i + x_{r,i}N_{r,i} + x_{f,i}N_{f,i} + e_{r,i}\dot{N}_{r,i} + e_{f,i}\dot{N}_{f,i} \tag{62}$$

with $e_{r,i}\dot{N}_{r,i}$ and $e_{f,i}\dot{N}_{f,i}$ being the expenditures for the innovation and imitation of new variants (see below). As in Barro and Sala-i-Martin (1997), trade is assumed to be balanced between the two economies, which means that the total output Y_i in both economies equals the total respective domestic expenditures. These expenditures are for consumption, $C_i = C_{r,i} + C_{f,i}$, production of the variants of intermediate goods, $x_{r,i}N_{r,i}$ and $x_{f,i}N_{f,i}$, and for innovation and imitation activities leading to the emergence of new variants, $e_{r,i}\dot{N}_{r,i}$ and $e_{f,i}\dot{N}_{f,i}$. With eq. (22), and (23), it is

$$\left[\gamma\left(\tilde{Y}_{r,i}N_{r,i}\right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma)\left(\tilde{Y}_{f,i}N_{f,i}\right)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} = C_i + x_{r,i}N_{r,i} + x_{f,i}N_{f,i} + e_{r,i}\dot{N}_{r,i} + e_{f,i}\dot{N}_{f,i}, \tag{63}$$

with $\tilde{Y}_{k,i} = Y_{k,i}/N_{k,i}$, and with eq. (60) and (61) we can write the growth rates of $N_{k,i}$ as

$$\frac{\dot{N}_{r,i}}{N_{r,i}} = \frac{1}{e_{r,i} + e_{f,i}\xi_i}\left\{\left[\gamma\left(\tilde{Y}_{r,i}\right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma)\left(\tilde{Y}_{f,i}\xi_i\right)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} - x_{r,i} - x_{f,i}\xi_i - \frac{C_i}{N_{r,i}} + (\dot{\tau_i^{CO2}})\right\} \tag{64}$$

and

$$\frac{\dot{N}_{f,i}}{N_{f,i}} = \frac{1}{e_{r,i}{\xi_i}^{-1} + e_{f,i}} \left\{ \left[\gamma\left(\tilde{Y}_{r,i}{\xi_i}^{-1}\right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma)\left(\tilde{Y}_{f,i}\right)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} - x_{r,i}{\xi_i}^{-1} - x_{f,i} - \frac{C_i}{N_{f,i}} - (\dot{\tau_i^{CO2}}) \right\}. \tag{65}$$

We define

$$\frac{(\dot{\widehat{N_k}})}{\widehat{N_k}} \equiv \frac{\left(\dot{\frac{N_{k,2}}{N_{k,1}}}\right)}{\frac{N_{k,2}}{N_{k,1}}} = \frac{\dot{N}_{k,2}}{N_{k,2}} - \frac{\dot{N}_{k,1}}{N_{k,1}} \tag{66}$$

as the growth rate of the number of variants in economies 2 as compared to economies 1—and, thus, the ratio of the growth rates of the two economies.

A Maximization of HH utility (eq.(1)) subject to a standard inter-temporal budget constraint reveals the Euler equation for HH consumption

$$\frac{\dot{C}_i}{C_i} = \frac{1}{\theta}[M_i - \rho]. \tag{67}$$

With the economy-wide interest rate M_i having been defined in eq. (34), hence,

$$\frac{\dot{C}_i}{C_i} = \frac{1}{\theta}\left[\frac{\pi_{r,i} + \pi_{f,i}}{e_{r,i} + e_{f,i}} + \frac{\dot{e}_{r,i} + \dot{e}_{r,i}}{e_{r,i} + e_{f,i}} - \rho\right]. \tag{68}$$

We further define

$$\frac{\dot{\Gamma}_{f,1}}{\Gamma_{f,1}} = \frac{\dot{C}_1}{C_1} - \frac{\dot{N}_{f,1}}{N_{f,1}}. \tag{69}$$

as the average consumption per variety in each of the two economies. We use $\Gamma_{f,1}$ as a control variable, which must converge to zero in the BGP. As the number of varieties increases, each variety's average consumption decreases. In a competitive market, in the long run, the price of each variety will be driven down to its marginal cost. As the number of varieties approaches infinity, the average consumption per variety approaches zero. This outcome reflects the idea that, with an ever-increasing number of varieties, the demand for each specific variety becomes negligible, and the market becomes highly competitive.

4 Analyses

4.1 Model Calibration

The preceding section shed light on the qualitative interrelations of economic growth based on the innovation and imitation of RES-based and fossil-based variants. The subsequent stage involves a meticulous quantitative examination to explore how the endogenous reaction to the change in the exogenous variables in general, and different financing frictions, impacts the advantages and disadvantages of different financing setups and approaches to their improvement. However, conducting such a quantitative study is outside the purview of this paper, as it necessitates an exact determination of the parameters of the innovation possibilities frontier and the precise extent of substitution between clean and dirty resources. Instead, we initiate progress in this direction by examining the influence of varying parameters on the economic outcomes in terms of total economic growth (as reflected by the number of total variants), the relation of growth in the leader vs. the follower economies and in the RES-based and fossil sectors, as well as the innovation intensity, i.e., the share of innovated in total variants. We select parameters that closely resemble existing quantitative studies, enabling us to emphasize the novel outcomes arising from financing frictions in an environment of directed technical change.

To determine the total sizes of the leader and the follower economies, we define the leader economies, i.e., the global North, to consist of the Group of Seven (G7) economies plus China and the Russian Federation ('G9 economies'), and the follower economies, i.e., the global South, as the rest of the world (ROW). We, hence, approximate L_1 with the share of the gross domestic product (GDP) of the G7 economies in the total global GDP, and L_2 with the remainder. In 2021, the global nominal GDP was 96.53 trillion USD, of which 62.22 trillion USD, and, hence, approx. 65% of the total global GDP are attributed to the G9 economies (The World Bank, 2023). In our model, $Y_{k,i}$ corresponds to the respective GDPs. We set the starting values for the number of variants in economies 1 and 2 according to the GDP shares. Furthermore, the variables $A_{k,i}$, $L_{k,i}$ and $p_{k,i}$ are set in a way that $Y_{k,1}/\left(Y_{k,1}+Y_{k,2}\right) \approx 65\%$. Note that the magnitude of the variables depends on the choice of the output elasticity of the intermediate inputs, $1-\beta$. Following Acemoglu et al. (2012), we set $1-\beta$ in the range of $1/3$.

4.2 Benchmark—The Economy Without Financing Frictions

We analyze the economy without financing frictions to the end of providing a benchmark for the subsequent analyses, as well as to the end of visualizing and explaining the basic dynamics of the model. We show different scenarios based on different model parametrizations. Scenario I will serve as a reference scenario for the subsequent analyses, while the remainder of the scenarios explains and visualizes the model dynamics.

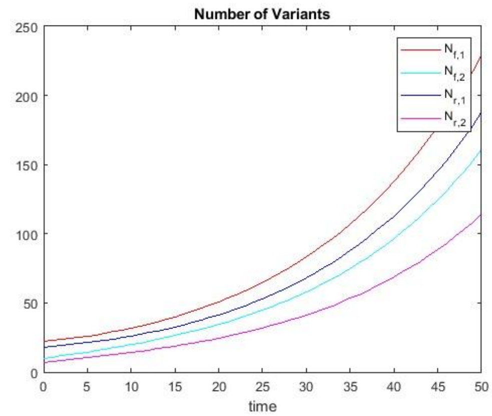
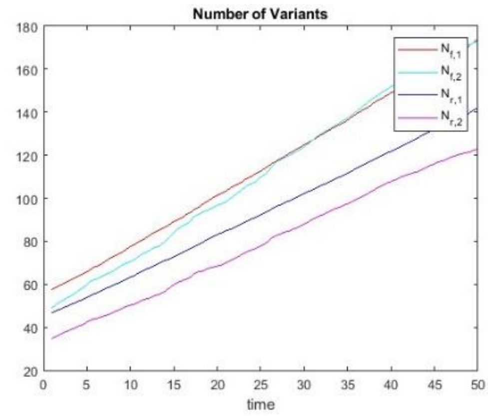
In a setup without financing frictions, innovators have access to capital at the cost of the economy-wide interest rate M_i, with the capital being provided by the HH directly based on their intertemporal consumption and savings preferences. The behavior of the real economy is characterized by the ratio of variants in economies 2 to economies 1, $\widehat{N_k}$, the number of variants from the RES-based and the fossil-based intermediate goods sectors, $N_{k,i}$, the ratio of RES-based variants in the total variants in both groups of economies, $N_{r,i}/\left(N_{r,i}+N_{k,i}\right)$, and the ratio of innovated variants in the number of total variants, $\lambda_{k,i}$. The behavior of the global economy depends on the relative prices, $p_{k,i}$, the relative labor supply, $L_{k,i}$, and the relative TFP, $A_{k,i}$ of economies 1 and 2 and of the sectors. Varying these parameters leads to different magnitudes of the characteristic variables. Higher prices, labor supply or TFP in an economy or sector lead to a stronger growth in the respective sector, as well as to increased innovation activity, while the transition path to the BGP follows a uniform structure (Graphs and parametrizations see scenarios I to IV in Appendix B). The same applies for the effects of increases in the relative efficiency of innovation in the respective economies and sectors, $\varsigma_{k,i}$, as well as for the substitution elasticity, ε, expressing a more complementary nature of the RES-based and the fossil-based products. A decrease of innovation costs leads to an increase of the growth in the respective economies or sectors. With regards to the impact of carbon taxes, both the magnitude of the outcomes and the structure of the transition path can change since we allow for increasing carbon taxes over time. An increase in carbon taxes affects the fossil-based intermediate sectors and has both a decreasing effect on the outcome of the fossil sectors and an increasing effect on the RES sectors.

4.3 I—The Economy with Financing Frictions

In the following, we provide analyses shedding light on the impact of different financial and financing frictions on the direction of innovation and imitation towards RES-based or fossil-based technological development. Building upon these analyses, we investigate the effect of different forms of setups and policy interventions fostering the development of RES-based technological development.

Firstly, we provide insights regarding an ‘initial state’, in which financing costs arise, but the financial markets are only subject to negligibly small information asymmetries, as well as to financiers’ preferences for debt stemming from less leveraged firms. We model the initial state in a way that it reflects a state in which the financial markets do not exhibit any differences across the regions, meaning that all parameters describing the financial markets are set to the same levels for economies 1 (E1) and economies 2 (E2). The initial state does not describe a realistic scenario, lacking all forms of market inefficiencies and differences in market inefficiencies of developed vs. developing economies prevailing in reality (see section 2.2). However, it serves to lay out the impact of financing costs in comparison to the benchmark scenario of the BGB without financing costs and financing frictions provided above. Going forward, it will also allow us to deploy it as a reference to compare the impact of different types and magnitudes of financial and financing frictions to this initial state, and the effect of different forms of policy intervention and regulation.

Comparing the initial state with the benchmark scenarios (see section 4.2) reveals that both the level and the growth rates of the number of variants $N_{k,i}$—and, thus, the levels of growth of the respective two sectors in the two economies—are negatively impacted by positive financing costs, see Figure 1[20]. While this is very intuitive, it is interesting that the prevalence of financing costs also impacts the relation of the number of variants between the E1 and E2. This can be explained with the structure of the financing costs, which, especially in the case of debt finance, increase disproportionately with increasing levels of external financing. In E1, where the endogenously determined total volumes of external financing, $\varphi_{k,i}$, are higher, the economic growth rates of the two sectors are impacted disproportionately strong in comparison with the ones in the developing economies.

	Benchmark—Economy Without Financing Frictions	**I—Initial State: Economy with Financing Frictions**
$N_{k,i}$		

[20] Exemplary display of selected results. For the full model outcomes, see Appendices B and C. Note that the time displayed in the Benchmark scenarios varies from the one displayed in the results of the scenarios with financing frictions for reasons of scenario-internal comparability.

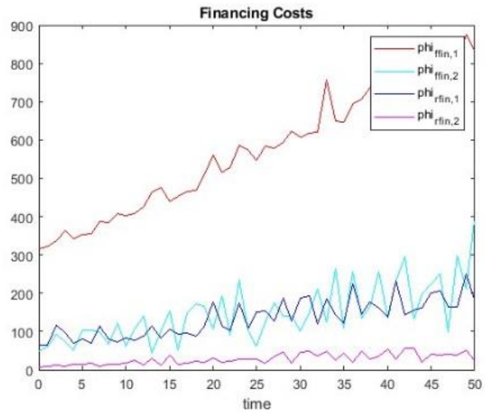
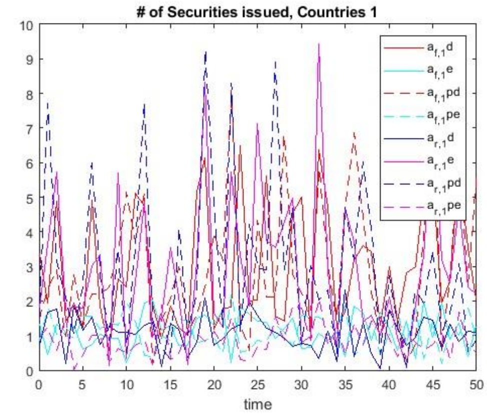
$\varphi_{k,i}$	n.a.	
$a^{s}_{k,1}$	n.a.	

Figure 1: Benchmark vs. Initial State
Note: we exemplarily provide the amount of securities issued for E1. In E2, while the magnitude levels differ, the structure is comparable, see Appendix C.

While we have not accounted for catch-up dynamics of developing to developed economies in the model of the economy without financing frictions, in the model with financing frictions, hence, some catch-up effects are accounted for. Concerning the composition of the external financing, $a^{s}_{k,1}$, we can observe that for the fossil sector—in line with the pecking order theory—a preference for debt financing prevails. In the case of the RES-sector, where the bankability—i.e., the access to sufficient amounts of private debt—is a major issue, the model outcomes reflect higher volumes of private equity financing as well as financing via public debt.

4.3.1 II—Financing Frictions

In the following, we present the impact of different forms of financing frictions on the outcomes. Within this section, we display select results, while, again, the full range of results can be found in Appendix C. We account for three different types of financing frictions: The tax advantage of debt, inefficiencies in capital markets due to information asymmetries and uncertainties, as well as the effects of a prevalence of transaction costs (see section 4.2).

Firstly, following Miller and Modigliani (1977), we incorporate a 'tax shield' on debt, meaning that interest payments on debt are tax-deductible. While this holds true for the G9 states, i.e., the

E1 in our model, it does not necessarily reflect the reality within the ROW, i.e., the E2 in our model. To account for this difference, we set the deductible tax rate $\tau_{k,2}^{d} < \tau_{k,1}^{d}$. Furthermore, assuming that governments intend to incentivize sustainable developments, we set $\tau_{r,i}^{d} = 1.5\tau_{f,i}^{d}$. As we can see in Figure 2, the effect on the structure of external financing is small. While we can observe higher levels of securities issuance overall (note the different calibration of the y-axes), there is only a small reduction in the levels of equity vs. debt finance in both economies and sectors. Also, the improvement of tax conditions for RES-related public debt is reflected in the related higher volumes of public debt financing. Regarding the share of RES-based in total variants, $N_{r,i}/N_{r,i}$, the higher (see Appendix C).

	I—Initial State	**II.a—Tax Advantage of Debt**
$a_{k,1}^{s}$		

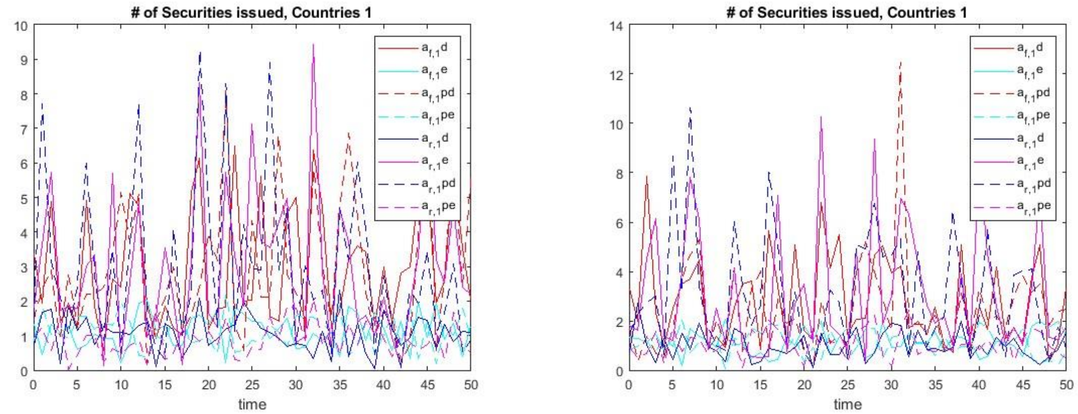
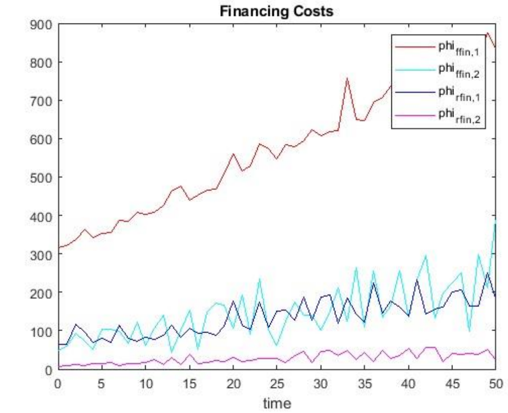


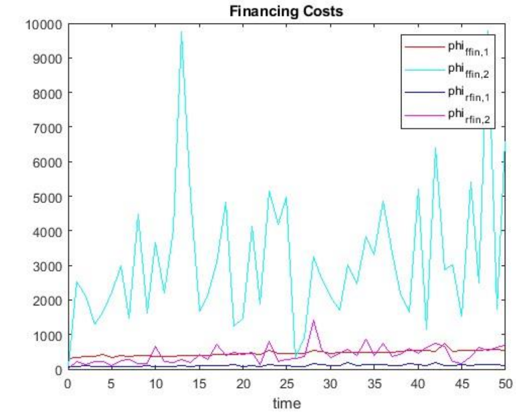
Figure 2: Initial State vs. Tax Advantage of Debt

Secondly, we account for different asymmetric-information- and uncertainty-related inefficiencies in the capital markets. We investigate three different constellations of relative inefficiencies: Higher inefficiencies in the developing vs. developed economies, but equally high inefficiencies in the respective two sectors (II.b), higher inefficiencies in the developing vs. developed economies, and higher inefficiencies in RES-related financing in the developing economies, (II.c), and higher inefficiencies in the developing vs. developed economies, but higher inefficiencies in both RES-related financing (II.d); the latter two constellations reflecting the considerations outlined in section 2.2.1. Compared to the initial state, the respective financing subject to inefficiencies becomes more expensive, reflected in a comparably higher $\varphi_{k,i}$. While equally high inefficiencies in the two sectors have a negligible impact on the share of RES-based in total intermediate goods, higher inefficiencies in the RES-related financing lead to a considerable change. While without the difference, the share of RES-based vs. fossil-based variants is degressively growing, with the difference prevailing, the share of RES-based variants declines either in just the E2 (II.c) or both economies (II.d), (see also Appendix C). This signifies that higher inefficiencies in the RES-related financing compared to fossil related financing, as prevalent in reality, leads to a re-direction of technical change towards non-sustainability. Sensitivity analyses reveal that this already holds true for relatively small levels of inefficiencies. The documentation of the according results is available upon request.

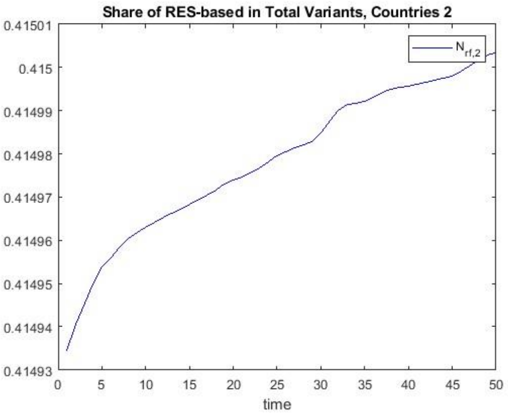
I—Initial State | **II.b—Inefficiencies in E2 Capital Markets**

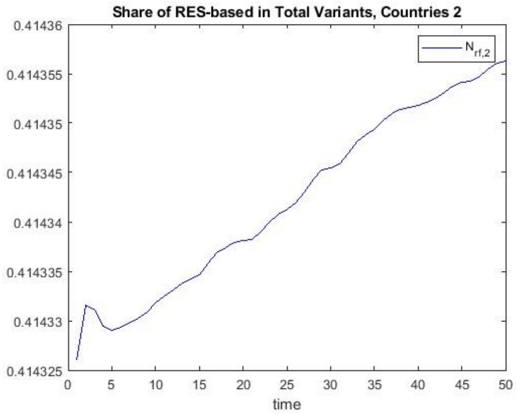
$\varphi_{k,i}$





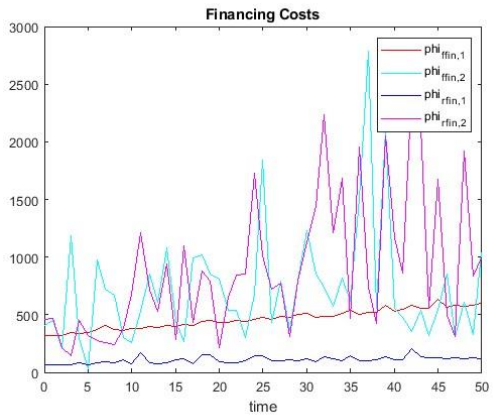
$\frac{N_{r,2}}{N_{k,2}}$

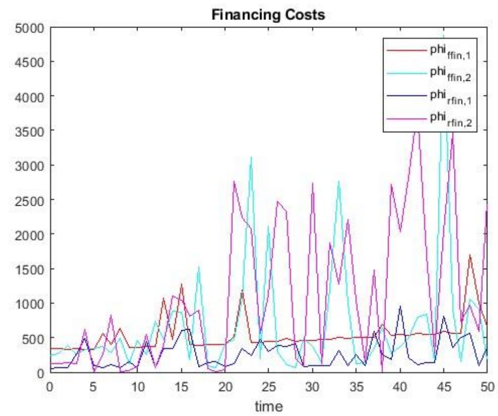




II.c— Inefficiencies in E2 RES Capital Markets | **II.d—Inefficiencies in All RES Capital Markets**

$\varphi_{k,i}$





$\frac{N_{r,i}}{N_{f,i}}$

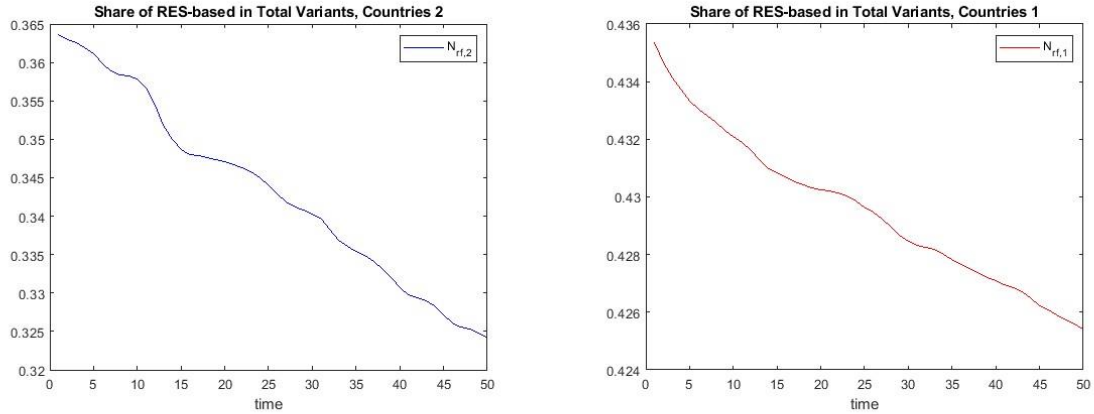


Figure 3: Initial State vs. Capital Market Inefficiencies

Thirdly, we account for capital market imperfections resulting from transaction costs. As reflected in section 3.5, we account for two types of transaction costs: flotation costs related to the issuance of private equity, $\varphi_{k,i}^{efix}$ (II.e) and holding costs of securities facing both private and public financial intermediaries, $h_{k,i}^{fix}$ and $h_{k,i}^{var}$ (II.f). The impact of flotation costs associated with the issuance of private equity is trivial. Higher flotation costs make private equity investments the comparatively less attractive financing option. Hence, the share of private equity finance will decrease, while the overall financing costs will be slightly elevated (see Appendix C). Holding costs facing intermediaries provide a tractable way to capture how costs of liquidity and risk-taking affect lenders to firms. Holding costs can be elevated, *inter alia*, due to lower liquidity in financial markets, elevated uncertainty and risk related to the investment, or constrained possibilities to diversify portfolios (Papoutsi et al., 2022). As outlined in section 2.2, all these aspects hold true for RES-related financing in particular. Again, elevated RES-related holding costs cause higher RES-related financing costs, while the volume of overall external finance decreases, accompanied by a stronger decline in the share of RES-based variants. While all this is very intuitive, imposing these two types of transaction leads to the situation that the financing needs in the RES-based sector in developing economies cannot be met, as reflected by the temporarily negative values of $\varphi_{r,2}$ in both scenarios[21], see Figure 4. While, due to constraints related to the model setup, this infeasibility of financing does not have any feedback effects apart from elevated RES-related financing costs in E2 on the way in which the RES-based innovation evolves[22], it will be interesting to further investigate the situation in which external financing fails in more detail in future research. For now, we remain with the hypothesis that those situations will

[21] The display of negative values in case of non-solvability of the system is a particularity of the type of algorithm deployed when writing the model in MATLAB.

[22] Negative values are not fed back into the model.

have a significantly negative impact on the growth in the RES-based sector and direct technical change strongly to non-sustainable growth.

	II.e—Elevated Flotation Costs	II.f—Elevated Holding Costs

$\varphi_{k,i}$

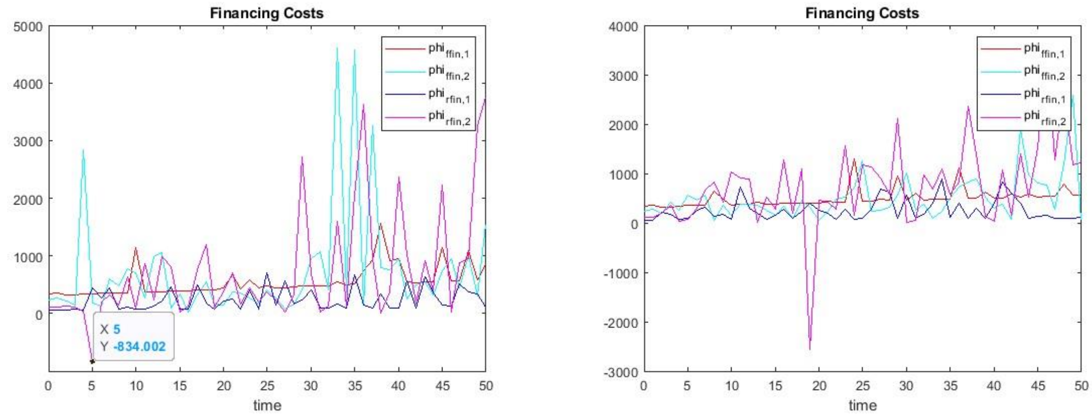


Figure 4: Elevated Transaction Costs

4.3.2 III—Green Public Investment

The subsequent set of scenarios investigates the role and impact, which governments and public FI can play and have in fostering sustainable growth. Therefore, we compare three different types of levers, which governments and public FI can use to influence the direction of growth: The valuation of sustainability over monetary return during the capital allocation decision (III.a and III.b), the financing conditions offered to private sector firms (III.c), as well as support in the development of improved real and financial markets in developing economies (III.d). As introduced in section 3.5.2, public FI choose the extent to which they value sustainability over financial returns, as reflected in their internal carbon price p_i^{CO2}. We consider two scenarios, of which in (III.a), an elevated internal carbon price is set by public FI from the developing world, such as development banks, while in (III.b), public FI in both the developed and the developing economies set high internal carbon prices. While the former is a realistic scenario reflecting developments in real-world public financial institutions, the second scenario serves the analytical purpose to extract the *ceteris paribus* effect of a higher internal carbon price of only public FI from the developed world. Scenario (III.c) accounts for the lever of public FI to adjust the financing conditions in order to incentivize RES-related innovation. With regards to equity-types of public financing, public FI can agree upon lower dividend payments or provide debt at lower interest rates or payback schedules in favor of RES-based firms. These conditions lead to lower financing costs for RES-based intermediate goods producers. The third lever, i.e., development aid aimed at improving real and financial market conditions (III.d) goes beyond the influence of public FI. Increased efficiency in the markets can reduce overall financing costs, as long as the development aids paid do not significantly exceed efficiency gains on the developing markets. In this context, it is interesting to observe that even under a considerably high internal carbon price set by public FI, economic growth cannot be directed to a sustainable path by these levers only. Even under significantly improved financing conditions provided by public FI (III.c) and significant improvements in the efficiency of real and financial markets in the developing economies (III.d), the growth path returns to a non-sustainable one, see Figure 5 and Appendix C.

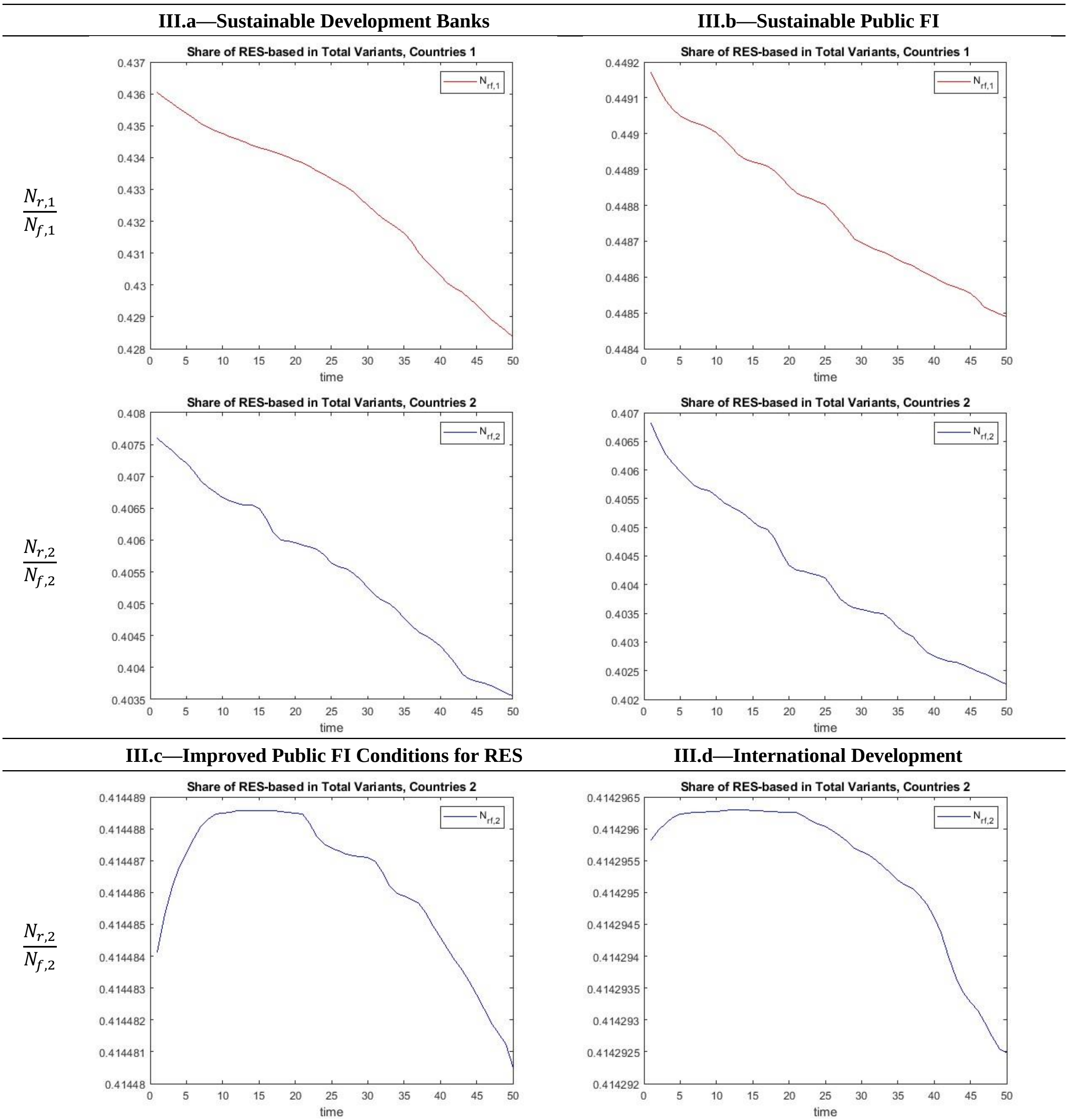


Figure 5: Sustainable Public Financial Intermediaries

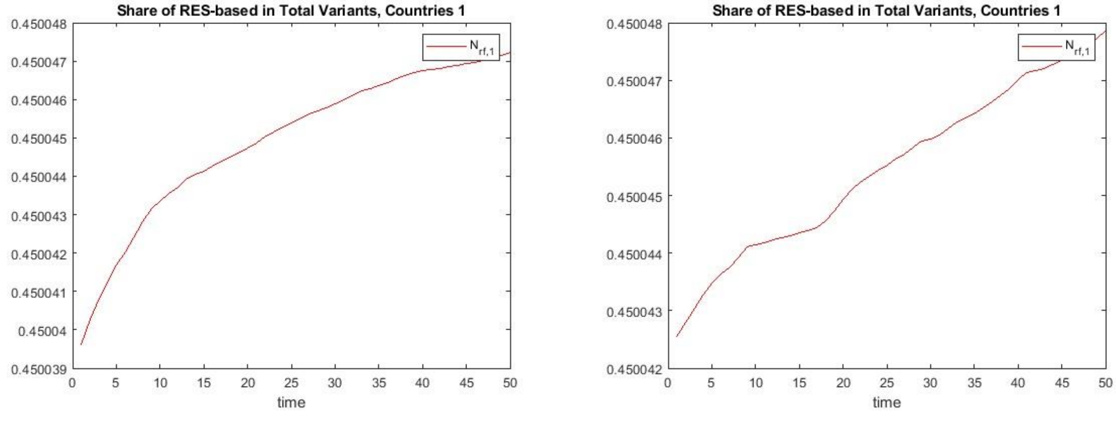
4.3.3 IV—Sustainable Private FI Regulation and Sustainable Investment Incentives

Apart from steering the capital allocation decision of public FI towards more sustainable investments, regulation and incentives can be set to incentivize private FI to allocate a higher share of their investments to RES-related securities. In this context, we consider two cases: Firstly, regulation is put in place, which forces private FI to offer better financing conditions related to sustainable securities (IV.a). The according regulation entails higher holding costs for private FI, since they are obliged to deviate from their decision-making purely based on financial returns considerations, including an optimized hedging strategy. Secondly, governments can put instruments in place, which reduce the risk for private FI and, thus allow them to offer improved financing conditions for sustainable investments (IV.b). The cost for the risk does not disappear from the economy, but is borne by the public sector. However, it is often argued that the total costs associated with the according risk can be reduced, as for certain types of risks, the public sector is able to bear them more efficiently (cf., e.g., OECD, 2017; 2020).

The according analysis reveals that under strict regulation of private FI, the developed economies can be led to a sustainable growth path. This holds true under the assumption that an according regulation can be enforced, which is reasonable to assume in the case of developed economies. In the developing economies, however, this assumption is less reasonable. Therefore, we set the cost of the regulation higher, reflecting a higher inefficiency in the implementation of the regulation. Other than in the global North, hence, in the global South, where the same set of regulatory enforcement faces a more inefficient implementation, the economy cannot be led to a sustainable growth path. We exhibit this setting in Figure 6. When imposing stricter regulation in the global South, at some point, the inefficiencies are outweighed, and the economy is led to a sustainable growth path. However, this only happens under very optimistic assumptions, making this approach potentially less feasible.

	IV.a—Sustainable Regulation Private FI	IV.b—Risk Buffering Private FI

$\frac{N_{r,1}}{N_{f,1}}$



$\frac{N_{r,2}}{N_{f,2}}$

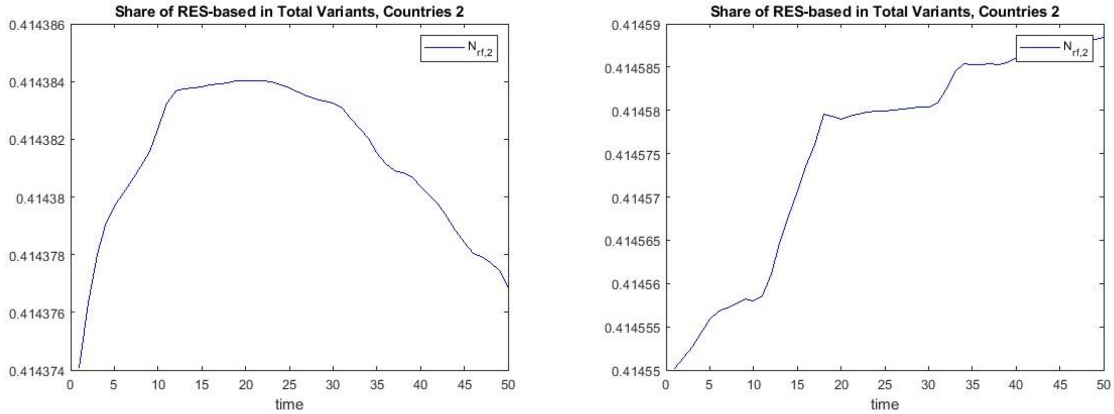


Figure 6: Sustainable Private FI

In contrast, under the above-mentioned assumption that the public sector is able to bear risk more efficiently than the private sector—this assumption is at least reasonable for regulatory risk, which constitutes a considerable share of sustainability-related risk—both the global North and the global South can be led to a sustainable growth path. The edgy shape of the according curve for $N_{r,2}/N_{f,2}$, however, points to an instability of this outcome.

4.3.4 V—Sustainable Public and Private Financial Intermediaries

In (III) and (IV), we have made the changes to the setup ceteris paribus—firstly accounting for only the increased valuation of sustainability by public FI, then only accounting for the (enforced or incentivized) increased valuation of sustainability by private FI. We now consider the two approaches jointly, accounting for coinciding increased valuation of sustainability by both the public and the private FI (V.a). The outcome of this scenario reveals that a combination of both higher valuation of sustainability of public FI and a regulation or incentivization of private FI can lead the global economy to a sustainable growth path, see Figure 7.

V.a—Sustainable Regulation Private FI

$\frac{N_{r,i}}{N_{f,i}}$

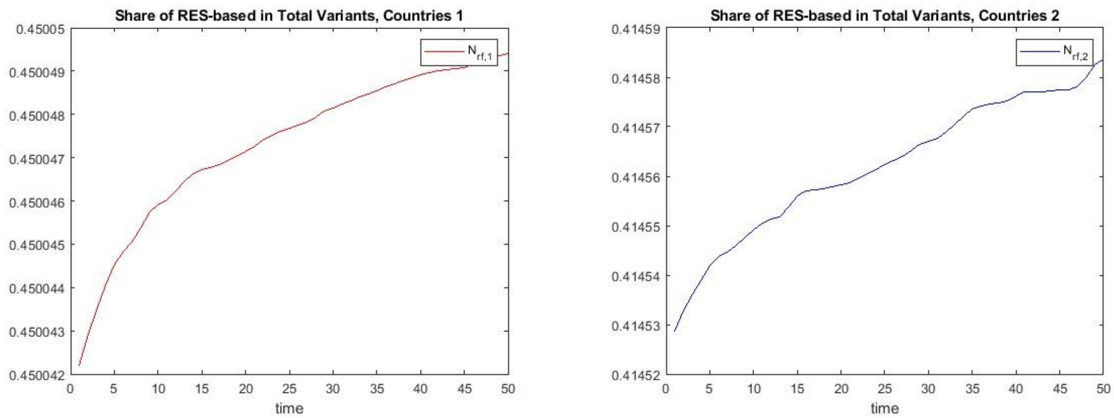


Figure 7: Sustainable Financial Sector

This outcome emphasizes the crucial role of the financial sector in the achievement of sustainable growth.

4.3.5 VI—Carbon Pricing

Lastly, we analyze the impact of a carbon price in form of a carbon tax in both economies on the direction of technical change. We consider two different types regarding the evolution of carbon prices: A degressive increase over time and a slight decrease over time. A sufficiently high degressively increasing carbon tax is sufficient to steer the global economy subject to financial frictions and a non-regulated or incentivized sector to a sustainable growth path, see Figure 8. However, achieving a such carbon price to be set globally is not a trivial task. Interestingly, also a decreasing carbon price suffices to lead the economy towards a sustainable growth path if the starting price is sufficiently high. However, the successful outcome of such a scenario would require immediate and very decisive action globally, to an extent that goes far beyond the current levels.

VI.a—Degressively Increasing CO_2 Tax | **VI.b—Decreasing CO_2 Tax**

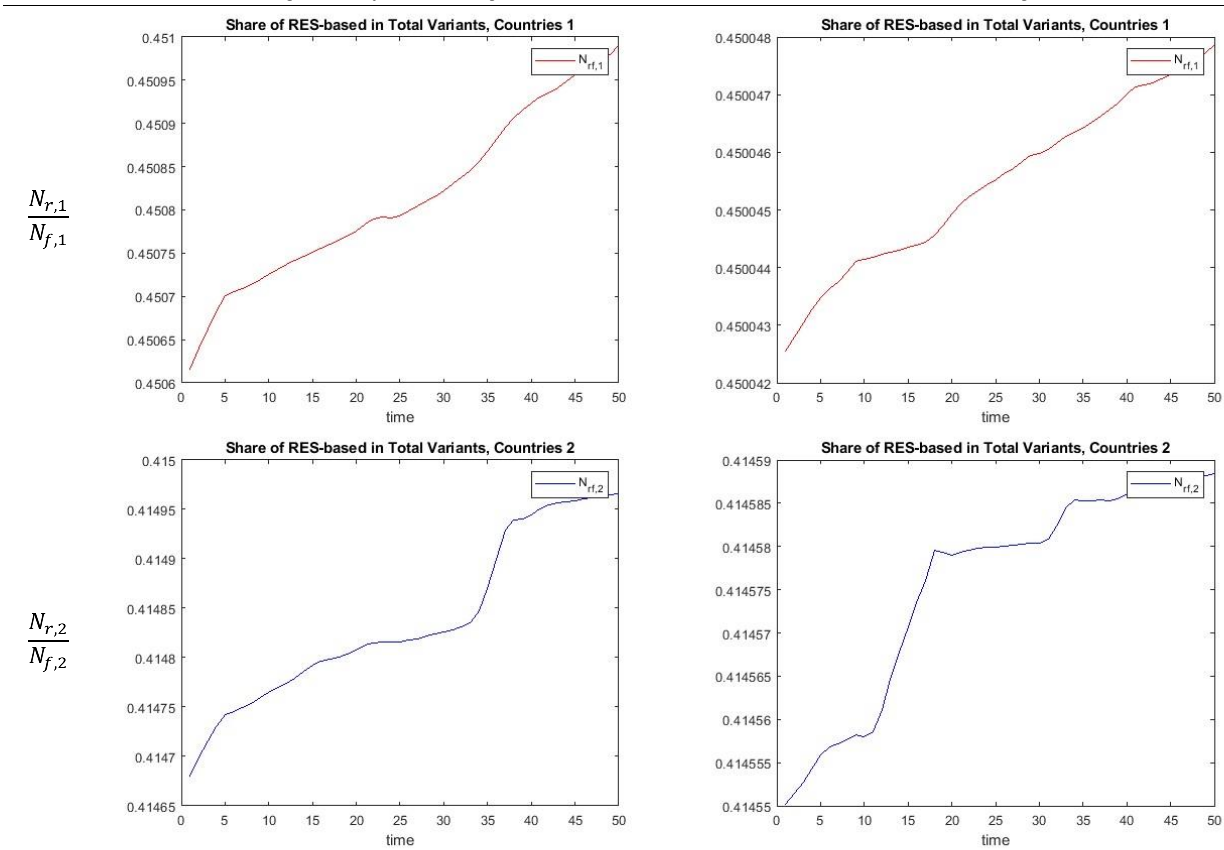


Figure 8: Carbon Taxation

5 Discussion of the Key Findings, Limitations and Avenues for Future Research

5.1 Discussion of Key Findings

The analyses reveal the crucial role and high significance of both private and the public financial actors in the achievement of a sustainable growth path. We have built upon a model of endogenous growth with two groups of countries and directed technical change towards a RES-based and a fossil-based sector. The extension of the model with an endogenous financing decision of RES-based vs. fossil-based innovation via different types of internal and external financing instruments allows us to investigate the role of the financing decision in achieving a sustainable vs. remaining on a (partially) non-sustainable growth path.

We find that in an economy without financing frictions, path dependencies and lock-in effects cause a settling of the relation of sustainable and non-sustainable growth at a constant level. Hence, in this setting, both RES-based and fossil-based innovation will persist. This means that the global economy is not led to a fully sustainable growth path, and that non-sustainable growth will remain, eventually causing critical GHG levels in the atmosphere. This can be counteracted by setting a sufficiently high carbon price, leading the economy to a (more) sustainable growth path. While we do not elaborate on the exact time structure of the necessary intervention, these findings are in line with existing research on the topic, such as Acemoglu et al. (2012), who discuss the optimal timing and intensity of carbon reduction incentives. However, the existing studies do not consider any change in the dynamics rooted in the financial economy and neglect the explicit consideration of financing costs and financial frictions.

Accounting for a financial sector in our model of endogenous growth reveals that if financing costs prevail under quasi-perfect capital markets, the transition dynamics towards the BGP are impacted, but the long-term behavior of the economy is comparable, albeit at other magnitudes of the characteristic endogenous variables. For instance, regarding the levels of sustainable vs. non-sustainable growth, the share of sustainable in total growth will also—as in the absence of financing costs—converge to a constant level, while the shape of the transition follows a different path. Also, assuming that financing costs occur at equal levels in RES-based and fossil innovation, the total growth rate will be impacted negatively, while the relative growth rates amongst sustainable and non-sustainable growth in the two economies remain unchanged.

However, *ceteris paribus*, the prevalence of different forms of financing frictions can cause a convergence of the economy towards a non-sustainable growth path, as we have shown in section 4.3.1. While tax advantages of debt do change the financing mix between private and public equity and debt, do not considerably impact the growth path, other financing frictions investigated, i.e., the prevalence of information asymmetries and uncertainty, as well as of transaction costs, which are elevated related to RES do. The economy is led to a non-sustainable growth path, as sustainable innovation finance becomes more costly. This effect is aggravated in developing economies, where, generally, institutions including capital markets are weaker and risk is even more elevated. The financing frictions occur up to a point at which financing for RES-related innovation in the developing countries becomes unavailable, constituting a major barrier to sustainable growth.

Considering different potential cures to this issue reveals that sustainable public financing alone—i.e., the higher valuation of sustainability by public financial intermediaries—does have a positive impact on the share of sustainable in total innovation, does not suffice, however, to steer the global economy to a sustainable growth path in the long run. This can be explained as public financiers cannot fully commit to sustainable investment but must also account for other monetary goals depending on their purpose (as discussed in section 3.5.2). In contrast, a stronger regulation or incentivization of private financial intermediaries can lead to a sustainable growth path, albeit only under strong assumptions. Therefore, we have considered a case in which both public financial intermediaries value sustainability more strongly, and private financial intermediaries are incentivized towards increased sustainable investment. This form of double-tracked intervention leads to a steering of the global economy to a sustainable growth path, on which also the share of sustainable in total innovation is constantly increasing. This signifies that, in the long run and eventually, a fully sustainable economic setup can be reached. However, referring to previous work on the timing of such intervention such as in the above-mentioned Aghion et al. (2012), a thorough investigation of the necessary timing of intervention related to the financial sector will be necessary in future work. This is especially to consider a 'tipping point', i.e., a critical level of carbon emissions in the atmosphere, from which onwards a self-enforcing degradation of the environmental quality will be unavoidable.

Lastly, a sufficiently high carbon price can also lead to the desired outcomes. However, it must be sufficiently high and cover a sufficient amount of carbon emissions. Also, related action must happen in a timely manner. If this is considered unrealistic given the current landscape of global pricing, a joint deployment of all above-outlined approaches might be advantageous to consider.

5.2 Limitations and Avenues for Future Research

While some—mostly empirical—work exists investigating the role of the financial sector in sustainable economic growth, the field is still rather rudimentarily investigated and substantial research will be necessary in the coming years to better understand the relationship of the financial and the reals sectors in an environment of desired sustainable growth. While we provide a first approach to conceptualize the relationship, a lot of work can be done to refine the assessment.

Regarding the representation of the financial sector in the model, we have selected an approach which incorporates the fundamental characteristics of financing decisions between private-sector security issuers and public and private financiers. Drawing upon sophisticated models in the field of optimal capital allocation decisions in the corporate and entrepreneurial world, such as dynamic trade-off models, the representation can be refined. For instance, in our setup, we do not consider loan maturities or any costs occurring at the point in time of default, but only reflect this type of costs in the costs of debt, which we model to be increasing in the firm leverage. Furthermore, future research can allow for a more detailed representation of different financing options or more explicitly account for the dynamics of cases in which demand for financing cannot be met. Furthermore, while having provided some quantitative analyses to show the dynamics of the modeled relations, empirical research will be necessary to substantiate the findings with more explicit numbers.

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