Endogenous Technology, Scarring and Fiscal Policy

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Abstract

This paper studies fiscal policy in a New Keynesian DSGE model with endogenous technology growth in which scarring can occur endogenously through cycle-trend interaction. Both demand- and supply-driven recessions can depress investment in R&D and technology adoption, thus generating permanent losses in the technology stock and hence the long-run output path. The costs of the ZLB are amplified due to monetary policy long-run non-neutrality, increasing the role of supplementary fiscal policy. While conventional government spending crowds out technology investment in normal times, the government spending multiplier at the ZLB can be higher under endogenous growth due to the increased importance of monetary-fiscal interaction. I propose novel fiscal policy tools in the form of growth policies which boost aggregate demand at present while simultaneously raising productivity-improving investment and hence the long-run trend. Multipliers of fiscal growth policies range considerably above generally prevailing assessments of government spending multipliers and are characterized by a permanent component. A fiscal policy mix of support to R&D and technology adoption optimally alleviates scarring by expanding the future technology frontier, while realizing instantaneous gains from delayed technological diffusion.

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1 Introduction

The COVID-19 crisis hit the global economy in both unprecedented rapidness and scale. Figure 1 shows the evolution of real GDP in the United States and the euro area and highlights that aggregate output in both countries permanently fell short of their pre-2008 trend levels following the Great Recession, suggesting permanent scarring effects. Moreover, the COVID-19 shock substantially exceeds the output drop inflicted by preceding crisis episodes, highlighting the elevated risk of permanent output losses also in the context of the current pandemic crisis. In light of these observations, the possibility of scarring effects in total factor productivity and the long-term output path has also substantially influenced the policy debate since the start of the COVID-19 crisis and the importance of fiscal policy in preventing permanent damage to aggregate output has been strongly emphasized by policy makers (Lagarde (2021), Lane (2021), IMF (2021), Powell (2020)). At the same time, efforts to counteract the COVID-19 crisis by means of fiscal policy have indeed been substantial, in particular in comparison with previous crises.

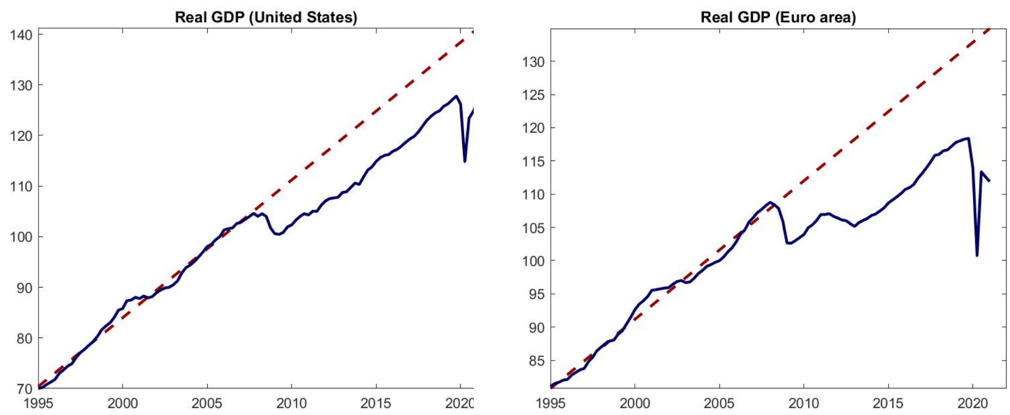

Figure 1: Real GDP and pre-2008 trend levels in the United States and the euro area

While the importance of fiscal policy in preventing scarring effects and a further, crisis-induced slowdown in total factor productivity is strongly emphasized in the current discussion, the interconnection of fiscal policy on the one hand and total factor productivity on the other hand is at this stage not well understood and previous evidence on the issue is scarce. This paper aims at bridging this gap by studying fiscal policy in a rich medium-scale DSGE model with endogenous technology growth, with a special focus on monetary-fiscal interaction, the design of fiscal policies and their role in reducing supply-side scarring. This analysis constitutes thus to my knowledge the first paper to study fiscal policy under endogenous technology growth through productivity-enhancing investment in R&D and technology adoption in an otherwise standard New Keynesian DSGE setup.

Standard macroeconomic models typically postulate strictly exogenous total factor productivity, driven solely by technology shocks. These frameworks thus abstract from endogenous technology dynamics and can as a consequence provide only very limited insights on the drivers underlying total factor productivity. Crucially, scarring is ruled out in this setting as cyclical fluctuations are assumed to be irrelevant for long-run supply dynamics. The model underlying this analysis departs from the simplifying assumption of strictly exogenous technology and, instead, models total factor productivity endogenously in general equilibrium. Specifically, the model features a rich endogenous technology growth mechanism (Comin and Gertler (2006), Romer (1990)), in which total factor productivity evolves in a two-stage process of R&D and technology adoption, as proposed by the previous literature (Moran and Queralto (2018), Anzoategui, Comin, Gertler and Martinez (2019), Ikeda and Koruzumi (2019), Elfsbacka Schmöller and Spitzer (2021)). The latter consists of entrepreneurs' investment in research and development which endogenously determines the technological frontier and firms' endogenous technology adoption choice which drives the degree of technological diffusion. Since technology is endogenous, this framework is capable of generating scarring effects as cyclical developments exert an impact on productivity-improving investments and thus the long-run output path, in sharp contrast to traditional New Keynesian frameworks. Otherwise, the main model structure constitutes a standard medium-scale DSGE model (Christiano et al. (2005), Smets and Wouters (2007)), which permits a detailed analysis of fiscal and monetary policy in this context, including also the simultaneous analysis of inflation implications. The model features an effective lower bound constraint, thus enabling the analysis of fiscal policy in normal times and when monetary policy is constrained.

The main results of the paper can be summarized as follows. In the first set of results, I analyze channels and mechanisms through which scarring effects can arise in this model and show that both demand-driven and supply-driven recession can inflict permanent harm to total factor productivity and thus the long-run output path. Regarding the COVID-19 crisis, I demonstrate that while the relative strength of demand- and supply-side factors influences the aggregate response of inflation, both channels underlying the COVID-19 shock work to generating pronounced scarring of the technology stock and thus permanent output losses induced by the crisis in the absence of further, supplementary policies.

The second set of results are based on the analysis of fiscal policy under a rich endogenous technology growth mechanism, especially with respect to its potential in reducing crisis-induced scarring effects and the role of monetary policy in this context and can be summarized as follows. Concerning monetary policy, I show that a binding effective lower bound constraint intensifies both the crisis and the long-term output losses. This result is founded in the altered role of monetary policy under the endogenous growth mechanism. Specifically, monetary policy does not only have a role in stabilizing the economy over the short-run but also influences via the spillovers from cycle to trend investment in technology growth and thus long-term supply, rendering monetary policy non-neutral also over the long-run. As a result, the costs resulting from a binding effective lower bound constraints are larger than conventionally assumed when abstracting from endogenous productivity dynamics. These results highlight the importance of additional support from fiscal policy in alleviating scarring effects when monetary policy is constrained by the effective lower bound.

As to government spending, I show that the relationship between technology growth and fiscal policy is non-trivial and depends on the response of monetary policy. In normal times, i.e. outside the effective lower bound, a positive shock to government spending is accompanied by an increase in the real interest rate and government spending crowds out not only investment in physical capital but also productivity-improving investment in research and development and technology adoption. As a consequence of the crowding out effects in TFP, the fiscal multiplier from government spending is - outside the effective lower bound - lower than in DGSE models with exogenous technology. I show, however, that at the effective lower bound increased government spending can be effective not only in supporting inflation and alleviating the recession, but in addition also in significantly reducing scarring effects by fostering investment in R&D and technology adoption in the recession. These results thus suggest that the role of monetary-fiscal interaction is amplified under endogenous technology dynamics.

A further contribution of this paper is the introduction of a novel fiscal policy tool in the New Keynesian DSGE context in the form of counter-cyclical growth policies. Growth-promoting policies are well-established tools in the endogenous growth literature and typically focus on the efficient long-run growth rate. Previous work demonstrates the role of innovation policies in preventing stagnation traps in Keynesian growth models (Fornaro and Wolf (2020), Benigno and Fornaro (2018)). I study growth-promoting policies in the form of fiscal support to R&D and technology adoption and show that they can constitute an effective short-run stabilization tool in the New Keynesian DSGE setup, while at the same time reducing adverse spillovers from cycle to trend and related scarring effects. This type of fiscal policy combines the effect of boosting aggregate demand at present, while at the same time directly raising technological investments and thus total factor productivity, rendering these fiscal tools very effective in promoting technology growth and in the reduction of long-run scarring effects. Moreover, and differently to conventional government spending, they show the desired sign both at and outside the effective lower bound and thus independently of constraints to monetary policy.

Given the two-stage process underlying technology growth in this model, growth-policies can be targeted to entrepreneurs' research and development, to technology adoption by firms or to both. Fiscal support to R&D is subject to the advantage of expanding the technological frontier itself and thus also the potential for future technology adoption activities. Their effect on total factor productivity realizes, however, only gradually over time as research and development constitutes a slowly-moving factor. Subsidies to firms' efforts in technology adoption can generate substantial productivity gains over short time horizons by instantaneously taking advantage of delays in technological diffusion, i.e. from existing technologies which have not yet diffused to the wider economy. A fiscal policy mix of these policy options can thus constitute an effective way of both counteracting scarring effects in an with only minor lags, while at the same exploiting the benefits from a push to the technology frontier itself.

Previous literature:

This paper contributes to the literature studying the role of endogenous total factor productivity growth in macroeconomic models and the interaction between cycle and the long-run trend in this context (Cerra, Fatás and Saxena (2021)). Recent estimated medium-scale DSGE models with endogenous technology growth (Anzoategui et al. (2019); Bianchi et al. (2019); Moran and Queralto (2018); Elfsbacka Schmöller and Spitzer (2021)) emphasize the role of a crisis-induced deceleration in total factor productivity growth in explaining the depth of the recessions and weakness of the recovery in the euro area following the Great Recession and the euro area sovereign debt crisis as well as the simultaneously observable intensification of the productivity slowdown. Benigno and Fornaro (2018) show how shortfalls in aggregate demand can depress innovation, leading into episodes of persistent stagnation as a combination of a growth trap and a liquidity trap. The non-neutrality of monetary policy over substantially longer periods than conventionally assumed is also empirically documented. Jorda et al. (2020) provide empirical evidence which suggests that monetary policy can affect the productive capacity of the economy and provide evidence for hysteresis effects in productivity. In addition, their analysis shows that DSGE models with endogenous TFP mechanism can reconcile their empirical observations, highlighting further the importance of the endogenous technology channel in otherwise standard macroeconomic models as the one underlying this analysis. Moran and Queralto (2018) give further empirical evidence supportive of the the persistent effects of monetary policy shocks on TFP growth. Amador (2021), Bertolotti, Gavazza and Lanteri (2021) and Furlanetto et al. (2021) provide empirical evidence on hysteresis effects in TFP and the role of aggregate demand in this context.

To the best of my knowledge, this is the first paper to study fiscal policy in a New Keynesian DGSE model with rich endogenous technology investment choice through R&D and technology adoption and the previous literature on fiscal policy under endogenous growth is, as stated earlier, scarce. Elfsbacka Schmöller and Spitzer (2021) show that the weakness in aggregate demand emerging in the context of and the phase following the euro area sovereign debt crisis significantly intensified the scarring effects in total factor productivity and the depth of the recession and the weakness in the recovery in the euro area relatively to the United States, which did not experience a double-dip recession and a subsequent phase of austerity. Benigno and Fornaro (2018) show the role of innovation policies in ruling out the possibility of demand-driven, self-fulfilling stagnation traps at the effective lower bound. Fornaro and Wolf (2021) demonstrate that innovation policies can be effective in countering crises induced by supply-side disruptions. Ilzetzki (2021) presents direct, causal empirical evidence on the positive effect of stimulus to aggregate demand through fiscal policy on total factor productivity growth and presents by means of a theoretical model the importance of a learning by necessity mechanism in TFP growth in this context.

This paper is structured as follows. Section 2 presents the model framework underlying this analysis. Section 3 studies mechanisms of scarring effects. Section 4 demonstrates the role of long-run non-neutrality and the effect of the effective lower bound constraint in this setting. Section 5 proceeds to analyze the role of government spending, both in normal times and when monetary policy is constrained by the effective lower bound. In section 6, I analyze growth-promoting fiscal policies in the form of subsidies to R&D and technology adoption. The analysis of fiscal multipliers over the short- and long-run is shown in section 7. Section 8 concludes.

2 Model

This section presents the theoretical model underlying this analysis. The main model structure follows a medium-scale New Keynesian DSGE model in the spirit of Christiano et al. (2005) and Smets and Wouters (2007) augmented by an endogenous total factor productivity mechanism. Specifically, technology growth evolves endogenously as the result of innovation through R&D and technology adoption. Fiscal policy can take the form of conventional government spending and, in addition, through fiscal growth policies as described in more detail in what follows.

2.1 Final good production

The economy features two types of firms, intermediate goods producers and final goods producers which use intermediate goods as inputs. There is a continuum of measure one of final goods producers which are monopolistically competitive. Each final good firm i produces differentiated output Y_t^i. The corresponding final good composite is a CES aggregate of the differentiated final goods

$$Y_t = \left[\int_0^1 Y_t^{i\,\frac{\mu-1}{\mu}} di \right]^{\frac{\mu}{\mu-1}}. \tag{1}$$

The price set by final good producer i is P_t^i and the price level of final output can be derived as $P_t = \left[\int_0^1 P_t^{i\,1-\mu} di \right]^{\frac{1}{1-\mu}}$. Final goods producer i's output follows from cost minimization and equals to

$$Y_t^i = \left(\frac{P_t^i}{P_t} \right)^{-\mu} Y_t. \tag{2}$$

Prices are sticky and each final good firm can adjust its price with probability $1 - \xi^p$. Firms which cannot adjust their price set it according to the indexation rule

$$P_t^i = P_{t-1}^i \pi_{t-1}^{\iota_p} \bar{\pi}^{1-\iota_p}, \tag{3}$$

where ι_p is the price indexation parameter and $\pi_t = \frac{P_t}{P_{t-1}}$ denotes time t inflation and $\bar{\pi}$ inflation in the steady state. Final good firms face nominal marginal costs in the form of intermediate good input price P_t^m. The final good producer's problem can be stated as choosing the optimal reset price P_t^* as follows

$$\max_{P_t^*} \mathbb{E}_t \sum_{j=0}^{\infty} \xi_p^j \Lambda_{t,t+j} \left(\frac{P_t^* \prod_{k=1}^{j} \pi_{t+k-1}^{\iota_p} \bar{\pi}^{1-\iota_p}}{P_{t+j}} - \frac{P_{t+j}^m}{P_{t+j}} \right) Y_{t+j}^i \tag{4}$$

subject to final good demand (2).

2.2 Intermediate goods production

Total factor productivity growth occurs in the form of expanding varieties A_t of intermediate goods used in production generated through both innovation and technology adoption. Each of these intermediate products A_t is produced by a monopolistically competitive producer. Y_t^{im} is output produced by intermediate good producer i and the composite of intermediate goods Y_t^m used as input by final good firms (section 2.1) can be stated as follows:

$$Y_t^m = \left[\int_0^{A_t} \left(Y_t^{im} \right)^{\frac{\vartheta-1}{\vartheta}} di \right]^{\frac{\vartheta}{\vartheta-1}}. \tag{5}$$

P_t^{im} refers to the nominal price set by producer i and the price level of the intermediate good composite equals to $P_t^m = \left[\int_0^{A_t} \left(P_t^{im} \right)^{1-\vartheta} di \right]^{\frac{1}{1-\vartheta}}$. Intermediate good firms produce using capital and labor by means of a Cobb-Douglas production technology:

$$Y_t^{im} = \theta_t \left(K_t^i \right)^{\alpha} \left(L_t^i \right)^{1-\alpha}, \tag{6}$$

where θ_t refers to the exogenous component of total factor productivity.[1]

Let R_t^k denote the rental rate of capital and W_t the nominal wage rate. Intermediate goods producers' cost minimization delivers the following first order conditions

$$\alpha \frac{\vartheta - 1}{\vartheta} \frac{P_t^m}{P_t} \frac{Y_t^m}{K_t} = R_t^k \tag{7}$$

$$(1-\alpha) \frac{\vartheta - 1}{\vartheta} P_t^m \frac{Y_t^m}{L_t} = W_t. \tag{8}$$

$\frac{\vartheta}{\vartheta-1}$ denotes the markup resulting from imperfect competition in the intermediate goods sector. $\frac{P_t}{P_t^m}$, in turn, denotes the markup of the price level of final output P_t over the price level of the intermediate good composite P_t^m.[2]

Profits from intermediate good production are a central determinant of R&D investment (2.3.1) and technology adoption (section 2.3.2). Intermediate goods profits are identical across firms ($\Pi_t^i = \Pi_t$) and can be derived as

$$\Pi_t = \frac{1}{\vartheta} \frac{\vartheta - 1}{\vartheta} \frac{Y_t^m}{A_t}. \tag{9}$$

[1] Note that while total factor productivity evolves endogenously in this model, TFP is also subject to the standard TFP shock, which captures exogenous TFP variations and drives changes in θ_t. Put differently, total factor productivity is a function of the endogenous component A_t and the exogenous component θ_t.

[2] P_t is described in more detail in section (2.1).

Market clearing in factor markets requires $K_t = \int_0^{A_t} K_t^i di$ and $L_t = \int_0^{A_t} L_t^i di$. Aggregate intermediate good output can be derived combining these conditions with (6), (7) and (8):

$$Y_t^m = \theta_t A_t^{1-\vartheta} K_t^{\alpha} L_t^{1-\alpha}. \tag{10}$$

Equation (10) demonstrates that the expansion of the varieties A_t generates total factor productivity growth. The subsequent section describes this central model feature and the underlying mechanisms in more detail.

2.3 Endogenous Technology Growth

Total factor productivity growth evolves endogenously, following the the approach by Comin and Gertler (2006). Technology growth is governed by a two-stage process, where innovation through R&D is followed by technology adoption. New technologies are invented as the result of research and development efforts, adding to the total stock of technologies Z_t. At the adoption stage, firms decide about whether to incorporate these technologies in production. Innovation only generates productivity gains once adopted by firms in production, where the stock of adopted technologies is denoted by A_t.

2.3.1 R&D sector: Innovation

Innovation is modeled in the form of horizontal innovation through expanding varieties (Romer (1990)). Specifically, innovations occur in the form of new varieties of intermediate goods as a result of R&D investment by private innovators. Competitive innovators invest in R&D to invent new intermediate goods. They sell the rights to use the newly invented technologies to the adopters (see section 2.3.2).

The stock of technologies Z_t corresponds to the technological frontier at time t. Each of these technologies can become obsolete with exogenous probability $1 - \phi$. The law of motion of the technology stock can be stated as

$$Z_{t+1} = \phi Z_t + \varphi_t X_t. \tag{11}$$

Hence, the technology stock at $t + 1$ is hence the sum of the technologies surviving from the previous period ϕZ_t and the newly invented technologies $\varphi_t X_t$. Innovator i

generates new technologies using the production technology

$$\varphi_t X_t^i, \tag{12}$$

where X_t^i denotes i's investment in R&D, measured in units of final output, and $\varphi_t = \frac{\chi Z_t}{Z_t^{\zeta} X_t^{1-\zeta}}$. Total R&D investment in the economy equals to $X_t = \int_i X_t^i di$. Hence, the innovation process is subject to a positive spillover from the aggregate stock of technologies Z_t to the productivity of an individual innovator (Romer (1990)). In addition, the R&D process features a congestion externality from aggregate R&D efforts $\frac{1}{Z_t^{\zeta} X_t^{1-\zeta}}$, where $0 < \zeta < 1$ denotes the R&D elasticity of the aggregate creation of new technologies. The congestion externality is increasing in Z_t which implies that R&D efficiency decreases with the aggregate technology stock becoming more advanced and ensures also the stationarity of the innovation process. At the same time, higher aggregate innovation activity X_t decreases the probability of successful innovation on the level of an individual innovator. The innovation parameter χ is calibrated to generate an adequate growth rate at the balanced growth path.

We now turn to innovator i's problem. J_t refers to the value of an undadopted technology, i.e. a technology which has been invented but not yet incorporated in production (see subsequent section). Technologies invented at t are available as of the following period. The innovator's problem can then be stated as follows:

$$\max_{\{X_{i,t+j}\}_{j=0}^{\infty}} \mathbb{E}_t \left\{ \sum_{j=0}^{\infty} \Lambda_{t,t+1+j} \left[J_{t+1+j} \varphi_{t+j} X_{i,t+j} - \left(1 + f^x \left(\frac{X_{i,t+j}}{X_{i,t+j-1}} \right) \right) X_{i,t+j} \right] \right\},$$

where $\Lambda_{t,t+1+j}$ denotes the stochastic discount factor of the household. R&D is subject to adjustment costs, captured by the convex function $f^x(\cdot)$ with the following properties. On the balanced growth path applies that $f^x\left(\frac{\bar{X}_{t+1}^i}{\bar{X}_t^i}\right) = f^{x\prime}\left(\frac{\bar{X}_{t+1}^i}{\bar{X}_t^i}\right) = 0$, where $\frac{\bar{X}_{t+1}^i}{\bar{X}_t^i} = 1 + g$ and g denotes the growth rate of R&D investment and hence of total factor productivity and output on the balanced growth path. Dropping subscript i, the corresponding optimality condition states that the marginal gains from R&D investment, i.e. the value of an unadopted technology at $t+1$ discounted to the current period, equal the respective marginal costs:

$$\mathbb{E}_t \left(\Lambda_{t,t+1} J_{t+1} \varphi_t \right) = 1 + f^{x\prime} \left(\frac{X_t}{X_{t-1}} \right) \frac{X_t}{X_{t-1}} + f^x \left(\frac{X_t}{X_{t-1}} \right) - \mathbb{E}_t \, \Lambda_{t,t+1} f^{x\prime} \left(\frac{X_t}{X_{t-1}} \right) \left(\frac{X_t}{X_{t-1}} \right)^2.$$

Time t innovation, i.e. the creation of new technologies, can be derived from $V_t =$

$\int_i V_t^i di = \chi Z_t^{1-\zeta} X_t^{\zeta}$, where ζ denotes the elasticity of innovation V_t to aggregate R&D investment. We now turn to the implications for the determinants of growth in the model. The growth rate of the technology stock $\frac{Z_{t+1}}{Z_t}$ can be derived as $\phi + \chi \left(\frac{X_t}{Z_t}\right)^{\zeta}$, which also demonstrates that the long-run growth rate of innovation is endogenous in this framework and shifts in the ratio $\frac{X_t}{Z_t}$ induce permanent changes in the growth rate.

2.3.2 Technology adoption

Newly created technologies do not instantaneously result in productivity gains as they first have to be adopted. This section describes the corresponding technology adoption decision, i.e. the process of converting innovations into technologies usable in production, which is performed by competitive adopters. Modeling technology adoption by means of an adoption sector permits the endogenous evolution of the diffusion of technologies to the economy, while at the same time simplifying aggregation.[3] Let λ_t denote an individual innovator's probability of successfully rendering a technology useable in production at time t which is increasing in adoption expenditures.
Adoption activity is subject to adjustment costs[4]. Specifically, we assume that technology adoption requires specialized input E_t, i.e. equipment, which is generated using final output and is bought at price Q_t^a. The probability of a successful adoption is an increasing function in the equipment used by the respective adopter E_t^i and follows

$$\lambda_t \left(E_t^i\right) = \kappa_\lambda \left(\frac{X_t}{A_t}\right)^{\eta} \left(E_t^i\right)^{\rho_\lambda}, \tag{15}$$

where $\kappa_\lambda > 0$, $0 < \eta < 1$ and $0 < \rho_\lambda < 1$ applies. The probability of successful adoption is thus increasing and concave in the adoption effort E_t^i.

Adopters buy the rights to use an unadopted technology from the innovators at the competitive price J_t. The adopter employs equipment E_t^i in order to render a technology useable in production which is successful with probability λ_t. In case of successful adoption, the adopter sells the technology at price H_t which is defined as

$$H_t = \Pi_t + \phi \mathbb{E}_t \left(\Lambda_{t,t+1} H_{t+1}\right). \tag{16}$$

[3]Specifically, the probability of successful adoption will be equal across technologies. Taking this approach hence permits aggregation without the need to track the share of firms which have adopted the respective technologies.

[4]The adjustment cost function is analogous to adjustment costs for capital producers (see section 2.4 for details.)

The adopters' problem can then be stated as

$$J_t = \max_{E_t^i} -Q_t^a E_t^i + \phi \mathbb{E}_t \left\{ \Lambda_{t,t+1} \left[\lambda_t \left(E_t^i \right) H_{t+1} + \left(1 - \lambda_t \left(E_t^i \right) \right) J_{t+1} \right] \right\}. \tag{17}$$

Adopters thus weigh the costs of adoption against its expected gains which corresponds to the probability weighted sum of the value of adopted and unadopted technologies respectively. Note that adoption effort will be identical across technologies ($E_t^i = E_t$). Dropping the subscript i the optimality condition for adoption can be stated as

$$\rho_\lambda \kappa_\lambda \phi \left(\frac{X_t}{A_t} \right)^\eta \mathbb{E}_t \left[\Lambda_{t,t+1} \left(H_{t+1} - J_{t+1} \right) \right] = Q_t^a E_t^{1-\rho_\lambda}. \tag{18}$$

Aggregate adoption equipment can then be derived as the product of the effort by an individual adopter E_t and the stock of unadopted technologies $(Z_t - A_t)$ and thus equal to $(Z_t - A_t) E_t$.

Lastly, the law of motion for adopted technologies can be stated as follows:

$$A_{t+1} = \phi \left[A_t + \lambda_t \left(Z_t - A_t \right) \right] \tag{19}$$

2.4 Capital producers: investment

Capital producers turn final output into capital which they sell to households at price Q_t. Capital is subject to adjustment costs. The representative capital producer's problem consists of choosing the sequence $\{I_{t+j}\}_{j=0}^{\infty}$ to maximize expected discounted profits

$$\mathbb{E}_t \left\{ \sum_{j=0}^{\infty} \Lambda_{t,t+j} \left[Q_{t+j} I_{t+j} - \left(1 + f_i \left(\frac{I_{t+j}}{I_{t+j-1}} \right) \right) I_{t+j} \right] \right\}. \tag{20}$$

The properties of the adjustment cost function are analogous to the properties of f_x. Profit maximization implies that the marginal costs of generating investment goods equals their price:

$$Q_t = 1 + f_i \left(\frac{I_t}{I_{t-1}} \right) + \frac{I_t}{I_{t-1}} f_i' \left(\frac{I_t}{I_{t-1}} \right) - \mathbb{E}_t \left[\Lambda_{t+1} \left(\frac{I_t}{I_{t-1}} \right)^2 f_i' \left(\frac{I_t}{I_{t-1}} \right) \right]. \tag{21}$$

The law of motion for capital can be stated as follows

$$K_{t+1} = (1 - \delta) K_t + I_t. \tag{22}$$

2.5 Employment agencies

A continuum of households $i \in [0,1]$ monopolistically supply specialized labor L_t^i.[5] There is a large number of competitive employment agencies which combine specialized labor to a homogeneous input L_t to be used in intermediate goods production

$$L_t = \left[\int_0^1 L_t^{i\,\frac{\omega-1}{\omega}} di \right]^{\frac{\omega}{\omega-1}}. \tag{23}$$

Labor demand for type i can be derived from the cost minimization problem of the employment agencies:

$$L_t^i = \left(\frac{W_t^i}{W_t} \right)^{-\omega} L_t. \tag{24}$$

W_t^i denotes the nominal wage of labor variety i. The wage rate at which the intermediate goods producers buy the labor composite corresponds to

$$W_t = \left[\int_0^1 W_t^{i\,1-\omega} di \right]^{\frac{1}{1-\omega}}. \tag{25}$$

2.6 Households

We now turn to the households' problem. Household i maximizes utility

$$\mathbb{E}_t \left\{ \sum_{j=0}^{\infty} \beta^j \left[log\left(C_{t+j} - bC_{t+j-1} \right) - \frac{\psi}{1+\nu} L_{i,t+j}^{1+\nu} \right] \right\} \tag{26}$$

subject to the budget constraint

$$\frac{W_t^i}{P_t} L_t^i + R_t \frac{B_t}{P_t} + \left(R_t^k + (1-\delta) Q_t \right) K_t + \Pi_t = C_t + \frac{B_{t+1}}{P_t} + Q_t K_{t+1}, \tag{27}$$

where C_t denotes consumption and b the habit formation parameter $(0 < b < 1)$. B_t are holdings of riskless bonds in nominal terms, Q_t the real price of capital and Π_t firm profits. Only a fraction $1 - \xi_w$ of households can adjust their wage in period t. They set the optimal wage by

$$\max_{W_t^*} \mathbb{E}_t \sum_{j=0}^{\infty} \left\{ (\xi_w \beta)^j \left[\frac{U_{c,t+j}}{P_{t+j}} L_{t+j}^i W_t^* \prod_{k=1}^{j} (1+g)\, \pi_{t+k-1}^{\iota_w} \bar{\pi}^{1-\iota_w} - \frac{\psi}{1+\nu} \left(L_t^i \right)^{1+\nu} \right] \right\} \tag{28}$$

[5]This approach follows Erceg et al. (2000).

subject to labor demand (24). Households which are prevented from adjusting their wage set it according to the following indexation rule

$$W_t^i = W_{t-1}^i (1+g)\, \pi_{t-1}^{\iota_w} \bar{\pi}^{1-\iota_w}. \tag{29}$$

2.7 Monetary policy

The central bank conducts monetary policy by setting the nominal interest rate R_t according to the monetary policy rule

$$R_t = (R_t))^{\rho_r} \left(\frac{(1+g)\,\bar{\pi}}{\beta} \left(\frac{\pi_t}{\bar{\pi}}\right)^{\gamma_\pi} \left(\frac{L_t}{L^{ss}}\right)^{\gamma_y} \right)^{1-\rho_r} r_t^m. \tag{30}$$

Monetary policy hence targets inflation, weighted by γ_π and in employment, weighted by γ_y. r_t^m follows an AR(1) process $(log\,(r_t^m) = \rho^m log\,(r_{t-1}^m) + \epsilon_t^m)$.

In addition, the central bank may be constrained by the effective lower bound on nominal interest rates:

$$R_t \geq 1. \tag{31}$$

2.8 Aggregation

The economy is subject to the aggregate resource constraint

$$Y_t = C_t + \left[1 + f_i\left(\frac{I_t}{I_{t-1}}\right)\right] I_t + \left[1 + f_a\left(\frac{I_t^a}{I_{t-1}^a}\right)\right] I_t^a + \left[1 + f_x\left(\frac{X_t}{X_{t-1}}\right)\right] X_t, \tag{32}$$

which states that final output is consumed, used for physical capital investment, as well as for expenditure on technology adoption and innovation.[6]

2.9 Calibration

We calibrate the model to quarterly frequency. Table 1 shows the calibration of the main model parameters.[7]

The calibration strategy with respect to the DSGE model parameters and the technology parameters closely follows the approach in recent estimated DSGE models with endogenous technology growth (Anzoategui et al. (2019), Moran and Queralto

[6]This section presented the central equilibrium conditions. The remaining conditions characterizing the equilibrium are to be added to the appendix.

[7]This is not a complete list as some parameters change in the various monetary policy strategies and some are discussed directly in the text.

Parameter	Description	Value
α	Capital share	0.33
β	Discount factor	0.999
δ	Depreciation	0.025
ν	Inverse Frisch elasticity	0.50
γ_π	Inflation weight	1.5
γ_y	Output gap weight	0.5
b	Habit persistence	0.50
ι_p	Price indexation	0.50
ι_w	Wage indexation	0.50
θ_p	Calvo prices	0.85
θ_w	Calvo wages	0.8
ρ^λ	Adoption probability	0.925

Table 1: Calibration of main model parameters

(2018), Elfsbacka Schmöller and Spitzer (2021)).

3 Scarring

The model presented in section 2 can endogenously create scarring effects of recessions subject to permanent losses in terms of total factor productivity and aggregate output. I study potential mechanisms which can generate scarring in demand-driven (section 3.1), as well as in supply-driven recessions (section 3.2). Section 3.3 studies mechanisms of scarring underlying the COVID-19 crisis and thus of an example of a recession driven by both demand- and supply-side factors.

3.1 Demand-driven recessions

This section studies macroeconomic dynamics in demand-driven recessions, as illustrated in Figure 2.[8] The fall in aggregate demand is discernible by means of a decline in aggregate consumption, investment and aggregate output. Employment declines and inflation falls in response to weakened aggregate demand. Monetary policy responds by lowering the policy rate, inducing a fall in nominal and real interest rates. Crucially from the perspective of this paper, the recession also affects total factor productivity as, differently to the standard DSGE setup, the latter is determined endogenously and thus no longer strictly exogenous and independent of cyclical fluctuations.

[8]The demand-driven recession is generated by means of a recessionary liquidity demand shock.

Specifically, the demand-induced output drop reduces firm profits (equ. 9), thus lowering the value of both an unadopted (equ. 17) and adopted technology (equ. 16) respectively. Given the diminished expected payoffs from both R&D and technology adoption activities investment in research and development (equ. 14) and in technology adoption (equ. 18) falls. As a result, total factor productivity decelerates and reinforces the initial output drop. Importantly, the technology stock falls permanently short of its initial trend path and the recession generates scarring effects in total factor productivity and thus permanent output losses.

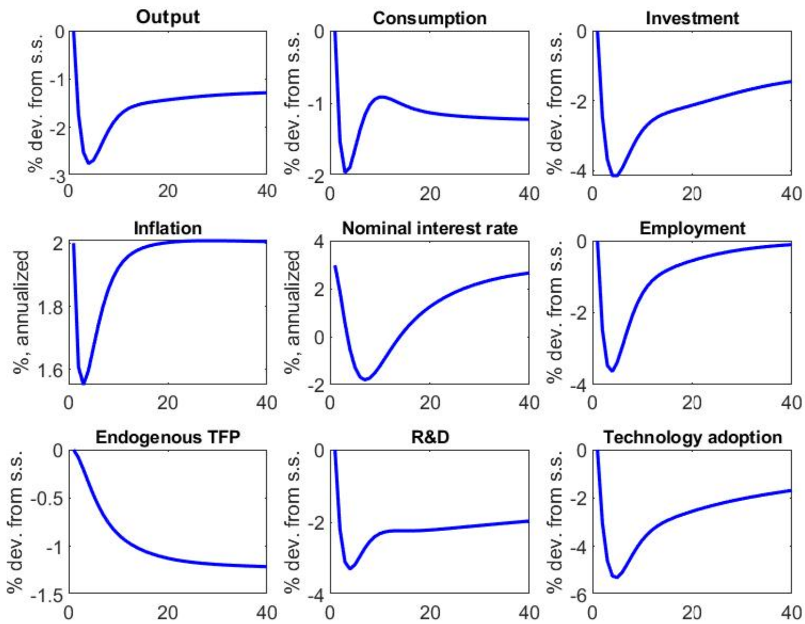

Figure 2: Macroeconomic dynamics in demand-driven recessions

3.2 Supply-driven recessions

We next consider macroeconomic dynamics underlying supply-driven recessions (Figure 3).[9]. The supply shock generates a recession in which output, consumption and investment fall. In a crucial difference to demand-driven recessions (section 3.1), inflation increases, inducing monetary policy to raise nominal interest rates. Importantly, the supply-shock induced recession lowers firm profits (9) and thus innovators' investment in R&D (equ. 14) and firms' technology adoption investment(equ. 18).

[9]Technically, the supply-driven recession is triggered by means of the technology shock, i.e. to intermediate goods producers TFP θ_t.

This applies as the decline in firm profits lowers the expected payoff from both research and development and technology adoption, induced by a fall of the value of an unadopted technology J_t (equ. 17) and an adopted technology H_t (equ. 16) respectively. Endogenous total factor productivity thus falls relative to trend and remains at permanently lower levels, thus generating permanent scars to the technology stock and the long-run path of aggregate output.

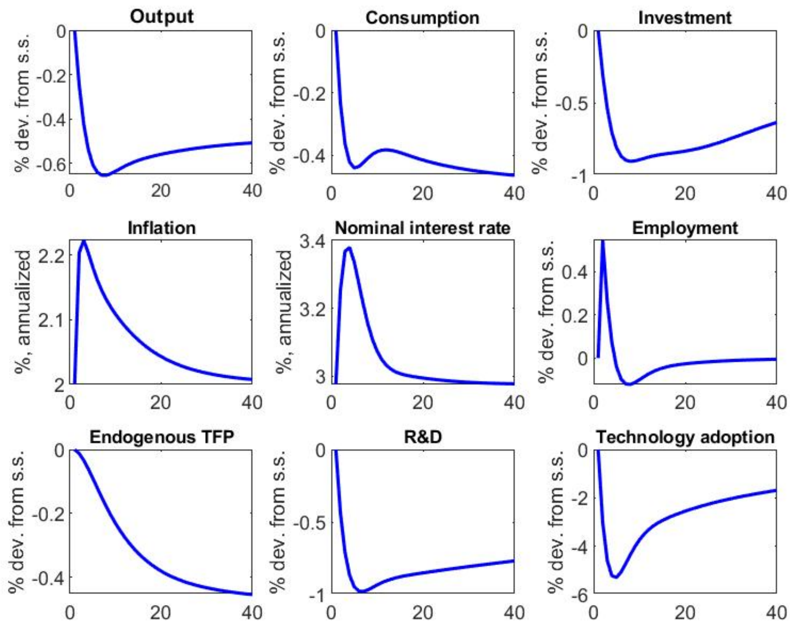

Figure 3: Macroeconomic dynamics in supply-driven recessions

3.3 Scarring effects and COVID-19

I next derive underlying mechanisms and potential scarring effects underlying the COVID-19 crisis which I model as a combination of both demand- and supply-side shocks, as discussed in isolation ins section 3.1 and 3.2 respectively.

The demand-side factors capture the risk of virus contraction while consuming in the sectors exposed to the virus, in the spirit of Guerrieri et al. (2020). Specifically, when the pandemic hits, consumers experience a disutility of consumption owed to the risk of virus contraction. The health-specific demand shock thus induces a wedge in the Euler equation, as economic agents become aware of the described underlying risk, raising savings at the expense of consumption.[10] In addition to substantially de-

[10]Technically, these dynamics are induced by means of a contractionary liquidity demand shock as

pressing aggregate demand, above all in the initial stages of the pandemic, COVID-19 also caused substantial disruptions to aggregate supply, predominantly in the form of lockdown policies and other production and operating constraints and in the form of supply-chain disruptions. The latter can, from the perspective of this model, be interpreted as a direct shock to total factor productivity in firms' production processes, as discussed in section 3.2.

Figure 4 shows the macroeconomic dynamics when the economy is simultaneously hit, as described, by both demand-side and supply-side shocks. Naturally, the aggregate response depends generally relative weight put on the respective channels and the relative strengths of these channels may as well change over time. In the presented scenario, I assume a relative stronger role of the demand-side shifts, resulting in an overall decline in the inflation response, albeit a less pronounced response vis-à-vis purely demand-driven recessions.[11] The COVID-19 shock induces a marked drop in GDP, as well as in consumption and investment in physical capital, as well as a decrease in employment. Both demand- and supply-side forces work to depress aggregate output and hence to cause a decline in firm profits, reducing the incentive to undertake productivity-enhancing investment in R&D and technology adoption[12] The COVID-19 shock thus induces a substantial deceleration in total factor productivity as innovators cut-back on R&D investment and firms reduce their investment in technology adoption. Hence, the model predicts scarring on the technology margin and permanent output effects in the absence of further, supplementary policy measures counteracting the economic crisis.

4 Long-run money non-neutrality and the effective lower bound

This section analyzes the effect of recessions on endogenous total factor productivity taking into account the nonlinearity and reinforcing effect resulting from the effective lower bound constraint on nominal interest rates. Specifically, while stabilizing the economy over the short-run, monetary policy can also positively influence technology-improving investment in R&D and technology adoption and hence the economy's

described in section 3.1.

[11]One could alternatively consider a scenario with relatively more pronounced supply-side forces. This would result in an increase in inflation in aggregate, however, leave the sign of the scarring effects - the main focus of this analysis - and their underlying mechanisms unaltered as both channels work, as discussed in the same direction.

[12]As described in the previous sections the recession-induced fall in firm profits lower the values of an unadopted technology J_t and of an adopted technology H and hence the incentive for R&D and technology adoption investment respectively.

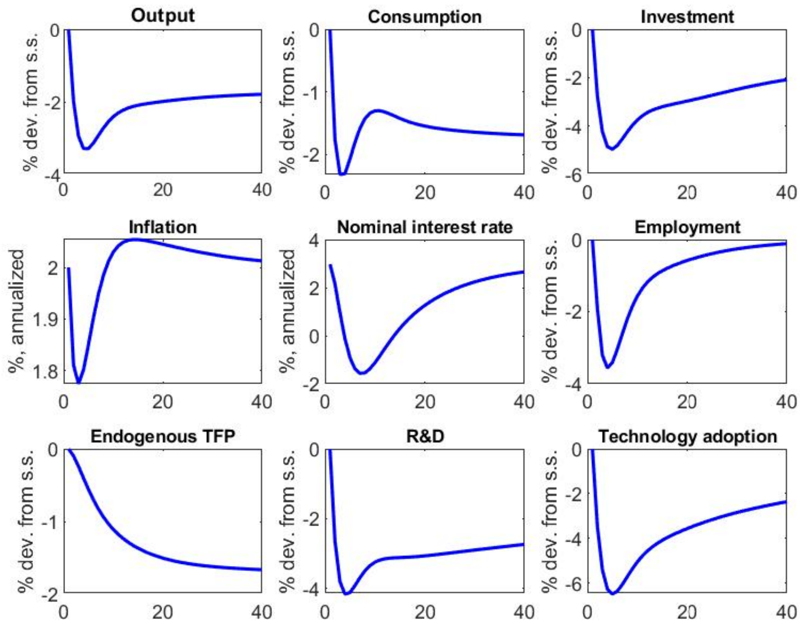

Figure 4: Macroeconomic response (combined COVID-19 shock)

medium- to long-run path. As a result, the effect of a binding effective lower bound constraint are particularly adverse, as it reinforces the scarring effects on the supply side, as illustrated in Figure 5.

Concretely, when the effective lower bound constraint binds, the drop in total factor productivity generated by the recession will be substantially larger, significantly amplifying both the magnitude and the persistence of the output drop. The model thus predicts that when monetary policy is constrained by the effective lower bound, the recovery will be protracted even further and the crisis will be further intensified. Due to this insight, the role of supplementary fiscal policy is substantially emphasized, which I study in more detail in the subsequent session.

5 Government spending under endogenous technology

The previous sections emphasized the role of constraints to monetary policy and demonstrated the adverse effect both on the depth of the crisis and the resulting adverse long-run costs via scarring effects in total factor productivity and output losses over the long run. This result clearly demonstrates the need for supplementary policies

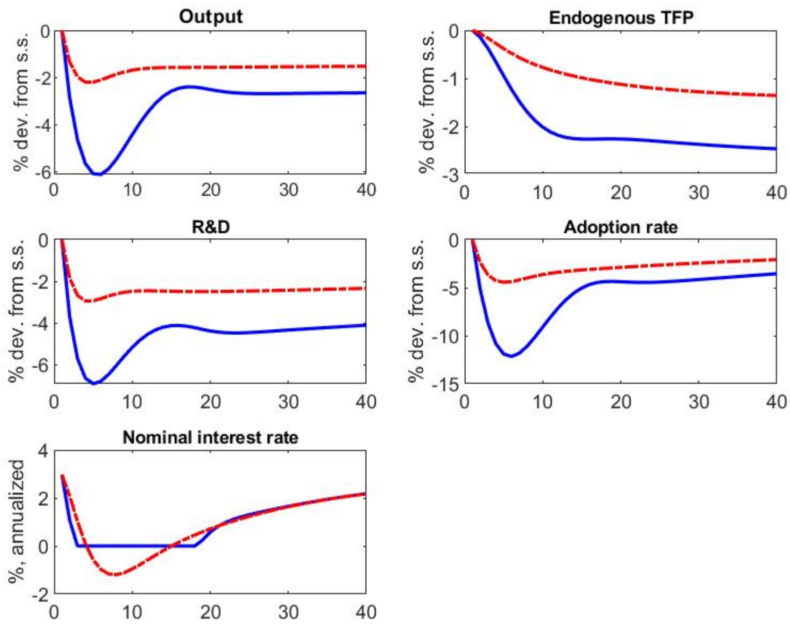

Figure 5: The ELB, scarring in TFP and long-run non-neutrality

when monetary policy is at the effective lower bound. This section analyses the role of government spending in this context. Section 5.1 discusses the effect of an increase in government spending in normal times. I proceed to analyze the effect of fiscal policy at the effective lower bound in section 5.2.

5.1 Government spending in normal times

This section analyses the effect of a government spending shock in normal times, i.e. away from the effective lower bound. Under this scenario, the natural rate of interest is sufficiently high so that in the case of the large-scale shocks discussed earlier, the central bank' action will not be constrained by the effective lower bound. Government spending is modeled as the following AR(1)-process

$$log(g_t) = \rho^g log(g_{t-1}) + \epsilon_t^G, \tag{33}$$

where ρ^g denotes shock persistence ($\rho^g \in [0,1]$) . Government expenditure is financed by means of lump sum taxes on households. Figure 6 demonstrates the economic response to a government spending shock. Output and inflation increase in response to the increase in government spending. Since monetary policy responds when outside the effective lower bound, consumption and investment in physical capital fall. Crucially, an increase in government spending also crowds out productivity-improving investment in both research and development and technology adoption. As a result, an increase in government spending leads to a deceleration in total factor productivity growth. The underlying channels for this observation are as follows. The increase in government spending leads to an increase in inflation and output, leading the central bank to raise interest rates which leads via the Taylor principle to an increase in the real interest rate. In addition, higher government expenditure and taxation decrease future gains from an unadopted and adopted technology. The latter work towards a decline in the value of an unadopted and adopted technology respectively, which depress innovators' investment in research and development and firms' investment in technology adoption, generating the deceleration in the technology stock.

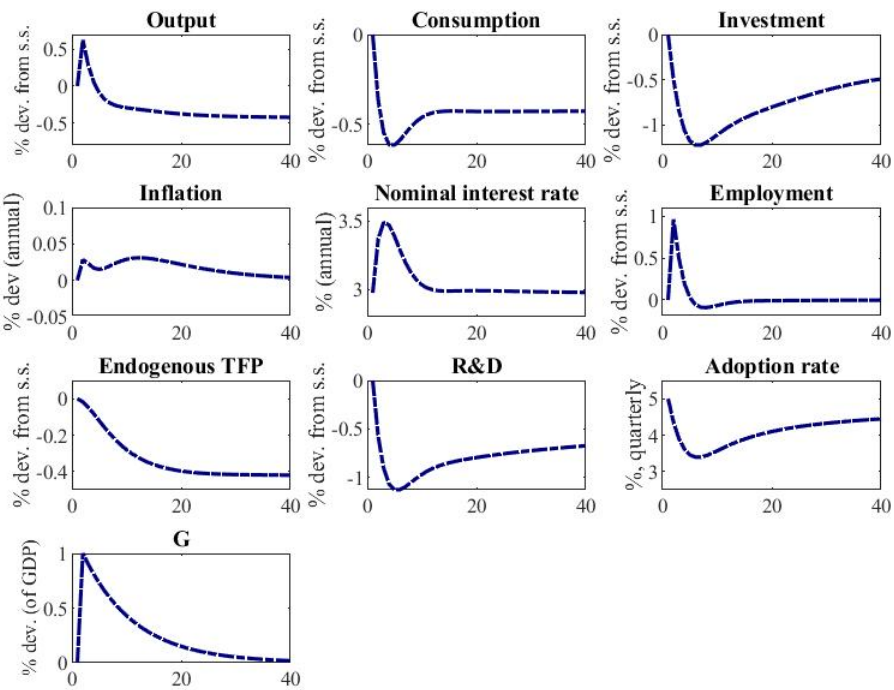

Figure 6: Impulse response to a one standard deviation government spending shock

This result demonstrates that even in the presence of endogenous technology growth, an increase in government spending does - in the representative agent framework with Ricardian households only - not lead to a in general different response of the economy to a government spending shock than under the standard DSGE model with exogenous technology. Put differently, the presence of endogenous TFP dynamics in itself does not alter the role of fiscal policy. In fact, an increase in government spending can in this setup be viewed more destructive than in the general representative agent New Keynesian model with strictly exogenous technology, driven by technology shocks only. The reason for this is the crowding out of not only of private consumption and physical capital investment, but in addition also its adverse effect on productivity-improving investment in R&D and technology adoption and thus the long-run trend path. It is important to note though that this result is also conditional on other model features, most notably the representative agent setup. Moreover, the impact of expansionary government spending changes when monetary policy is constrained by the effective lower bound, as demonstrated in section 5.2 and this result does not generalize to other fiscal policy measures which can be highly beneficial also outside the effective lower bound, as discussed in detail in section 6.

5.2 Government spending at the effective lower bound

This section considers the effect of government spending under endogenous technology growth and when monetary policy is constrained by the effective lower bound on nominal interest rates. Given the proximity of most advanced economies to the effective lower bound before the eruption of the COVID-19 crisis, this is also the relevant scenario for the analysis of the role of the potential increase in government spending in the context of the pandemic crisis.

Figure 7 shows the reaction to a government spending shock when monetary policy is constrained by the effective lower bound (red line), relatively to the same recessionary shocks in the absence of government spending (blue line). We observe that shocks to government spending can significantly alleviate the depth of the recession. Differently to the case with active monetary policy, private consumption and investment in capital and investment increases. In addition, increased government spending fosters the return of inflation to target. Taken together, the positive shock to government spending also reduces the time spent at the effective lower bound. Importantly, government spending can in this scenario also reduce the crisis-induced scarring effects, discernible from a reduced permanent loss in terms of total factor productivity during the crisis episode. This is due to the supportive effect on investment in research and development and technology adoption. In sum, government spending can help in alleviating scarring effects on the technology stock when monetary policy is constrained by the effective lower bound.

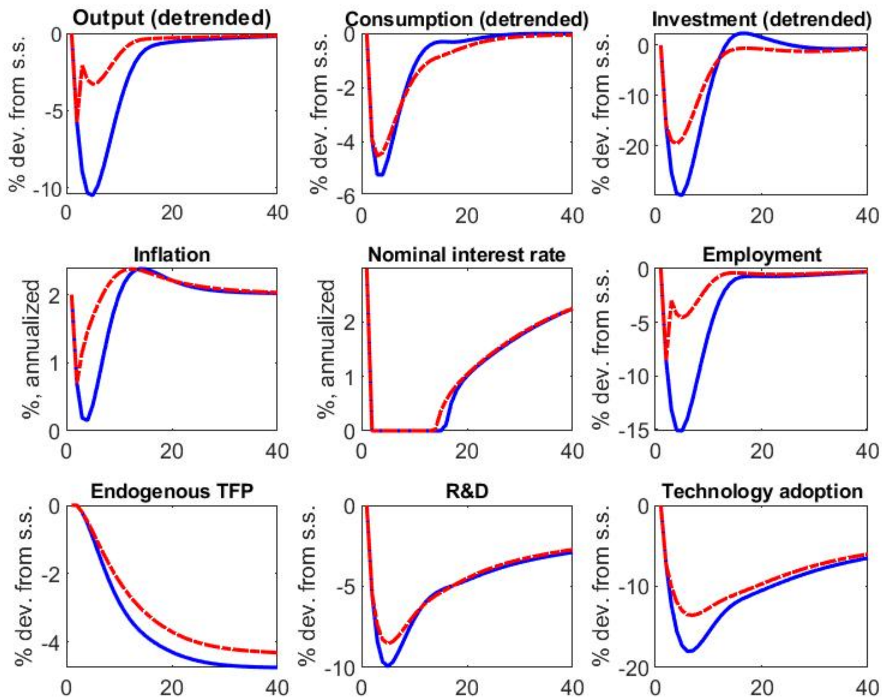

Figure 7: Effect of government spending at the effective lower bound

6 Fiscal policy: Growth policies

In addition to government spending, fiscal policy may choose to stabilize the economy and prevent scarring effects by means of growth policies which are directly aim at raising investment in productivity-enhancing technologies. This type of fiscal policy is the main focus of this section. Given the two-stage technology process, two main types of growth promoting policies are considered, specifically fiscal support to R&D and innovation (section 6.1) and policies promoting technology adoption by firms (6.2). Importantly, while the beneficial role of growth policies is well-established in the endogenous growth literature with respect to long-run growth, this analysis specifically considers their effect not only with respect to the evolution of the supply side, but also as a demand management tool during crisis times.

6.1 R&D subsidies

This section analyzes direct fiscal support to research and development, modeled in the form of subsidies to research and development. Specifically, I assume that the government decides to temporarily raise subsidies to innovation in the economy by paying a fraction $s_{R\&D}$ of entrepreneurs research and development investment. The subsidies to R&D are financed by means of lump sum taxation on households. Under these assumptions, innovators' costs of R&D reduces to

$$(1 - s_{R\&D})\, costs_{R\&D}. \tag{34}$$

The optimality condition for research and development spending under subsidies can be accordingly derived as:

$$\mathbb{E}_t \left(\Lambda_{t,t+1} J_{t+1} \varphi_t\right) = (1 - s_{R\&D}))\left(1 + \Delta_{AC}\right), \tag{35}$$

where Δ_{AC} denotes the derivative to R&D investment adjustment costs. Equation 35 highlights that the subsidies to R&D raise the optimal investment in R&D for a given state of the economy and related value of an unadopted technology J_t. I assume $s_{R\&D}$ follows an AR(1) process

$$log(s_t^{R\&D}) = \rho^{s_{R\&D}} log(s_{t-1}^{R\&D}) + \epsilon_t^{s_{R\&D}}, \tag{36}$$

where $\rho^{s_{R\&D}}$ denotes the persistence of the shock ($\rho^{s_{R\&D}} \in [0, 1]$). The inherent assumption is also that subsides are non-divertible, meaning that firms cannot divert them to other purposes than for research and development.

Figure 8 illustrates the effect of transitory, countercyclical subsidies to research and development. A transitory subsidy to R&D raises aggregate demand at present, as visible in the increase in detrended output. Crucially, from the perspective of the long-run growth path, the subsidy strongly raises entrepreneurs' investment in research and development. In addition, via the complementarity property of the innovation and adoption process, the increased innovation output is also accompanied by an increase in technology adoption activity. As a result, total factor productivity increases substantially, leading to permanent output gains and counteracting potential scarring effects in crisis times. The increase in productivity decreases firms' marginal costs, temporarily mildly reducing inflation.

A crucial benefit of subsidies to R&D are, as discussed, the advantage that they raise aggregate demand instantaneously, while also raising the long-term output path.

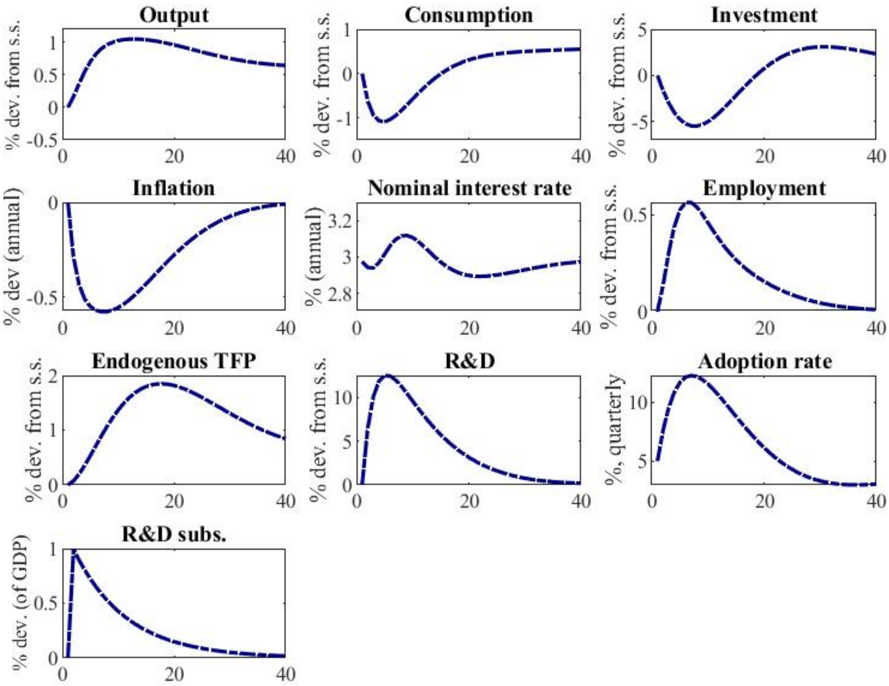

Figure 8: Effect of R&D subsidies

With respect to timing, it is important to note that research and development is a slowly moving process, i.e. the peak impact on innovation is reached only over the medium-term and thus comes with a lag. Subsidizing R&D can regardless of its lagged impact in terms of total factor productivity be considered a powerful fiscal policy tool from the perspective of this model given that it raises the entire technology frontier and thus simultaneously also significantly expands the possibilities for future technology adoption and related productivity gains. Importantly, this result holds true also outside the effective lower bound on nominal interest rates and its beneficial impact is thus not conditional on the responsiveness of monetary policy.

6.2 Subsidies to technology adoption

Another possible option to counteract the crisis and avoid long-term scarring effects are subsidies to firms' technology adoption. I model technology adoption subsidies s_t^{TA}in the form of the following AR(1) process $\log(s_t^{TA}) = \rho^{s_{TA}} log(s_{t-1}^{TA}) + \epsilon_t^{s_{TA}}$,with $\rho^{s_{TA}}$ denotes the persistence of the shock ($\rho^{s_{TA}} \in [0,1]$). Specifically, the subsidies are payed by the government to the adoption sector and financed by lump sum taxes on households. The cost of technology adoption under government subsidies to technology adoption thus reduces to $\left(1 - s_t^{TA}\right) Q_t^a E_t^{1-\rho_\lambda}$. Optimal effort in technology adoption E_t is thus characterized by

$$\rho_\lambda \kappa_\lambda \phi \left(\frac{X_t}{A_t}\right)^\eta \mathbb{E}_t \left[\Lambda_{t,t+1} \left(H_{t+1} - J_{t+1}\right)\right] = \left(1 - s_t^{TA}\right) Q_t^a E_t^{1-\rho_\lambda}. \tag{37}$$

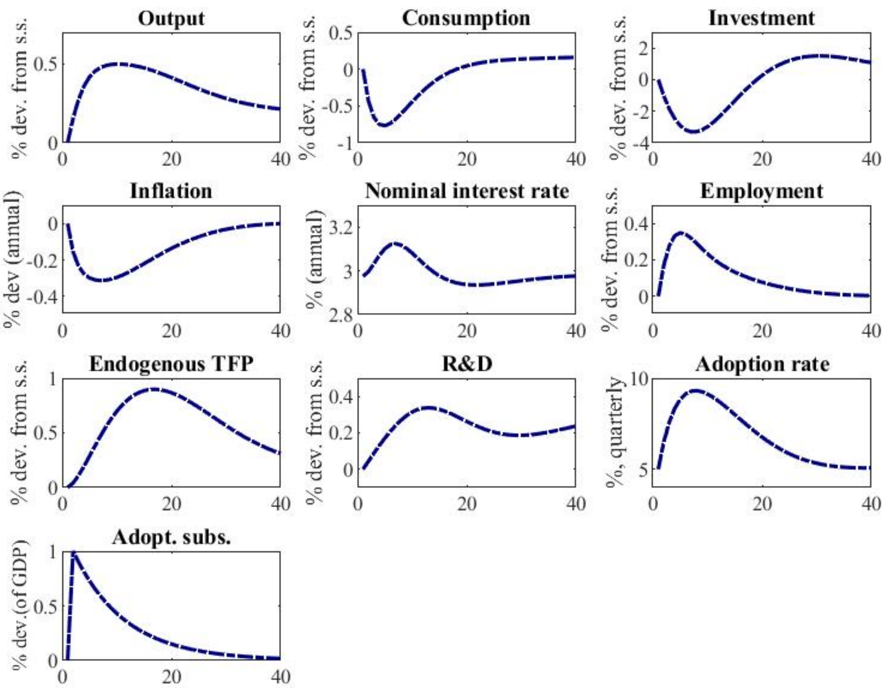

Figure 9: Effect of subsidies to technology adoption

This highlights that for any specific gain from adopting a technology, the efforts undertaken in technology adoption will increase, owed to the diminished costs of adoption effort in the presence of subsidies. Via this channel, fiscal policy can directly raise technology adoption in a downturn, thus alleviating the related supply-side scarring effects. Figure 9 illustrates the effect of subsidies to technology adoption on the macroeconomy. We observe that a temporary subsidy to firms' technology adoption boosts aggregate demand instantaneously, discernible from an increase in detrended output. Importantly with respect to the avoidance of scarring effects, subsidizing technology adoption increases firms' efforts in undertaken investment on the technology diffusion margin and to incorporate new technologies in production, thus reaping productivity gains from delayed diffusion. The corresponding positive effect on total factor productivity induces permanent output gains and counteracts scarring effects in the context of a recession. The boost to productivity reduces firms' marginal costs, inducing a temporary and slight slowdown in inflation.

6.3 Growth policy mix

Growth policies in this model can be implemented by means of fiscal support to the R&D sector, to technology adoption efforts by firms or to both. Supporting technology adoption would feature the particular benefit of raising TFP growth rapidly by enabling a swift catch up to the technology frontier. In the context of the COVID-19 crisis, this may exert the additional beneficial impact of supporting the mitigation of the crisis by encouraging digital technology adoption, for instance in the form of remote working tools or by enabling firms' digital sales channels in otherwise closed sectors. Fiscal policy used to foster R&D investment, in turn, has the benefit of raising the technological frontier and hence strongly boosting the potential for all future technology adoption possibilities. While this may hold substantial productivity gains in store, they would show larger effect only with a lag due to innovation through research and development constituting a slowly-moving process. Taken together, a combination of support to research and development could be desirable in avoiding crisis-induced scarring effects.

7 Fiscal multipliers over the short- and long-run

We turn next to fiscal multipliers over the short- and long-run. The detailed analysis is currently in progress and this section summarizes the main results. As demonstrated in the preceding sections, the endogeneity of total factor productivity enables the study of novel fiscal policy tools in the form of growth-promoting fiscal policies to research and development and technology adoption. When comparing the fiscal multipliers to government spending relative to the described fiscal growth policies the following key results emerge, as presented in Table 2.

Firstly, the short-run government spending multiplier is substantially higher than the multipliers of R&D and technology adoption subsidies, as discernible from the significantly higher relative impact multiplier of government spending. The underlying reason is that the peak response of government spending is reached instantaneously, while the full impact of growth policies builds up only over time. Technology adoption

	Impact multiplier	Peak output response	Long-run TFP impact
G	0.63	0.63 (1q)	- 0.42%
R&D subs.	0.19	0.99 (15q)	+0.62%
Techn. adopt. subs.	0.17	0.43 (7q)	+0.18 %

Table 2: Fiscal multipliers over the short-, medium- and long-run.

and in particular R&D are slowly-moving factors and the peak multiplier is reached after 7 and 15 quarters respectively, reflecting the medium- to long-term orientation of these fiscal policy tools. Crucially, and novel to this paper, there is a long-run dimension to fiscal stimulus under endogenous growth, as it exerts a long-run TFP impact. Crucially, while government spending boosts aggregate output over the short-run, the long-run effect on TFP is negative due to the described crowding out effects. The long-run TFP impact of both fiscal support to R&D and technology adoption, by contrast, is positive, demonstrating the positive and permanent effect of fiscal stimulus. The described long-term multiplier underlying R&D policies is substantially higher than the adoption-specific multiplier as fiscal support to research and development generates an expansion of the entire technological frontier, including future technology adoption possibilities, thus rendering it more far-reaching than corresponding fiscal technology adoption policies.

8 Conclusion

Since the emergence of the COVID-19 crisis, the risk of its possible long-run damage to productive capacity, commonly referred to as *"scarring"*, has constituted a major concern to policy makers. At the same time, the reduction of crisis-induced scarring effects was also a central motivation of the large-scale fiscal policy interventions undertaken over the course of the crisis. The interaction between fiscal policy and total factor productivity growth is, however, not well understood by the previous literature. In particular, previous studies on the design of fiscal policy and on the size of fiscal multipliers are based on models in which the technology stock evolves strictly exogenously, i.e. independently of cyclical fluctuations and demand-side shifts in the economy. This paper departs from this setup by studying fiscal policy in a model in which the technology stock and thus total factor productivity evolves endogenously as the result of investment in research and development and technology adoption and in which cyclical fluctuations can thus exert an effect on long-run aggregate supply. The effect and mechanisms of fiscal policy under endogenous growth, as well as the role of monetary-fiscal interaction in this setup are the key focus of this paper. In this context, I analyze the effectiveness of various fiscal policy tools in alleviating scarring effects and restoring long-run aggregate supply.

The main results can be summarized as follows. Firstly, I show that both demand- and supply-driven recessions can induce scarring on the TFP margin, thus highlighting also the risk of supply-side scarring and permanent output losses in the context of the COVID-19 crisis in the absence of counteracting policy measures. With respect to monetary policy in this context, I show that a binding effective lower bound constraint intensifies both the crisis and the long-term output losses. This result is founded in the altered role of monetary policy under the endogenous growth mechanism. Specifically, monetary policy does not only have a role in stabilizing the economy over the short-run but also influences via the spillovers from cycle to trend investment in technology growth and thus long-term supply, rendering monetary policy non-neutral also over the long-run. As a result, the costs resulting from a binding effective lower bound constraint are larger than conventionally assumed when abstracting from endogenous productivity dynamics.

These results highlight the importance of additional, supplementary fiscal policy in alleviating scarring effects when monetary policy is constrained by the effective lower bound. As to government spending, I show that the relationship between technology growth and fiscal policy is non-trivial and depends on whether or not monetary policy is constrained. In normal times, i.e. outside the effective lower bound, a positive shock to government spending is accompanied by an increase in the real interest rate and government spending crowds out not only investment in physical capital but also productivity-improving investment in research and development and technology adoption. As a consequence of the crowding out effects in TFP, the fiscal multiplier from government spending is - outside the effective lower bound - lower than in DGSE models with exogenous technology. I show, however, that at the effective lower bound increased government spending can be effective not only in supporting inflation and alleviating the recession, but in addition also in significantly reducing scarring effects by fostering investment in R&D and technology adoption in the recession. Taken together, my results suggest that the extent of monetary-fiscal interaction is amplified under endogenous technology dynamics.

I study a fiscal policy tool novel in the New Keynesian DSGE context in the form of counter-cyclical growth policies. Growth policies can constitute an effective short-run stabilization tool, while at the same time alleviating adverse spillovers from cycle to trend and corresponding scarring effects. These fiscal policies combine the effect of boosting aggregate demand at present, while at the same time directly raising technological investments and thus total factor productivity, making these measures very effective in the reduction of long-run scarring effects. Differently to government spending, they are effective both at and outside the effective lower bound and thus independent of constraints to monetary policy.

Fiscal support to R&D is subject to the advantage of expanding the technological frontier itself and thus also the potential for future technology adoption. Their effect on TFP is realized, however, only gradually as research and development constitutes a slowly-moving factor. Subsidies to firms' technology adoption efforts can instantaneously generate substantial productivity gains by taking advantage of delayed technological diffusion. A fiscal policy mix of these policy options thus represents an effective way of counteracting scarring effects in a timely manner, while at the same reaping the benefits from an expansion of the technology frontier itself in the future.

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