Dynamic General Equilibrium Model for Climate Resilient Economic Development (DGE-CRED)

Technical Report

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1 Introduction

Projections by the international panel on climate change (IPCC) show that the global average temperature, the sea level and the frequency of weather extremes are likely to change as a consequence of higher greenhouse gas concentration in the atmosphere Stocker et al. (2013). Climate change has the potential to affect the further economic development of Vietnam. Previous studies (e.g. Arndt et al. 2015, Chen et al. 2012, Wassmann et al. 2004) show that an increase in temperature, sea level rise and a higher frequency of weather extremes (e.g. cyclones and droughts) are hazards to the future economic development. Vietnam belongs to the group of highly vulnerable countries to climate change

The impact of climate change on Vietnam will be different across regions. Official statistics differentiate between six different statistical regions in Vietnam: Red River Delta, Northern Midlands and Mountain Areas (North East and North West), North Central and Central Coastal area (North Central Coast and South Central Coast), Central Highlands, South East, and Mekong River Delta. The map in Figure 1 shows that four of the six regions are located at the coast. The impact of sea level rise in Vietnam will be different for coastal and non-coastal regions. For economic adaptation measures a regional dimension is important.

Further, climate change will affect economic activities like agriculture, forestry and fishery differently than manufacturing. Climate variables have different effects on the production factors labour and capital used in the different economic sectors. Adaptation measures can target different sectors and different production factors. Building a damn will reduce the damage by sea level rise on land use. Early warning systems for cyclones are able to reduce the damage on capital. Water management systems are able to tackle the issue of water scarcity due to higher temperatures. Labour productivity will be affected by heatwaves as well. Adaptation measures replacing labour intensive tasks using more capital intensive production processes are potential adaptation measures. To prioritize and evaluate different adaptation measures a cost benefit analysis is necessary. A cost benefit analysis needs to account for the dynamic nature of the problem. It is also necessary to evaluate the sensitivity of the results to different assumptions made in order to get robust policy decisions. Further, the analysis needs to be transparent and all the assumptions made are explicitly stated. Structural mathematical models are a suitable tool for this task.

Dynamic general equilibrium models with optimizing agents are a standard tool to assess the impact of different policy measures. All adaptation measures will either reduce productivity in the short-run by relocating economic activity or reduce available public funds for other development measures. Therefore, a general equilibrium framework is necessary to assess the economic implications of different adaptation measures. Investment decisions today will affect the future development of specific sectors. This implies path dependency and requires a dynamic framework. We need to differentiate between different regions and economic activities to account for different regional climate developments.

Our model is implemented in the open source environment Dynare and can be run using Matlab or Octave. An open surce environment allows low costs to acquire the necessary skills and experience to workith the model. The model is calibrated to represent the current economic structure. Sectors in the model correspond to economic activities and the classification by the General Statistical Office (GSO). Regions are based on the statistical regions depicted in Figure 1. It is possible to modify the number of sectors and regions by aggregating the official data. This allows to reduce the size of the model and makes it easier to test new modifications and features of the model. The core of the model can be extended to feature different aspects of the economy. Currently, there are extensions of the model available only for a accessible .

We extend the approach by Nordhaus (1993) to model the impact of climate change through damage functions. The link between climate and the economy is modeled using sector and region specific damage functions. Damage functions will affect the productivity of all production factors, or only labour productivity, or the formation of capital. We know that the impact of Vietnamese economic variables on average annual temperature, precipitation, wind speed, average intensity of cyclones and droughts are negligible. Our cost beenfit analysis will use the results of metreological models to define paths for climate variables.

We will define different scenarios to evaluate the costs and benefits associated with different climate variables. Therefore, we first need to define a *Baseline* scenario. The Baseline scenario is necessary to define the evolution of the Vietnamese economy without any climate change. Costs associated with climate change are defined as the difference between the Baseline path and another scenario with climate change for any target variable like gross domestic product. The model is a laboratory for policy makers and researchers to conduct experiments by alternating different climate variables and adaption measures. Data is required to set up the experiments and to get plausible results. Reporting the structural equations of the model is equivalent to a protocol and ensures replication of the experiment. Only replication and transparency ensures that the results can be judged by experts and the public. The model simulates long-run developments. The simulations are not meant to predict bumps in the road, e.g. the economic downturn caused by the coronavirus disease 2019 (COVID-19) virus. But, it is possible to include the impact of the COVID-19. One easy way to do this is to use economic forecasts as conducted by the April 2020 World Economic Outlook by the International Monetary Fund (IMF) to adjust the Baseline scenario to reflect recent developments. Model users are able to quantify upper limits for costs of adaptation measures to reduce damages by climate change. e.g., it is possible to evaluate the impact of temperature increases on different sectors and the overall impact on total gross value added. The discounted cumulative difference between a scenario without a temperature increase and with temperature increase can be used to determine the upper bound for the costs to reduce the damage caused by a temperature increase.

In the following Section 2 the derivation of the model equations is explicitly described. Readers who are interested in using the model can skip the model section and can directly go to Section 3.

2 Model

This report is a guide on how to use the spatial small open economy dynamic general equilibrium model for climate change and adaptation simulations. In general the model belongs to the class of real business cycle models, because no nominal rigidities are explicitly considered. Nevertheless, it is possible to extend the model to feature also nominal rigidities. The model structure is depicted in Figure 2. Regional climate variables (precipitation, wind speed, temperature and sea level) are exogenous to economic variables. Regional sectoral production functions depend on regional climate variables. The model is meant to reflect small open economies and therefore the climate system is unaffected by the domestic economic system.

The model consists of an arbitrary number of regions and sectors. Regional differentiation is only provided on the supply side and not on the demand side. Representative households consume sectoral goods and supply capital and labour to the firms in the regions. Households also demand goods and services from the rest of the world. Firms use capital and labour to produce sectoral goods with sectoral and regional specific constant elasticity of substitution production functions.

The government collects taxes, consumes and can use its funds to finance adaptation measures for specific regions and sectors. So far, adaptation measures will reduce overall damage by all climate variables at the same time. The effectiveness of government expenditure in one specific region and sector can vary.

Table 1 provides a comprehensive list of all variables and parameters. Appendix A reports all equations of the model.

Figure 1: Map of Vietnam

Source: The illustration is published in Boateng (2012).

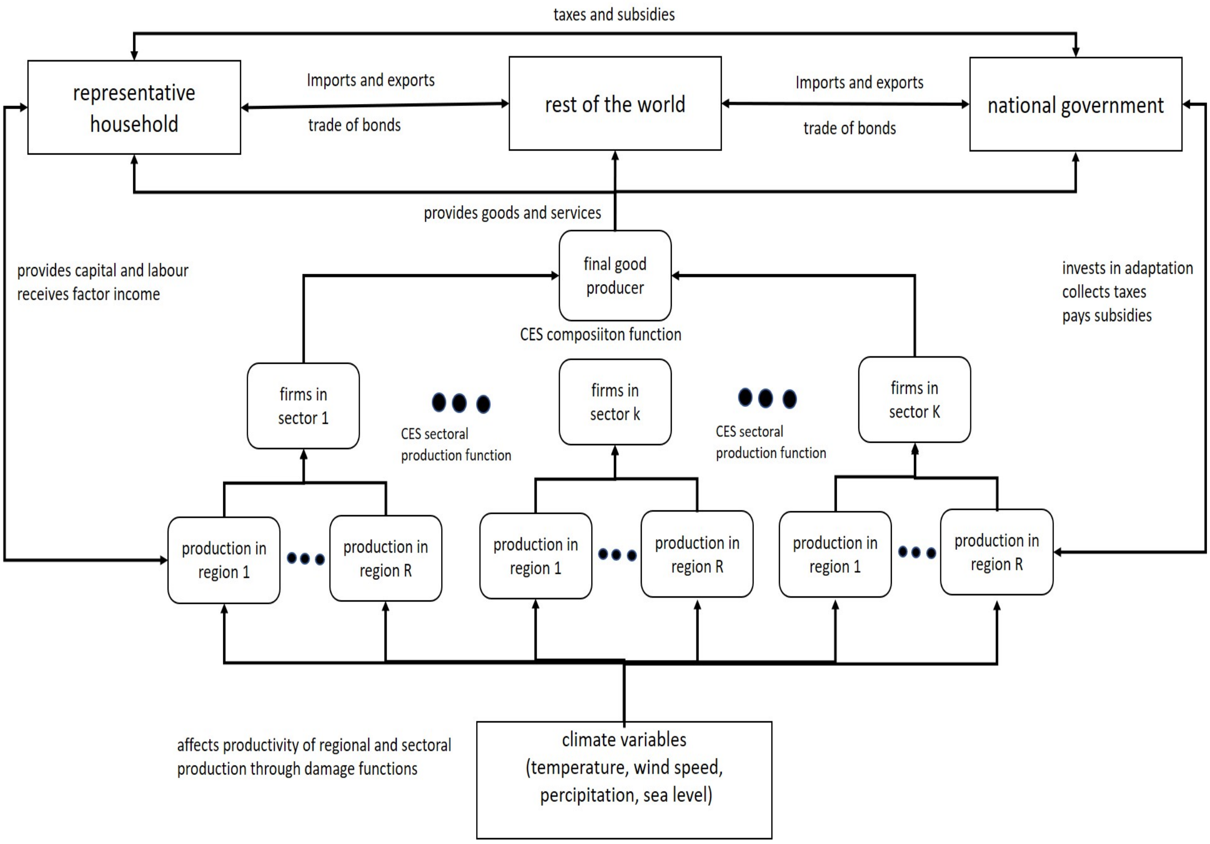
2.1 Climate variables

In order to capture the effect of climate change on the economy it is necessary to include climate variables into the model. A small open economy model does not need to include the impact of domestic economic activity on climate variables. Therefore, in contrast to Nordhaus (1993) we do not need to model the interaction between economic activity and climate change. Climate variables are independent of other endogenous variables in the model. We explicitly model the regional average annual temperature $T_{r,t}$, the average precipitation $PREC_{r,t}$, the average annual wind speed $WS_{r,t}$, the sea level SL_t, cyclones $CYC_{r,t}$ and droughts $DRO_{r,t}$.

$$\begin{aligned} T_{r,t} &= T_{r,0} + \eta_{T,r,t} \\ PREC_{r,t} &= PREC_{r,0} + \eta_{PREC,r,t} \\ W^S_{r,t} &= W^S_{r,0} + \eta_{W^S,r,t} \\ SL_t &= SL_0 + \eta_{SL,r,0} \\ CYC_t &= CYC_0 + \eta_{CYC,r,0} \\ DRO_t &= SL_0 + \eta_{DRO,r,0} \end{aligned} \tag{1}$$

The approach in eq. 1 allows to specify the evolution of climate variables according to the projections by meteorological models (Stocker et al. 2013, e.g.).

Figure 2: Model Structure



Source: own exhibition.

2.2 Demand

2.2.1 Households

As depicted in Figure 2 the demand side is represented by representative households h providing labour N and capital K to domestic firms f. Households maximize discounted utility over an infinite horizon by choosing consumption $C_t(h)$, capital $K_{k,r,t+1}(h)$, investments $I_{k,r,t}(h)$, labour $N_{k,r,t}(h)$ and foreign net bond holdings B_{t+1} to maximize utility constrained by the budget constraint and the law of motion for sectoral and regional capital. Therefore, the Lagrangian eq. 2 of the representative household is

$$\begin{aligned}\sum_{t=0}^{\infty} \beta^t \Bigg[\Bigg(\frac{C_t(h)^{1-\sigma^C}}{1-\sigma^C} - \sum_{k=1}^{K}\sum_{r=1}^{R} \phi^L_{k,r} \frac{N_{k,r,t}(h)^{1+\sigma^L}}{1+\sigma^L} \Bigg) \\ - \lambda_t(h) \Bigg(P_t\, C_t(h)\,(1+\tau^C) + \sum_{k=1}^{K}\sum_{r=1}^{R} P_{k,r,t} I_{k,r,t}(h) + S^f_t\, \phi^B_t\,(1+r^f_t)\, B_t(h) \\ - \sum_{k=1}^{K}\sum_{r=1}^{R} (1-\tau^N)\, W_{k,r,t} N_{k,r,t}(h) - \sum_{k=1}^{K}\sum_{r=1}^{R} P_{k,r,t}\, r_{k,r,t}\,(1-\tau^K)\, K_{k,r,t}(h) - B_{t+1}(h) \Bigg) \\ - \sum_{k=1}^{K}\sum_{r=1}^{R} \lambda_t(h) \omega^I_{k,r,t}(h) \left\{ K_{k,r,t+1} - (1-\delta)\, K_{k,r,t} - I_{k,r,t}\, S\left(\frac{I_{k,r,t}}{I_{k,r,t-1}} \right) \right\} \Bigg].\end{aligned} \tag{2}$$

Households receive utility by consuming goods, where the inter temporal elasticity of consumption is defined by σ^C. Dis-utility from labour is sector and region specific $\phi^L_{k,r}$, the inverse Frisch elasticity σ^L is identical for all sectors and regions. Households spent money either on consumption goods $P_t\, C_t(h)\,(1+\tau^C)$, regional and sector specific investment $P_{k,r,t} I_{k,r,t}(h)$ and need to repay foreign bonds $B_{t+1}(h)$. They receive income from labour $W_{k,r,t}\, N_{k,r,t}(h)\,(1-\tau^L)$, capital renting $P_{k,r,t}\, r_{k,r,t}\, K_{k,r,t}(h)\,(1-\tau^K)$ and can use their borrowed money from the foreign economy $B_t(h)$. The first order conditions to the problem are the behavioral equations. As is standard in teh literature we replace the Lagrange multiplier λ_t by the marginal utility of consumption $\frac{C_t(h)^{-\sigma^C}}{P_t\,(1+\tau^C)}$ derived from the first order condition (FOC) of the above problem with respect to (w.r.t.) consumption. Households supply labour according to the FOC w.r.t. labour eq. 3 for each sector and region depending on the wage $W_{k,r,t}$ and the marginal dis-utility of labour for the specific sector and region

$$\phi^L_{k,r}\, A^N_{k,r,t}\, N_{k,r,t}(h)^{\sigma^L} = \lambda_t(h)\, W_{k,r,t}\,(1-\tau^N). \tag{3}$$

The household also needs to decide how much of its income it wants to consume or invest into capital. The famous Euler equation eq. 4 is obtained by taking the first derivative of the Lagrangian w.r.t. sector and region specific capital

$$\lambda_{t+1}(h)\,\beta\,\left(P_{k,r,t+1}\, r_{k,r,t+1} + (1-\delta)\,\omega^I_{k,r,t+1}\right) = \lambda_t(h)\,\omega^I_{k,r,t}. \tag{4}$$

Further, the household also faces investment adjustment cost $S(\frac{I_{k,r,t}}{I_{k,r,t-1}}) = 3 - exp\left\{\sqrt{\phi^K/2}\left(\frac{I_{k,r,t}}{I_{k,r,t-1}} - 1\right\}\right) - exp\left\{-\sqrt{\phi^K/2}\left(\frac{I_{k,r,t}}{I_{k,r,t-1}} - 1\right)\right\}$, which are sector and region specific. The specification of the investment adjustment cost function is the same as proposed and estimated by Christiano et al. (2014) for the US. The marginal value of sectoral and regional investment $\omega^I_{k,r,t}$ is determined by

$$\begin{aligned} &P_{k,r,t}\,\lambda_t(h) \\ &= \lambda_t(h)\,\omega^I_{k,r,t}\left(S(\frac{I_{k,r,t}}{I_{k,r,t-1}}) - \frac{\partial S(\frac{I_{k,r,t}}{I_{k,r,t-1}})}{\partial I_{k,r,t}}\,\frac{I_{k,r,t}}{I_{k,r,t-1}}\right) + \beta\lambda_{t+1}(h)\,\omega^I_{k,r,t+1}\,\frac{\partial S(\frac{I_{k,r,t+1}}{I_{k,r,t}})}{\partial I_{k,r,t}}\,\left(\frac{I_{k,r,t+1}}{I_{k,r,t}}\right)^2 \end{aligned} \tag{5}$$

Households have access to the international financial market to purchase and sell internationally traded bonds. We only consider net foreign positions.

$$\lambda_{t+1}\,\beta\, S^f_{t+1}\,\phi^B_{t+1}\,\left(1 + {r^f}_{t+1}\right) = \lambda_t \tag{6}$$

The required interest rate will increase if the foreign debt relative to GDP increases and current net exports relative to GDP will decrease.

$$\phi^B_{t+1} = exp\left(-\phi^B\,(S^f_{t+1}\, r^f_{t+1}\,\frac{B_t}{Y_{t+1}} + \frac{NX_t}{Y_t})\right) \tag{7}$$

2.2.2 Government

We are interested in different policy measures taken by the government to adapt to a new climate regime. Government behavior is not a result of an optimization problem. The Government collects taxes from consumption $\tau^C\, C_t$, labour income $\sum_k^K \sum_r^R (\tau^N + \tau^N_{k,r,t})\, W_{k,r,t}\, N_{k,r,t}\, Pop_t$ and capital income $\sum_k^K \sum_r^R (\tau^K + \tau^K_{r,k,t})\, P_{k,r,t}\, r_{k,r,t}\, K_{k,r,t}$. In order to finance its activities the government can also get loans from the rest of the world B^G_{t+1} and has to repay loans and interest from the previous period denominated in foreign currency $(1 + r^f_t)$ identical to the household. The government budget constraint boils down to eq. 8.

$$\begin{aligned} G_t + \sum_k^K \sum_r^R G^A_{k,r,t} + B^G_t = &\sum_k^K \sum_r^R \left\{(\tau^K + \tau^K_{r,k,t})\, P_{k,r,t}\, r_{k,r,t}\, K_{k,r,t} + (\tau^N + \tau^N_{k,r,t})\, W_{k,r,t}\, N_{k,r,t}\, Pop_t\right\} \\ &+ (1 + r^f_t)\, S^f_t\,\phi^B_t\, B^G_{t-1} \end{aligned} \tag{8}$$

Government expenditures can be used to finance adaptation measures in specific sectors and regions $G^{A}_{k,n,t}$. Government expenditures on adaptation measures, taxes on regional and sectoral capital expenditure, and government debt are independent of other variables or to formulate it differently are discretionary. This allows us to evaluate different policy paths for the future and to model the variables by exogenous processes as stated in eq. 9.

$$\begin{aligned} G^{A}_{k,r,t} &= G^{A}_{k,r,0} + \eta^{A}_{k,r,t} \\ \tau^{K}_{k,r,t} &= \tau^{K}_{k,r,0} + \eta^{\tau^{K}}_{k,r,t} \\ \tau^{N}_{k,r,t} &= \tau^{N}_{k,r,0} + \eta^{\tau^{N}}_{k,r,t} \\ B^{G}_{t} &= B^{G}_{0} + \eta^{B^{G}}_{t} \end{aligned} \tag{9}$$

2.2.3 Resource constraint

Households and the Government use domestic final goods Y_t produced by firms for consumption, investment and for exports X_t and can also use imports M_t for consumption and investment. This gives rise to the well known resource constraint or the expenditure approach to define GDP

$$Y_t = C_t + I_t + G_t + \underbrace{X_t - M_t}_{NX_t} \tag{10}$$

2.3 Production

Households demand final domestic goods Y_t combining goods from different sectors $Y_{k,t}$ using a CES composition function. They minimize expenditures subject to the composition function

$$\underset{Y_{k,t}}{min} \sum_k Y_{k,t}\, P_{k,t} \tag{11}$$

$$Y_t = \left(\sum_k {\omega^{Q}_{k}}^{\frac{1}{\eta^Q}} Y_{k,t}^{\frac{\eta^Q - 1}{\eta^Q}} \right)^{\frac{\eta^Q}{\eta^Q - 1}} \tag{12}$$

Therefore demand for sectoral products correspond to the first order conditions of the above optimization problem. The Lagrange multiplier is the price level P_t of domestic products.

$$\frac{P_{k,t}}{P_t} = {\omega^{Q}_{k}}^{\frac{1}{\eta^Q}} \left(\frac{Y_{k,t}}{Y_t} \right)^{\frac{-1}{\eta^Q}} \tag{13}$$

In order to model regional economic activity we further decompose the production process on a regional level. One can either think about this approach as modeling the optimization problem of a representative firm operating in one sector on a national level allocating production activity across the nation. Another way is to consider that households make direct purchases from regional operating firms in one sector. In this case the following optimization problem would be part of the above optimization problem.

$$\underset{Y_{k,r,t}}{min} \sum_k Y_{k,r,t}\, P_{k,r,t} \tag{14}$$

$$Y_{k,t} = \left(\sum_k {\omega^{Q}_{k,r}}^{\frac{1}{\eta^Q_k}} Y_{k,r,t}^{\frac{\eta^Q_k - 1}{\eta^Q_k}} \right)^{\frac{\eta^Q_k}{\eta^Q_k - 1}} \tag{15}$$

Demand for sectoral and regional products correspond to the first order conditions of the above optimization problem. The Lagrange multiplier is the sectoral price level $P_{k,t}$ of domestic products.

$$\frac{P_{k,r,t}}{P_{k,t}} = {\omega^{Q}_{k,r}}^{\frac{1}{\eta^Q_k}} \left(\frac{Y_{k,r,t}}{Y_{k,t}} \right)^{\frac{-1}{\eta^Q_k}} \tag{16}$$

At the regional and sectoral level are representative firms maximizing profits using capital $K_{k,r,t}$ and labour $L_{k,r,t} = N_{k,r,t}\, Pop_t$ provided by households to produce products. They charge a price $P_{k,r,t}$ for their products and have to pay households wages $W_{k,r,t}$, interest on rented capital $P_{r,k,t}\, r_{r,k,t}$, taxes related to the wage bill $\tau^N_{r,k,t}$ and on capital expenditure $\tau^K_{r,k,t}$. Representative firms have access to a regional and sector specific constant elasticity of substitution production function. The productivity of capital and labour of a firm in one sector and region depends on the climate variables, and the adaption measures by the government represented by a damage function affecting total factor productivity $A_{k,r,t}$ by $D_{k,r,t} = D_{k,r}\left(T_{r,t},\, PREC_{r,t},\, W^S_{r,t},\, SL_{r,t},\, CYC_{r,t},\, DRO_{r,t},\, G^A_{r,k,t}\right)$. Further, we explicity differenitate between climate induced damages affecting labour productivity $D_{N,k,r,t}$ and capital depreciation $D_{K,k,r,t}$. As in Nordhaus (1993) we assume a polynomial functional form of the damage functions, but the damages are different across regions and sectors eq. 17.

$$
\begin{aligned}
D_{k,r_t} =& exp\left(-\phi^{G^A_{k,r}}\, G^A_{k,r,t}\right) \Big(\\
& \underbrace{a_{T,1,k,r}\, T_{rt} + a_{T,2,k,r}\, \left(T_{rt}\right)^{a_{T,3,k,r}}}_{\text{impact of temperature}} + \underbrace{a_{SL,1,k,r}\, SL_t + a_{SL,2,k,r}\, \left(SL_t\right)^{a_{SL,3,k,r}}}_{\text{impact of sea level}} \\
& + \underbrace{a_{W^S,1,k,r}\, W^S_{r\ t} + a_{W^S,2,k,r}\, \left(W^S_{r\ t}\right)^{a_{W^S,3,k,r}}}_{\text{impact of wind speed}} + \underbrace{a_{PREC,1,k,r}\, PREC_{rt} + a_{PREC,2,k,r}\, \left(PREC_{rt}\right)^{a_{PREC,3,k,r}}}_{\text{impact of precipitation}} \\
& + \underbrace{a_{CYC,1,k,r}\, CYC_{rt} + a_{CYC,2,k,r}\, \left(CYC_{rt}\right)^{a_{CYC,3,k,r}}}_{\text{impact of cyclones}} + \underbrace{a_{DRO,1,k,r}\, DRO_{rt} + a_{DRO,2,k,r}\, \left(DRO_{rt}\right)^{a_{DRO,3,k,r}}}_{\text{impact of droughts}} \\
& \Big).
\end{aligned}
\tag{17}
$$

$$
\begin{aligned}
D^N_{k,r_t} =& exp\left(-\phi^{G^A_{k,r}}\, G^A_{k,r,t}\right) \Big(\\
& \underbrace{a^N_{T,1,k,r}\, T_{rt} + a^N_{T,2,k,r}\, \left(T_{rt}\right)^{a^N_{T,3,k,r}}}_{\text{impact of temperature}} + \underbrace{a^N_{SL,1,k,r}\, SL_t + a^N_{SL,2,k,r}\, \left(SL_t\right)^{a^N_{SL,3,k,r}}}_{\text{impact of sea level}} \\
& + \underbrace{a^N_{W^S,1,k,r}\, W^S_{r\ t} + a^N_{W^S,2,k,r}\, \left(W^S_{r\ t}\right)^{a^N_{W^S,3,k,r}}}_{\text{impact of wind speed}} + \underbrace{a^N_{PREC,1,k,r}\, PREC_{rt} + a^N_{PREC,2,k,r}\, \left(PREC_{rt}\right)^{a^N_{PREC,3,k,r}}}_{\text{impact of precipitation}} \\
& + \underbrace{a^N_{CYC,1,k,r}\, CYC_{rt} + a^N_{CYC,2,k,r}\, \left(CYC_{rt}\right)^{a^N_{CYC,3,k,r}}}_{\text{impact of cyclones}} + \underbrace{a^N_{DRO,1,k,r}\, DRO_{rt} + a^N_{DRO,2,k,r}\, \left(DRO_{rt}\right)^{a^N_{DRO,3,k,r}}}_{\text{impact of droughts}} \\
& \Big).
\end{aligned}
\tag{18}
$$

$$
\begin{aligned}
D^K_{k,r_t} =& exp\left(-\phi^{G^A_{k,r}}\, G^A_{k,r,t}\right) \Big(\\
& \underbrace{a^K_{T,1,k,r}\, T_{rt} + a^K_{T,2,k,r}\, \left(T_{rt}\right)^{a^K_{T,3,k,r}}}_{\text{impact of temperature}} + \underbrace{a^K_{SL,1,k,r}\, SL_t + a^K_{SL,2,k,r}\, \left(SL_t\right)^{a^K_{SL,3,k,r}}}_{\text{impact of sea level}} \\
& + \underbrace{a^K_{W^S,1,k,r}\, W^S_{r\ t} + a^K_{W^S,2,k,r}\, \left(W^S_{r\ t}\right)^{a^K_{W^S,3,k,r}}}_{\text{impact of wind speed}} + \underbrace{a^K_{PREC,1,k,r}\, PREC_{rt} + a^K_{PREC,2,k,r}\, \left(PREC_{rt}\right)^{a^K_{PREC,3,k,r}}}_{\text{impact of precipitation}} \\
& + \underbrace{a^K_{CYC,1,k,r}\, CYC_{rt} + a^K_{CYC,2,k,r}\, \left(CYC_{rt}\right)^{a^K_{CYC,3,k,r}}}_{\text{impact of cyclones}} + \underbrace{a^K_{DRO,1,k,r}\, DRO_{rt} + a^K_{DRO,2,k,r}\, \left(DRO_{rt}\right)^{a^K_{DRO,3,k,r}}}_{\text{impact of droughts}} \\
& \Big).
\end{aligned}
\tag{19}
$$

Firms in each region and sector have access to a constant elasticity of substitution production function with production factors labour and capital. Eq. 20 states the optimization problem of the firm.

$$\max_{Y_{k,r,t},N_{k,r,t},K_{k,r,t}} P_{k,r,t}\,Y_{k,r,t} - W_{k,r,t}\,N_{k,r,t}\,Pop_t - r_{k,r,t}P_{k,r,t}K_{k,r,t}$$

$$\text{s.t.}\, Y_{k,r,t} = A_{k,r,t}(1-D_{k,r,t})\left[\alpha_{k,r}^{N}{}^{\frac{1}{\eta_{k,r}^{NK}}}\left(A_{k,r,t}^{N}\,(1-D_{k,r,t}^{N})\,Pop_t\,N_{k,r,t}\right)^{\rho_{k,r}} + \alpha_{k,r}^{K}{}^{\frac{1}{\eta_{k,r}^{NK}}}\left(K_{k,r,t}\right)^{\rho_{k,r}}\right]^{\frac{1}{\rho_{k,r}}},$$

$$\text{where } \rho_{k,r} = \frac{\eta_k^{NK}-1}{\eta_k^{NK}}. \tag{20}$$

Demand for production factors are given by the first order condition of the above optimization problem. The Lagrange multiplier is equal to the price charged by companies.

$$\frac{W_{k,r,t}}{P_{k,r,t}} = \alpha_{k,r}^{N}{}^{\frac{1}{\eta_{k,r}^{NK}}}\left(A_{k,r,t}\,(1-D_{k,r,t})\,A_{k,r,t}^{N}\,(1-D_{k,r,t}^{N})\right)^{\rho_{k,r}}\left(\frac{Pop_tN_{k,r,t}}{Y_{k,r,t}}\right)^{-\frac{1}{\eta_{k,r}^{NK}}}$$

$$r_{k,r,t} = \alpha_{k,r}^{K}{}^{\frac{1}{\eta_{k,r}^{NK}}}\left(A_{k,r,t}\,(1-D_{k,r,t})\right)^{\rho_{k,r}}\left(\frac{K_{k,r,t}}{Y_{k,r,t}}\right)^{-\frac{1}{\eta_{k,r}^{NK}}} \tag{21}$$

$$\tag{22}$$

We use the more general case of the CES production function rather than the more commonly used Cobb-Douglas production function. The parameter $\eta_{k,r}^{NK}$ allows us to control the response of capital and labour demand to temporary productivity shocks. Temporary productivity shocks are in our set-up also weather extremes. We will discuss the problem later.

2.4 Rest of the world

The demand for domestic exports and foreign imports is not explicitly modeled in this version of the model. We assume that net exports follow an auto-regressive process of order one and that the long run value of net exports depend on the long-run development of gross domestic product. We therefore assume that imports and exports will grow at the same speed as GDP. Sluggish adjustments in export and import behavior of companies is captured by an auto-regressive process.

$$NX_t = \rho^{NX}\,NX_{t-1} + (1-\rho^{NX})\omega^{NX}P_t\,Y_t \tag{23}$$

The effective exchange rate S_t^f and the world interest rate r_t^f determine how much governments and households have to pay back in domestic currency as net lender or how much they receive as net borrower to the rest of the world. Here the world interest rate is independent of domestic developments and only the effective exchange rate adjusts according to eq. 6.

2.5 Model extension: intermediate consumption and sectoral trade

Table 2 provides a list of all additional variables and parameters included for the extension. Appendix B reports all additional and modified equations associated with the respective extension.

In order to consider the impact of climate change on exports and imports, we need to extend the model to feature sectoral exports $X_{k,t}$ and imports $M_{k,t}$. It is also necessary to include intermediate consumption $Q_{k,r,t}^I$ by firms to ensure that the model can be calibrated to match export and import ratios for different sectors. In contrast to the baseline version imports are used to produce final domestically used output Q_t^U. Final domestically used output is provided by a representative firm using domestic output from different sectors and regions $Q_{k,t}^D$ and sectoral imports. Imports and domestic products from different sectors are combined using a CES composition function. The production function of the firm is a nested CES function.

$$Q_t^U = \left((1-\omega^F)^{\frac{1}{\eta^F}} \, Q_t^{D\,\rho^F} + \omega^{F\,\frac{1}{\eta^F}} \, M_t{}^{\rho^F} \right)^{\frac{1}{\rho^F}}, \text{where } \rho^F = \frac{\eta^F - 1}{\eta^F} \tag{24}$$

$$M_t = \left(\sum_k^K \omega_k^{M\,\frac{1}{\eta^M}} \, M_{k,t}{}^{\rho^M} \right)^{\frac{1}{\rho^M}}, \text{where } \rho^M = \frac{\eta^M - 1}{\eta^M} \tag{25}$$

$$Q_t^D = \left(\sum_k^K \omega_k^{Q\,\frac{1}{\eta^Q}} \, Q_{k,t}^{D\;\rho^Q} \right)^{\frac{1}{\rho^Q}}, \text{where } \rho^Q = \frac{\eta^Q - 1}{\eta^Q} \tag{26}$$

$$Q_k^D = Q_{k,t} - X_{k,t}$$

$$Q_{k,t} = \left(\sum_k^K \omega_{k,r}^{Q\;\frac{1}{\eta_k^Q}} \, Q_{k,r,t}{}^{\rho_k^Q} \right)^{\frac{1}{\rho_k^Q}}, \text{where } \rho_k^Q = \frac{\eta_k^Q - 1}{\eta_k^Q}$$

Prices of sectoral imports $P_{k,t}^M$ are exogenous eq. (90) as well as the export demand eq. (89) for domestic produced sectoral products. The optimization problem of the final goods producer can be split up into different parts. At the top level eq. (24) they choose the amount of imports according to eq. (78) and domestically used and produced products eq. (77). In the next layer the final goods producer minimizes costs for a given level of imports eq. (25) and domestically used and produced output eq. (26). This leads to demand functions for sectoral domestic output eq. (74) and sectoral imports eq. (79).

Further, imports and domestic production are used to consume, invest and for intermediate goods $Q_{k,r,t}^I$ in the domestic production process. Therefore, firms are using labour and capital, but also intermediate input to produce goods and services. The production function of firms operating in different regions is now modified to feature another layer of the CES production function. The firm is now maximizing profits combining value-added $Y_{k,r,t}$ and intermediate products $Q_{k,r,t}^I$ to produce output $Q_{k,r,t}$. They sell their products under prefect competition for the price $P_{k,r,t}^D$. The optimization problem is

$$\underset{Q_{k,r,t}^I,\,Y_{k,r,t}}{min} \; P_{k,r,t}^D \, Q_{k,r,t} - P_t \, Q_{k,r,t}^I - P_{k,r,t} \, Y_{k,r,t}$$

$$Q_{k,r,t} = \left(\omega_{k,r}^{Q^I\;\frac{1}{\eta_{k,r}^I}} \, Q_{k,r,t}^I{}^{rho_{k,r}^I} + (1-\omega_{k,r}^{Q^I})^{\frac{1}{\eta_{k,r}^I}} \, Y_{k,r,t}{}^{\rho_{k,r}^I} \right)^{\frac{1}{\rho_{k,r}^I}}, \text{where } \rho_{k,r}^I = \frac{\eta_{k,r}^I - 1}{\eta_{k,r}^I} \tag{27}$$

Therefore, we obtain equations determining the demand for value added eq. (28) and intermediate products eq. (29) by one sector in a region depending on the relative prices of labour, capital and intermediate products.

$$\frac{P_{k,r\,t}}{P_{k,r,t}^D} = \left(1 - \omega_{k,r}^{Q^I}\right)^{\frac{1}{\eta_k^I}} \left(\frac{Y_{k,r,t}}{Q_{k,r,t}} \right)^{\frac{(-1)}{\eta_k^I}} \tag{28}$$

$$\frac{P_t}{P_{k,r,t}^D} = \omega_{k,r}^{Q^I\;\frac{1}{\eta_k^I}} \left(\frac{Q_{k,r,t}^I}{Q_{k,r,t}} \right)^{\frac{(-1)}{\eta_k^I}} \tag{29}$$

Net exports eq. (88) are now the difference between aggregate export expenditures $P_t^D X_t$ and aggregate import expenditures $P_t^M M_t$. The resource constraint now equates total domestic production with domestic consumption, investment, government consumption, net exports and intermediate products eq. (80). Gross value added is total domestic output less total intermediate consumption.

2.6 Model extension: energy consumption

Table 3 provides a list of all additional variables and parameters included for the extension. Appendix C reports all additional and modified equations associated with the respective extension.

To model the impact of mitigation policy on the economy we define an energy sector k^E. We add two new layers to the production function in the energy sector. The energy sector uses intermediate products $Q^I_{k^E,r,t}$ and a composite energy product $E_{k,r,t}$ to produce a composite intermediate product $Q^{I,E}_{k,r,t}$ eq. (92). The composite energy input is a combination of different energy carriers $c \in \{1, \ldots, EC\}$ using a CES production function eq. (93). The price of an energy carrier is the same across regions and exogenous to other variables eq. (99). Aggregate consumption of energy carriers eq. (98) is necessary to compute emissions associated with different energy carriers. Total intermediate input Q^I_t expenditures is the sum over all intermediate inputs demanded by different sectors including expenditures on energy carriers eq. (97).

3 How to use the model?

3.1 Usage

1. In order to use the model you need to install Dynare (at least version 4.6.1) and Matlab (at least 2018b) or Octave on your computing machine. For Octave you need to have the version 5.2.0 as reported by the Dynare team.

2. You need to download the repository from Github.

3. Open Octave or Matlab GUI and browse to the location of the folder in your computer. You have the right folder if the command `pwd()` returns `YourPath/DGE-CRED/DGE_CRED_Model`.

4. The script `RunSimulations.m` has to be executed in order to run simulations for different scenarios. Make sure that the scenarios and model parameters are defined in the file `ModelSimulationandCalibrationKSectorsandRRegions.xlsx`. We need to adopt the number of sectors and regions in the file `DGE_CRED_Model.mod`.

5. The simulation results are stored in the file `ResultsScenariosKSectorsandRRegions.xlsx`.

4 Folder structure

1. The main file containing all necessary mod files is `DGE_CRED_Model.mod`. This file includes the following files stored in the `ModFiles` folder:

    (a) `DGE_CRED_Model_Declarations.mod` declares all endogenous and exogenous variables if the model and structural parameters.

    (b) `DGE_CRED_Model_Parameters.mod` assigns values to the structural parameters of the model.

    (c) `DGE_CRED_Model_Equations.mod` contains the equations of the model.

    (d) `DGE_CRED_Model_LatexOutput.mod` produces latex output for documentation of the declared variables and model equations.

    (e) `DGE_CRED_Model_SteadyState.mod` computes initial and terminal condition for the dynamic simulation.

    (f) `DGE_CRED_Model_Simulations.mod` starts the dynamic simulation.

2. Subroutines responsible for finding the initial and terminal conditions are located in the subfolder `Functions`:

    (a) `Calibration.mat` finds the initial conditions to reflect a specific year of the economy.

    (b) `FindA.mat` looks for exogenous productivity shocks across sectors and regions to meet the terminal conditions.

    (c) `FindK.mat` looks for a capital allocation across sectors and regions to fulfill the static equations of the model.

    (d) `rng.mat` random number generator function necessary for Octave users.

    (e) `LoadExogenous.mat` reads exogenous variables for different scenarios.

3. To define scenarios and structural parameters one needs to create an Excel workbook located in the subfolder `ExcelFiles`:

    (a) `ModelSimulationandCalibrationforKSectorsandRregions.xlsx` has multiple sheets:

        i. initial `Start`
        ii. terminal `Terminal`
        iii. parameters to define rigidity parameters `Dynamics`
        iv. elasticity parameters and tax rates `Structural Parameters`
        v. coefficients for regional and sector specific damage functions `Climate Damage Functions`

vi. Baseline scenario and other optional scenario sheets defining paths for exogenous varibales

(b) ResultsScenariosKSectorsandRregions.xlsx has as many sheets as Scenarios defined in the previous Excel file.

4. The latex files produced by DGE_CRED_Model_LatexOutput.mod are stored in LatexFiles.

   (a) the system of dynamic equations as implemented in Matlab DGE_CRED_Model_Dynamic, DGE_CRED_Model_Dynamic_content

   (b) names of endogenous, exogenous variables and parameters DGE_CRED_Model_latex_definitions

   (c) the system of dynamic equations in original form without auxiliary variables for leads and lags DGE_CRED_Model_original, DGE_CRED_Model_original_content

5. The file to run different simulations is RunSimulations.m.

6. A Matlab function to find solutions to the static system of equations is DGE_CRED_Model_steady_state.m.

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A Model equations for baseline version

A.1 Regional Industries

damage function TFP

$$D_{k,r_t} = exp\left(-\phi^{G^A_{k,r}}\, G^A_{k,r,t}\right)\left(a_{T,1,k,r}\, T_{rt} + a_{T,2,k,r}\, (T_{rt})^{a_{T,3,k,r}} + a_{SL,1,k,r}\, SL_t + a_{SL,2,k,r}\, (SL_t)^{a_{SL,3,k,r}} + a_{W,1,k,r}\, W^S_{r\ t} + a_{W,2,k,r}\left(W^S_{r\ t}\right)^{a_{W,3,k,r}} + a_{P,1,k,r}\, PREC_{rt} + a_{P,2,k,r}\, (PREC_{rt})^{a_{P,3,k,r}} + a_{C,1,k,r}\, CYC_{rt} + a_{C,2,k,r}\, (CYC_{rt})^{a_{C,3,k,r}} + a_{D,1,k,r}\, DRO_{rt} + a_{D,2,k,r}\, (DRO_{rt})^{a_{DRO,3,k,r}}\right) \tag{30}$$

damage function capital

$$D^K_{k,r_t} = exp\left(-\phi^{G^A_{k,r}}\, G^A_{k,r,t}\right)\left(a^K_{T,1,k,r}\, T_{rt} + a^K_{T,2,k,r}\, (T_{rt})^{a^K_{T,3,k,r}} + a^K_{SL,1,k,r}\, SL_t + a^K_{SL,2,k,r}\, (SL_t)^{a^K_{SL,3,k,r}} + a^K_{W,1,k,r}\, W^S_{r\ t} + a^K_{W,2,k,r}\left(W^S_{r\ t}\right)^{a^K_{W,3,k,r}} + a^K_{P,1,k,r}\, PREC_{rt} + a^K_{P,2,k,r}\, (PREC_{rt})^{a^K_{P,3,k,r}} + a^K_{C,1,k,r}\, CYC_{rt} + a^K_{C,2,k,r}\, (CYC_{rt})^{a^K_{C,3,k,r}} + a^K_{D,1,k,r}\, DRO_{rt} + a^K_{D,2,k,r}\, (DRO_{rt})^{a^K_{DRO,3,k,r}}\right) \tag{31}$$

damage function labour productivity

$$D^N_{k,r_t} = exp\left(-\phi^{G^A_{k,r}}\, G^A_{k,r,t}\right)\left(a^N_{T,1,k,r}\, T_{rt} + a^N_{T,2,k,r}\, (T_{rt})^{a^N_{T,3,k,r}} + a^N_{SL,1,k,r}\, SL_t + a^N_{SL,2,k,r}\, (SL_t)^{a^N_{SL,3,k,r}} + a^N_{W,1,k,r}\, W^S_{r\ t} + a^N_{W,2,k,r}\left(W^S_{r\ t}\right)^{a^N_{W,3,k,r}} + a^N_{P,1,k,r}\, PREC_{rt} + a^N_{P,2,k,r}\, (PREC_{rt})^{a^N_{P,3,k,r}} + a^N_{C,1,k,r}\, CYC_{rt} + a^N_{C,2,k,r}\, (CYC_{rt})^{a^N_{C,3,k,r}} + a^N_{D,1,k,r}\, DRO_{rt} + a^N_{D,2,k,r}\, (DRO_{rt})^{a^N_{DRO,3,k,r}}\right) \tag{32}$$

government expenditure for adaptation measures

$$G^A_{k,r,t} = \eta_{G^A,k,r,t} \tag{33}$$

TFP

$$A_{k,r,t} = A_{k,r,0}\, exp\left(\eta_{A,k,r,t}\right) \tag{34}$$

capital specific productivity

$$A^K_{k,r,t} = A^K_{k,r,0}\, exp\left(\eta_{A^K,k,r,t}\right) \tag{35}$$

labour specific productivity

$$A^N_{k,r,t} = A^N_{k,r,0}\, exp\left(\eta_{A^N,k,r,t}\right) \tag{36}$$

price of regional sectoral goods

$$\frac{P_{k,r_t}}{P_{k_t}} = {\omega^Q_{k,r}}^{\frac{1}{\eta^Q_k}}\left(\frac{Y_{k,r_t}}{Y_{k_t}}\right)^{\frac{(-1)}{\eta^Q_k}} \tag{37}$$

production function

$$Y_{k,r_t} = A_{k,r_t}\,\left(1 - D_{k,r_t}\right)\left({\alpha^K_{k,r}}^{\frac{1}{\eta^{N,K}_{k,r}}}\left(A^K_{k,r_t}\, K_{k,r_{t-1}}\right)^{\frac{\eta^{N,K}_{k,r}-1}{\eta^{N,K}_{k,r}}} + {\alpha^N_{k,r}}^{\frac{1}{\eta^{N,K}_{k,r}}}\left(A^N_{k,r_t}\,(1 - Pop_t\, N_{k,r_t}\right)^{\frac{\eta^{N,K}_{k,r}-1}{\eta^{N,K}_{k,r}}}\right)^{\frac{\eta^{N,K}_{k,r}}{\eta^{N,K}_{k,r}-1}} \tag{38}$$

firms FOC capital

$$r_{k,r_t}\left(1 + \tau^K_{k,r,t}\right) = {\alpha^K_{k,r}}^{\frac{1}{\eta^{N,K}_{k,r}}}\, {A^K_{k,r_t}}^{\frac{\eta^{N,K}_{k,r}-1}{\eta^{N,K}_{k,r}}}\left(\frac{K_{k,r_{t-1}}}{Y_{k,r_t}}\right)^{\frac{-1}{\eta^{N,K}_{k,r}}} \tag{39}$$

Firms FOC labour

$$\frac{W_{k,r_t}\left(1 + \tau^N_{k,r,t}\right)}{P_{k,r_t}} = {\alpha^N_{k,r}}^{\frac{1}{\eta^{N,K}_{k,r}}}\left(\frac{A^N_{k,r_t}\, Pop_t\, N_{k,r_t}}{Y_{k,r_t}}\right)^{\frac{-1}{\eta^{N,K}_{k,r}}} \tag{40}$$

A.2 Aggregation

relative price of sectoral output

$$\frac{P_{k\,t}}{P_t} = {\omega^Q_k}^{\frac{1}{\eta^Q}} \left(\frac{Y_{k\,t}}{Y_t}\right)^{\frac{(-1)}{\eta^Q}} \tag{41}$$

sectoral CES aggregation

$$Y_k, t = \left(\sum_r^R {\omega^Q_{k,r}}^{\frac{1}{\eta^Q_k}} \; {Y_{k,r\,t}}^{\frac{\eta^Q_k - 1}{\eta^Q_k}}\right)^{\frac{\eta^Q_k}{\eta^Q_k - 1}} \tag{42}$$

A.3 Households

households FOC labour

$$\frac{W_{k,r\,t}\;\left(1-\tau^N\right)\;\left(\frac{C_t}{Pop_t}\right)^{\left(-\sigma^C\right)}}{\left(1+\tau^C\right)\;P_t} = \phi^L\;{N_{k\,t}}^{\sigma^L} \tag{43}$$

households FOC capital

$$\frac{\left(\frac{P_{t+1}\,C_{t+1}}{Pop_{t+1}}\right)^{\left(-\sigma^C\right)}}{\left(1+\tau^C\right)\;P_{t+1}}\,\beta\,P_{k,r\,t+1}\,r_{k,r\,t+1}\;\left(1-\tau^K\right) + \beta\,\omega^I_{k,r\,t+1}\;\left(1-\delta\right) = \omega^I_{k,r\,t} \tag{44}$$

households FOC investment

$$\begin{aligned} P_{k,r,t}\,\frac{\left(\frac{C_t}{Pop_t}\right)^{\left(-\sigma^C\right)}}{P_t\;\left(1+\tau^C\right)} &= \omega^I_{k,r\,t}\,\frac{\left(\frac{C_t}{Pop_t}\right)^{\left(-\sigma^C\right)}}{P_t\;\left(1+\tau^C\right)}\;\left(S\left(\frac{I_{k,r\,t}}{I_{k,r\,t-1}}\right) - S'\left(\frac{I_{k,r\,t}}{I_{k,r\,t-1}}\right)\;\left(\frac{I_{k,r\,t}}{I_{k,r\,t-1}}\right)\right) \\ &+ \omega^I_{k,r\,t+1}\,\frac{\left(\frac{C_{t+1}}{Pop_{t+1}}\right)^{\left(-\sigma^C\right)}\;\beta}{\left(1+\tau^C\right)\;P_{t+1}}\,S'\left(\frac{I_{k,r\,t+1}}{I_{k,r\,t}}\right)\;\frac{{I_{k,r\,t+1}}^2}{{I_{k,r\,t}}^2} \end{aligned} \tag{45}$$

households LOM capital

$$K_{k,r\,t} = K_{k,r\,t-1}\;\left(1-\delta\right) + I_{k,r,t}\,S\left(\frac{I_{k,r\,t}}{I_{k,r\,t-1}}\right) \tag{46}$$

households FOC foreign bonds

$$\frac{\left(\frac{C_{t+1}}{Pop_{t+1}}\right)^{\left(-\sigma^C\right)}}{\left(1+\tau^C\right)\;P_{t+1}}\,\beta\,{S^f}_{t+1}\;\exp\left(-\phi^B\;\left(\frac{B_t\,{S^f}_{t+1}\,{r^f}_{t+1}}{Y_{t+1}} + \frac{NX_t}{Y_t}\right)\right)\;\left(1+{r^f}_{t+1}\right) = \frac{\left(\frac{C_t}{Pop_t}\right)^{\left(-\sigma^C\right)}}{P_t\;\left(1+\tau^C\right)} \tag{47}$$

A.4 Climate Variables

temperature

$$T_{r\,t} = T_{0,r} + \eta_{T,r\,t} \tag{48}$$

wind speed

$$W^S_{r\;t} = W^S_{0,r} + \eta_{W^S,r\,t} \tag{49}$$

precipitation

$$PREC_{r\,t} = PREC_{0,r} + \eta_{PREC,r\,t} \tag{50}$$

sea level

$$SL_t = SL_0 + \eta_{SL\,t} \tag{51}$$

A.5 Trade

trade balance

$$NX_t = -\left(B_t - \left(1+{r^f}_t\right)\;S^f_t\;B_{t-1}\right) \tag{52}$$

net exports

$$NX_t = \rho^{NX}\;NX_{t-1} + Y_t\;\left(1-\rho^{NX}\right)\;exp\left(\eta_{NX\,t}\right)\;\omega^{NX} \tag{53}$$

foreign interest rates

$$r^f_t = \bar{r}^f \tag{54}$$

A.6 Government

budget constraint

$$P_t\, G_t + \sum_r^R \sum_k^K P_t\, G^A_{k,r,t} + P_t\, S^f_t\, \left(1 + {r^f}_t\right)\, BG_{t-1} = P_t\, BG_t + C_t\, P_t\, \tau^C + \sum_k^K \sum_r^R N_{k,r,t}\, W_{k,r,t}\, \left(\tau^N + \tau^N_{k,r,t}\right) \tag{55}$$
$$+ K_{k,r_t}\, r_{k,r_t}\, P_{k,r_t}\, \left(\tau^K + \tau^K_{k,r,t}\right)$$

government foreign debt

$$BG_t = \eta_{BG\,t} \tag{56}$$

tax rates on capital expenditure

$$\tau^K_{k,r,t} = \tau^K_{k,r,0} + \eta^{\tau^K}_{k,r,t} \tag{57}$$

tax rates on labour compensation

$$\tau^N_{k,r,t} = \tau^N_{k,r,0} + \eta^{\tau^N}_{k,r,t} \tag{58}$$

A.7 Aggregates

national price level

$$P_t = exp\left(\eta_{P\,t}\right) \tag{59}$$

national Population

$$PoP_t = \rho^{Pop}\, Pop_{t-1} + \left(1 - \rho^{Pop}\right)\, Pop_0\, exp\left(\eta_{Pop\,t}\right) \tag{60}$$

resource constraint

$$Y_t = C_t + I_t + G_t + \sum_k^K \sum_r^R G^A_{k,r,t} + NX_t \tag{61}$$

sector labour

$$N_{k\,t} = \sum_r^R N_{k,r_t} \tag{62}$$

sector wage bill

$$N_{k\,t}\, W_{k\,t} = \sum_r^R N_{k,r_t}\, W_{k,r_t} \tag{63}$$

sector investment

$$P_{k\,t}\, I_{k\,t} = \sum_r^R P_{k,r_t}\, I_{k,r_t} \tag{64}$$

sector capital stock

$$P_{k\,t}\, K_{k\,t} = \sum_r^R P_{k,r_t}\, K_{k,r_t} \tag{65}$$

national investment

$$P_t\, I_t = \sum_k^K P_{k\,t}\, I_{k\,t} \tag{66}$$

national capital

$$P_t\, K_t = \sum_k^K P_{k\,t}\, K_{k\,t-1} \tag{67}$$

national output

$$P_t\, Y_t = \sum_k^K P_{k\,t}\, Y_{k\,t} \tag{68}$$

national labour share

$$N_t = \sum_k^K N_{k\,t} \tag{69}$$

B Additional and modified model equations for input-output extension

B.1 Regional Industries

demand for regional sector output

$$\frac{P^D_{k,r_t}}{P^D_{k\ t}} = \omega^Q_{k,r}{}^{\frac{1}{\eta^Q_k}} \left(\frac{Q_{k,r_t}}{Q_{k\,t}}\right)^{\frac{(-1)}{\eta^Q_k}} \tag{70}$$

output production function

$$Q_{k,r_t} = \left(\omega^{Q^I}_{k,r}{}^{\frac{1}{\eta^I_{k,r}}} \left(Q^I_{k,r,t}\right)^{\frac{\eta^{Q^I}_{k,r}-1}{\eta^{Q^I}_{k,r}}} + \left(1-\omega^{Q^I}_{k,r}\right)^{\frac{1}{\eta^I_{k,r}}} \left(Y_{k,r,t}\right)^{\frac{\eta^I_{k,r}-1}{\eta^I_{k,r}}}\right)^{\frac{\eta^I_{k,r}}{\eta^I_{k,r}-1}} \tag{71}$$

demand for gross value added products

$$\frac{P_{k,r_t}}{P^D_{k,r,t}} = \left(1-\omega^{Q^I}_{k,r}\right)^{\frac{1}{\eta^I_k}} \left(\frac{Y_{k,r,t}}{Q_{k,r,t}}\right)^{\frac{(-1)}{\eta^I_k}} \tag{72}$$

demand for intermediate products

$$\frac{P_t}{P^D_{k,r,t}} = \omega^{Q^I}_{k,r}{}^{\frac{1}{\eta^I_k}} \left(\frac{Q^I_{k,r,t}}{Q_{k,r,t}}\right)^{\frac{(-1)}{\eta^I_k}} \tag{73}$$

B.2 Aggregation

demand for domestically used sectoral products

$$\frac{P^D_{k,t}}{P^D_t} = \omega^Q_k{}^{\frac{1}{\eta^Q}} \left(\frac{Q^D_{k,t}}{Q^D_t}\right)^{\frac{(-1)}{\eta^Q}} \tag{74}$$

use of domestically produced products

$$Q_{k,t} = Q^D_{k,t} + X_{k,t} \tag{75}$$

sectoral CES aggregation

$$Q_{k,t} = \left(\sum_r^R \omega^Q_{k,r}{}^{\frac{1}{\eta^Q_k}} Q_{k,r_t}{}^{\frac{\eta^Q_k-1}{\eta^Q_k}}\right)^{\frac{\eta^Q_k}{\eta^Q_k-1}} \tag{76}$$

demand for domestically used and produced products

$$\frac{P^D_t}{P_t} = (1-\omega^F)^{\frac{1}{\eta^F}} \left(\frac{Q^D_t}{Q^U_t}\right)^{\frac{(-1)}{\eta^F}} \tag{77}$$

demand for imports

$$\frac{P^M_t}{P_t} = (\omega^F)^{\frac{1}{\eta^F}} \left(\frac{M_t}{Q^U_t}\right)^{\frac{(-1)}{\eta^F}} \tag{78}$$

demand for sectoral imports

$$\frac{P^M_{k,t}}{P^M_t} = (\omega^F)^{\frac{1}{\eta^F}} \left(\frac{M_{k,t}}{M_t}\right)^{\frac{(-1)}{\eta^F}} \tag{79}$$

B.3 Aggregates

resource constraint

$$\frac{P^D_t}{P_t} Q_t = C_t + I_t + G_t + \sum_k^K \sum_r^R G^A_{k,r,t} + Q^I_t + NX_t \tag{80}$$

total demand for intermediate products

$$P_t Q^I_t = \sum_k^K \sum_r^R P_t\, Q^I_{k,r,t} \tag{81}$$

total sectoral demand for intermediate products

$$P_t Q^I_{k,t} = \sum_r^R P_t\, Q^I_{k,r,t} \tag{82}$$

definition of domestically used and produced products

$$P_t^D\,Q_t^D = \sum_k P_{k,t}^D\,Q_{k,t}^D \tag{83}$$

definition of domestic output

$$P_t\,Q_t = \sum_k^K P_{k,t}^D\,Q_{k,t}^D \tag{84}$$

definition of domestically used products

$$P_t\,Q_t^U = P_t^M\,M_t + P_t^D\,Q_t^D \tag{85}$$

exports

$$P_t^D X_t = \sum_k^K P_{k,t}^D\,X_{k,t} \tag{86}$$

imports

$$P_t^M M_t = \sum_k^K P_{k,t}^M\,M_{k,t} \tag{87}$$

net exports

$$P_t NX_t = P_t^D\,X_t - P_t^M\,M_t \tag{88}$$

B.4 Trade

demand for sectoral exports

$$\begin{aligned} X_{k,t} &= D_{k,t}^X\,Q_{k,t} \\ D_{k,t}^X &= D_{k,0}^X + \eta_{k,t}^X \end{aligned} \tag{89}$$

price for sectoral imports

$$P_{k,t}^M = P_{k,0}^M + \eta_{k,t}^M \tag{90}$$

C Additional and modified model equations for energy extension

C.1 Regional Energy industries

output production function

$$Q_{k,r_t} = \left(\omega_{k,r}^{Q^I \frac{1}{\eta^I_{k,r}}} \left(Q_{k,r,t}^{I,E}\right)^{\frac{\eta^{Q^I}_{k,r}-1}{\eta^{Q^I}_{k,r}}} + \left(1-\omega_{k,r}^{Q^I}\right)^{\frac{1}{\eta^I_{k,r}}} \left(Y_{k,r,t}\right)^{\frac{\eta^I_{k,r}-1}{\eta^I_{k,r}}} \right)^{\frac{\eta^I_{k,r}}{\eta^I_{k,r}-1}} \tag{91}$$

nested composition function for intermediate energy and non-energy inputs

$$Q_{k,r\ t}^{I,E} = \left((1-\omega_{k,r}^{Q^E})^{\frac{1}{\eta^E_{k,r}}} \left(Q_{k,r,t}^{I,E}\right)^{\frac{\eta^E_{k,r}-1}{\eta^E{}_{k,r}}} + \left(\omega_{k,r}^{E}\right)^{\frac{1}{\eta^E_{k,r}}} \left(E_{k,r,t}\right)^{\frac{\eta^E_{k,r}-1}{\eta^E_{k,r}}} \right)^{\frac{\eta^E_{k,r}}{\eta^E_{k,r}-1}} \tag{92}$$

nested composition function for energy inputs

$$E_{k,r,t} = \left(\sum_{c}^{EC} \omega_{k,r,c}^{Q^E \frac{1}{\eta^{EC}_{k,r}}} \left(E_{k,r,c,t}\right)^{\frac{\eta^{EC}_{k,r}-1}{\eta^{EC}{}_{k,r}}} \right)^{\frac{\eta^{EC}_{k,r}}{\eta^{EC}_{k,r}-1}} \tag{93}$$

demand for intermediate products

$$\frac{P^I_{k,r,t}}{P^D_{k,r,t}} = \omega_{k,r}^{Q^I \frac{1}{\eta^I_k}} \left(\frac{Q^I_{k,r,t}}{Q^{I,E}_{k,r,t}} \right)^{\frac{(-1)}{\eta^I_k}} \tag{94}$$

demand for energy as intermediate product

$$\frac{P^E_{k,r,t}}{P^I_{k,r,t}} = \omega_{k,r}^{E \frac{1}{\eta^E_{k,r}}} \left(\frac{E_{k,r,t}}{Q^{I,E}_{k,r,t}} \right)^{\frac{(-1)}{\eta^E_k}} \tag{95}$$

demand for non-energy intermediate products

$$\frac{P_t}{P^I_{k,r,t}} = (1-\omega^E_{k,r})^{\frac{1}{\eta^E_{k,r}}} \left(\frac{Q^I_{k,r,t}}{Q^{I,E}_{k,r,t}} \right)^{\frac{(-1)}{\eta^E_k}} \tag{96}$$

C.2 Aggregates

total demand for intermediate products

$$P_t Q_t^I = \sum_k^K \sum_r^R \begin{cases} P^I_{k,r,t}\, Q^{I,E}_{k,r,t} & \text{if} k = k^E \\ P_t\, Q^I_{k,r,t} & \text{otherwise} \end{cases} \tag{97}$$

total consumption of energy carrier

$$E_{c,t} = \sum_r^R E_{k^E,r,c,t} \tag{98}$$

price of energy carrier

$$P^{EC}_{c,t} = P^{EC}_{c,0} + \eta^{EC}_{c,t} \tag{99}$$

Table 1: List of symbols for baseline version

Variable	LaTeX	Description
	Endogenous	
P	P	price level
K	K	capital stock
C	C	consumption
PoP	Pop	population
B	B	international traded bonds
Sf	S^f	effective exchange rate with the rest of the world
BG	BG	government debt
NX	NX	net exports
rf	r^f	foreign interest rate
G	G	government expenditure
I	I	private investment
Y	Y	GDP
N	N	labour
SL	SL	sea level
PREC_k	$PREC_r$	regional PRECipitation
T_k	T_r	regional temperature
WS_k	W^S_r	regional wind speed
Y_k	Y_k	sector GDP
K_k	K_k	sector capital
N_k	N_k	sector employment
I_k	I_k	sector private investment
P_k	P_k	sector price index
W_k	W_k	sector wage index
Y_k_r	$Y_{k,r}$	regional sector GDP
D_k_r	$D_{k,r}$	regional sector damages
K_k_r	$K_{k,r}$	regional sector capital
N_k_r	$N_{k,r}$	regional sector employment
W_k_r	$W_{k,r}$	regional sector wages
A_k_r	$A_{k,r}$	regional sector TFP
G_A_k_r	$G^A_{k,r}$	regional sector adaptation government expenditure
gA_k_r	$g^A_{k,r}$	regional growth rate of sector TFP
A_N_k_r	$A^N_{k,r}$	regional sector labour specific TFP
A_K_k_r	$A^K_{k,r}$	regional sector capital specific TFP
I_k_r	$I_{k,r}$	regional sector private investment
P_k_r	$P_{k,r}$	regional sector price index
omegaI_k_r	$\omega^I_{k,r}$	shadow value of regional private sector investment
r_k_r	$r_{k,r}$	regional sector rental rate on capital
tauK_k_r	$\tau^K_{k,r}$	regional sector corporate tax rate on capital
tauN_k_r	$\tau^N_{k,r}$	regional sector labour tax rate on capital
	Exogenous	
exo_P	η_P	exogenous price index evolution
exo_PoP	η_{Pop}	exogenous population
exo_SL	η_{SL}	exogenous sea level
exo_NX	η_{NX}	exogenous net exports
exo_BG	η_{BG}	exogenous structural balance
exo_tauK_k_r	$\eta_{\tau^K,k,r}$	exogenous sector and region corporate tax rate
exo_tauN_k_r	$\eta_{\tau^N,k,r}$	exogenous sector and region labour tax rate
exo_k_r	$\eta_{A,k,r}$	exogenous TFP
exo_N_k_r	$\eta_{A^N,k,r}$	exogenous labour specific TFP
exo_K_k_r	$\eta_{A^K,k,r}$	exogenous capital specific TFP
exo_GA_k_r	$\eta_{G^A,k,r}$	exogenous sector adaptation expenditure
exo_T_k	$\eta_{T,n}$	exogenous regional temperature
exo_PREC_k	$\eta_{PREC,n}$	exogenous regional precipitation
exo_WS_k	$\eta_{W^S,n}$	exogenous regional wind speed
	Parameters	
omegaQ_k_p	$\omega^Q_{k,}$	distribution parameter for output from one sector
etaQ_k_p	η^C_k	elasticity of substitution between regional production
tauK_k_r_p	$\tau^K_{k,r}$	region and sector specific tax rate on capital
tauN_k_r_p	$\tau^N_{k,r}$	region and sector specific tax rate on labour
rhoA_k_r_p	$\rho^A_{k,r}$	persistence productivity shock
rhoA_N_k_r_p	$\rho^{A,N}_{k,r}$	persistence labour specific productivity shock
rhoA_K_k_r_p	$\rho^{A,K}_{k,r}$	persistence capital specific productivity shock
phiY_k_r_p	$\frac{P_{k,r,0}\,Y_{k,r,0}}{P_0\,Y_0}$	long-run share of regional and sectoral output

Table 1 – Continued

Variable	LaTeX	Description
phiN_k_r_p	$N_{k,r,0}$	long run share of regional and sectoral employment
phiY0_k_r_p	$\frac{P_{k,r,0}\,Y_{k,r,0}}{P_0\,Y_0}$	terminal share of regional and sectoral output
phiN0_k_r_p	$N_{k,r,0}$	initial share of regional and sectoral employment
phiYT_k_r_p	$\frac{P_{k,r,0}\,Y_{k,r,0}}{P_0\,Y_0}$	terminal share of regional and sectoral output
phiNT_k_r_p	$N_{k,r,0}$	terminal share of regional and sectoral employment
phiW_k_r_p	$\frac{W_{k,r,0}\,N_{k,r,0}}{P_{k,r,0}\,Y_{k,r,0}}$	share of regional and sectoral employment
phiP_k_r_p	$\frac{P_{k,r,0}}{P_0}$	share of regional and sectoral employment
phiL_k_r_p	$\phi^L_{k,r}$	coefficient of disutility to work
omegaQ_k_r_p	$\omega^Q_{k,r}$	distribution parameter for regional production
alphaK_k_r_p	$\alpha^K_{k,r}$	distribution parameter capital share
alphaN_k_r_p	$\alpha^N_{k,r}$	distribution parameter labour share
etaNK_k_r_p	$\eta^{N,K}_{k,r}$	elasticity of substitution between labour and capital
A_k_r_p	$A_{k,r}$	sector long-run TFP
GAT_k_r_p	$G^A_{T,k,r}$	sector region specific government expenditure for adaptation
phiGA_k_r_p	$\phi^{GA}_{k,r}$	coefficient of effectiveness of government expenditure on adaptation measures
gY0_k_r_p	$\frac{Y_{2,k,r}}{Y_{1,k,r}}$	initial sector growth
gN0_k_r_p	$\frac{\frac{N_{2,k,r}}{N_2}}{\frac{N_{1,k,r}}{N_1}}$	initial sector labour growth
omegaA_k_r_p	$\omega^A_{k,r}$	exponent for productivity growth
A_N_k_r_p	$A^N_{k,r}$	sector labour specific TFP
A_K_k_r_p	$A^K_{k,r}$	sector capital specific TFP
a_T_k_k_r_p	$a_{1,k,r}$	intercept of damage function temperature
a_T_2_k_r_p	$a_{2,k,r}$	slope of damage function temperature
a_T_3_k_r_p	$a_{3,k,r}$	exponent of damage function temperature
a_P_k_k_r_p	$a_{1,k,r}$	intercept of damage function PRECipitation
a_P_2_k_r_p	$a_{2,k,r}$	slope of damage function PRECipitation
a_P_3_k_r_p	$a_{3,k,r}$	exponent of damage function PRECipitation
a_W_k_k_r_p	$a_{1,k,r}$	intercept of damage function wind speed
a_W_2_k_r_p	$a_{2,k,r}$	slope of damage function wind speed
a_W_3_k_r_p	$a_{3,k,r}$	exponent of damage function wind speed
a_SL_k_k_r_p	$a_{1,k,r}$	intercept of damage function sea level
a_SL_2_k_r_p	$a_{2,k,r}$	slope of damage function sea level
a_SL_3_k_r_p	$a_{3,k,r}$	exponent of damage function sea level
beta_p	β	discount factor
delta_p	δ	capital depreciation rate
sigmaL_p	σ^L	inverse Frisch elasticity
sigmaC_p	σ^C	intertemporal elasticity of substitution
etaQ_p	η^Q	elasticity of substitution between sectoral production
phiB_p	ϕ^B	coefficient of foreign adjustment cost
phiK_p	ϕ^K	coefficient of investment adjustment cost
tauC_p	τ^C	consumption tax
tauN_p	τ^N	labour tax
tauK_p	τ^K	capital tax
omegaNX_p	ω^{NX}	share of net exports relative to domestic GDP
omegaNX0_p	$\omega^{NX,0}$	initial share of net exports relative to domestic GDP
omegaNXT_p	$\omega^{NX,T}$	terminal share of net exports relative to domestic GDP
rhoNX_p	ρ^{NX}	persistency in net exports
rhoA_p	ρ^A	persistency in TFP
rhoPoP_p	ρ^{Pop}	persistency in population
rhoSL_p	ρ^{SL}	persistency in sea level
rhoT_p	ρ^T	persistency in temperature
rhoWS_p	ρ^T	persistency in wind speed
rhoPREC_p	ρ^T	persistency in PRECipitation
inbsectors_p	K	number of sectors
inbregions_p	R	number of regions
lCalibration_p	l^{Calib}	logical indiactor whether model is calibrated or not
T0_r_p	$T_{0,n}$	initial regional temperature
PREC0_r_p	$PREC_{0,n}$	initial regional PRECipitation
WS0_r_p	$W^S_{0,n}$	initiial regional wind speed
TT_r_p	$T_{T,n}$	terminal regional temperature
PRECT_r_p	$PREC_{T,n}$	terminal regional PRECipitation
WST_r_p	$W^S_{T,n}$	terminal regional wind speed

Table 1 – Continued

Variable	LaTeX	Description
SL0_p	SL_0	initial sea level
PoP0_p	POP_0	initial population
Y0_p	Y_0	initial output
P0_p	P_0	initial price level
N0_p	N_0	initial employment
SLT_p	SL_T	terminal sea level
PoPT_p	Pop_T	terminal population
YT_p	Y_0	terminal output
NT_p	Y_0	terminal employment

Table 2: List of symbols for input-output extension

Variable	LaTeX	Description
		Endogenous
P_D	P^D	price level of domestic produced products
P_M	P^M	price level of imports
Q_U	Q^U	domestic used products
Q_D	Q^D	domestic produced and used products
Q_I	Q^I	intermediate products
Q	Q	doesmtic output
M	M	imports
X	X	exports
Q_k	Q_k	sectoral exports
Q_D_k	Q_k^D	domestic used and produced products
Q_I_k	Q_k^I	domestic used intermediate products
M_k	M_k	sectoral imports
X_k	X_k	sectoral exports
P_D_k	P_k^D	sectoral price index of domestic products
P_M_k	P_k^D	sectoral price index of imports
Q_k_r	$Q_{k,r}$	regional sector output
Q_I_k_r	$Q_{k,r}$	regional sector demand for intermediate products
P_D_k_r	$P_{k,r}^D$	sectoral and regional price index of domestic products
		Exogenous
exo_X_k	η_k^X	exogenous demand for sectoral exports
exo_M_k	η_k^M	exogenous sectoral price of imports
		Parameters
phiM_k_p	ϕ_k^M	initial share of sectoral imports
phiX_k_p	ϕ_k^X	initial share of sectoral exports
phiQI_k_p	$\phi_k^{Q^I}$	initial share of sectoral intermediate inputs
D_X_k_p	D_k^X	initial demand for sectoral exports
P_M_k_p	P_k^M	initial price level for sectoral imports
omega_M_k_p	ω_k^M	distribution parameter for imports
eta_I_k_p	η_k^I	elasticity of substitution between intermediate products and value added
omegaQI_k_r_p	$\omega_{k,r}^{Q^I}$	distribution parameter between intermediate products and value added
etaM_p	η^M	elasticity of substitution between sectoral imports
etaF_p	η^F	elasticity of substitution between imports and domestic products
omegaF_p	ω^F	distribution parameter for imports
phiM_p	ϕ^M	initial share of imports on toal output

Table 3: List of symbols for energy extension

Variable	LaTeX	Description
		Endogenous
P_EC_c	P_c^E	price of energy source
EC_c	E_c	consumption of energy source
E_k_r	$E_{k,r}$	composite energy consumption
Q_IE_k_r	$Q_{k,r}^{I,E}$	composite intermediate products for energy sector
P_I_k_r	$P_{k,r}^{E,Q^I}$	price of composite intermediate products for energy sector
P_E_k_r	$P_{k,r}^E$	price of composite energy
E_k_r_c	$E_{k,r,c}$	regional and sectoral consumption of energy source
		Exogenous
exo_E_c	η_c^E	exogenous price for energy source
		Parameters
phiE_k_r_p	$\phi_{k,r}^E$	initial share of energy on intermediate products
phiE_k__r_c_p	$\phi_{k,r,c}^E$	initial share of energy source on energy composite intermediate product
omegaE_k_r_p	$\phi_{k,r}^E$	distribution parameter for energy on intermediate products
omegaE_k__r_c_p	$\phi_{k,r,c}^E$	distribution parameter for energy source on energy as intermediate product
etaE_k_r_p	$\eta_{k,r}^E$	elasticity of substitution between energy and other intermediate products
etaEC_k_r_p	$\eta_{k,r}^{E,C}$	elasticity of substitution between energy carriers
P_EC_c_p	$P_{c,0}^E$	initial price for energy source