Stock-flow consistent modelling and ecological macroeconomics

Yannis Dafermos[1] Maria Nikolaidi[2]

[1]SOAS University of London, [2]University of Greenwich

FMM Summer School
Berlin, 29 July 2022

- Over the last years, **stock-flow consistent** (SFC) modelling has become a very popular approach in heterodox macro modelling (Godely and Lavoie, 2012;Caverzasi and Godin, 2015; Nikiforos and Zezza, 2017).
- The SFC approach has proved successful in formulating the complex interactions between the **financial** and the **real** spheres of the economy.
- This approach has its origins to the work of the **Yale group** of James Tobin and the **Cambridge Economic Policy Group** of Wynne Godley that used SFC structures to analyse the US and the UK economy in the 1970s and the 1980s.

Introduction

- There is currently a lot of research on **theoretical SFC modelling**. This is partly explained by the fact that SFC models are characterised by a high flexibility that allows them to be deployed for the analysis of a wide range of topics.
- There is also research on **empirical SFC modelling**. However, the empirical SFC literature is much less developed than the theoretical one (see Zezza and Zezza, 2019).
- Recently, SFC models have been used for the analysis of **ecological macroeconomic** issues.
- SFC models are currently viewed as **alternative models to the DSGE models** (especially when they are combined with agent-based structures).

Introduction

The aims of this lecture are:

1. To provide an introduction to the features and the methodology of SFC models. Particular emphasis will be placed on the **steps** that need to be followed in practice in order to construct and simulate SFC models.
2. To present how **ecological aspects** can be incorporated into SFC models.

Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in calibrating and simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. E-DSGE modelling
7. Conclusion

Outline

(1) There are no black holes

'Everything comes from somewhere and goes somewhere'. This is ensured by using two matrices: (i) the balance sheet matrix and (ii) the transactions flow matrix.

(2) The financial and the real spheres are integrated

Following the post-Keynesian tradition on the non-neutrality of money and finance, the SFC models explicitly formulate the various links between financial and real variables.

(3) Behavioural equations are based on post-Keynesian assumptions

The behavioural equations (such as the consumption and investment functions) are constructed following post-Keynesian theories.

(1) There are no black holes

Balance sheet matrix

	Households	Firms	Commercial banks	Total
Deposits	$+D_t$		$-D_t$	0
Loans		$-L_t$	$+L_t$	0
Capital		$+K_t$		$+K_t$
Total (net worth)	$+D_t$	$+V_{Ft}$	0	$+K_t$

(1) There are no black holes

Transactions flow matrix

	Households	Firms		Commercial banks		Total
		Current	Capital	Current	Capital	
Consumption	$-C_t$	$+C_t$				0
Firms' investment		$+I_t$	$-I_t$			0
Wages	$+W_t$	$-W_t$				0
Firms' profits	$+DP_t$	$-TP_t$	$+RP_t$			0
Banks' profits	$+BP_t$			$-BP_t$		0
Interest on deposits	$+int_D D_{t-1}$			$-int_D D_{t-1}$		0
Interest on loans		$-int_L L_{t-1}$		$+int_L L_{t-1}$		0
Change in deposits	$-\Delta D_t$				$+\Delta D_t$	0
Change in loans			$+\Delta L_t$		$-\Delta L_t$	0
Total	0	0	0	0	0	0

(2) The financial and the real spheres are integrated

- The post-Keynesian SFC models integrate the real with the financial side of the economy.
- All SFC models have **at least one financial asset/liability**.
- Money is introduced both as a **stock** and as a **flow** variable.
- Two **examples** of the real sector-financial sector interlinkages:
  1. Financing of firms' investment.
  2. Asset price effects on consumption and investment.

(2) The financial and the real spheres are integrated

- Firms take out **loans** to finance their investment.
- In most SFC models loans are provided upon demand. However, in some SFC models banks can also play a more active role via quantity and price **credit rationing**.
- Firms' investment can also be funded via equities and bonds.

(2) The financial and the real spheres are integrated

- The **portfolio choice** (i.e. the allocation of wealth of households among financial assets) is determined by the (expected) relative rates of return and liquidity preference.
- The portfolio choice can affect the **price of financial assets** (e.g. government bonds or equities) having feedback effects on consumption (since wealth is incorporated in the consumption function) and investment (if, for example, Tobin's q is included in the investment function).

(3) Behavioural equations are based on post-Keynesian assumptions

- Labour and product markets do not clear through changes in wages and prices (as in neoclassical models). On the contrary, they clear via the **adjustment of supply to demand**.
- The **pricing mechanism** only plays a clearing role in the **financial markets**.
- Although the post-Keynesian SFC models are primarily demand-led, it is possibly to introduce **supply-side** effects (by including inflation, debt defaults etc.).

(3) Behavioural equations are based on post-Keynesian assumptions

- The **decisions of households** are formulated using **Davidson's** two-step decision process: The **1st step** refers to the decision about the proportion of income that will be saved. The **2nd step** refers to the way that savings will be allocated between the various assets (portfolio choice).
- In many behavioural equations economic agents have **stock-flow targets** (e.g. wealth-to-income ratios, debt-to-income ratios, inventories-to-sales ratios) and **react to disequilibria** in order to achieve these targets.
- Behaviour can be different between **classes**.
- There is no intertemporal **utility maximisation**.

Mainstream vs SFC models

Mainstream models	**SFC (and other post-Keynesian) models**
Supply-determined output (demand might matter only in the short run)	Demand-determined output (with supply-side constraints)
Banks are financial intermediaries (when they exist)	Money is endogenous
Utility and profit maximisation	Fundamental uncertainty/bounded rationality
Income distribution does not typically matter	Income distribution interacts with economic activity

Outline

Steps in developing an SFC model

- **Step 1**: Identify the accounting structure of the model.
- **Step 2**: Specify the identities that stem from the accounting structure of the model.
- **Step 3**: Identify equations for the variables that are not defined through the accounting identities.
- **Step 4**: Put together all the equations of the model.

Step 1: Identify the accounting structure of the model

Suppose that we have an economy with the following features:

- There are three sectors: firms, households and commercial banks.
- **Firms** make investment by using retained profits and loans. A part of firms' profits is distributed to households.
- **Households** accumulate savings in the form of deposits.
- **Banks** provide firm loans by creating deposits. Banks distribute all their profits to households.

This is a model with private bank money.

Step 1: Identify the accounting structure of the model

Balance sheet matrix

	Households	**Firms**	**Banks**	**Total**
Deposits	$+D_t$		$-D_t$	0
Loans		$-L_t$	$+L_t$	0
Capital		$+K_t$		$+K_t$
Total (net worth)	$+D_t$	$+V_{Ft}$	0	$+K_t$

Step 1: Identify the accounting structure of the model

Transactions flow matrix

	Households	Firms		Commercial banks		Total
		Current	Capital	Current	Capital	
Consumption	$-C_t$	$+C_t$				0
Firms' investment		$+I_t$	$-I_t$			0
Wages	$+W_t$	$-W_t$				0
Firms' profits	$+DP_t$	$-TP_t$	$+RP_t$			0
Banks' profits	$+BP_t$			$-BP_t$		0
Interest on deposits	$+int_D D_{t-1}$			$-int_D D_{t-1}$		0
Interest on loans		$-int_L L_{t-1}$		$+int_L L_{t-1}$		0
Change in deposits	$-\Delta D_t$				$+\Delta D_t$	0
Change in loans			$+\Delta L_t$		$-\Delta L_t$	0
Total	0	0	0	0	0	0

Step 2: Specify the identities that stem from the accounting structure of the model

	Households	Firms		Commercial banks		Total
		Current	Capital	Current	Capital	
Consumption	$-C_t$	$+C_t$				0
Firms' investment		$+I_t$	$-I_t$			0
Wages	$+W_t$	$-W_t$				0
Firms' profits	$+DP_t$	$-TP_t$	$+RP_t$			0
Banks' profits	$+BP_t$			$-BP_t$		0
Interest on deposits	$+int_D D_{t-1}$			$-int_D D_{t-1}$		0
Interest on loans		$-int_L L_{t-1}$		$+int_L L_{t-1}$		0
Change in deposits	$-\Delta D_t$				$+\Delta D_t$	0
Change in loans			$+\Delta L_t$		$-\Delta L_t$	0
Total	0	0	0	0	0	0

- Deposits: $D_t = D_{t-1} + Y_{Ht} - C_t$
- Total profits of firms: $TP_t = Y_t - W_t - int_L L_{t-1}$
- Loans: $L_t = L_{t-1} + I_t - RP_t$
- Profits of banks: $BP_t = int_L L_{t-1} - int_D D_{t-1}$
- Deposits: $D_{redt} = L_t$
- Distributed profits: $DP_t = TP_t - RP_t$
- Output: $Y_t = C_t + I_t$
- Disposable income of households: $Y_{Ht} = W_t + DP_t + BP_t + int_D D_{t-1}$

Step 3: Identify equations for the variables that are not defined through the accounting identities

- Consumption expenditures: C_t
- Wage income: W_t
- Deposits (identity): D_t
- Total profits of firms (identity): TP_t
- Retained profits: RP_t
- Distributed profits (identity): DP_t
- Investment: I_t
- Capital stock: K_t
- Loans (identity): L_t
- Profits of banks (identity): BP_t

Step 3: Identify equations for the variables that are not defined through the accounting identities

- Consumption expenditures: $C_t = c_1 Y_{Ht-1} + c_2 D_{t-1}$
- Wage income: $W_t = s_W Y_t$
- Retained profits: $RP_t = s_F TP_t$
- Investment: $I_t = \left(\alpha_0 + \alpha_1 r_{t-1}\right) K_{t-1}$
- Rate of profit: $r_t = TP_t / K_t$
- Capital stock: $K_t = K_{t-1} + I_t$

Auxiliary equations:

- Potential output: $Y_t^* = vK_t$
- Capacity utilisation: $u_t = Y_t / Y_t^*$
- Growth rate of output: $g_{Yt} = \left(Y_t - Y_{t-1}\right) / Y_{t-1}$
- Leverage ratio: $lev_t = L_t / K_t$

Step 4: Put together all the equations of the model

Households

- Disposable income of households (additional identity): $Y_{Ht} = W_t + DP_t + BP_t + int_D D_{t-1}$ (1)
- Wage income: $W_t = s_W Y_t$ (2)
- Consumption expenditures: $C_t = c_1 Y_{Ht-1} + c_2 D_{t-1}$ (3)
- Deposits (identity): $D_t = D_{t-1} + Y_{Ht} - C_t$ (4)

Step 4: Put together all the equations of the model

Firms

- Output (additional identity): $Y_t = C_t + I_t$ (5)
- Total profits of firms (identity): $TP_t = Y_t - W_t - int_L L_{t-1}$ (6)
- Retained profits: $RP_t = s_F TP_t$ (7)
- Distributed profits (identity): $DP_t = TP_t - RP_t$ (8)
- Investment: $I_t = (\alpha_0 + \alpha_1 r_{t-1}) K_{t-1}$ (9)
- Rate of profit: $r_t = TP_t / K_t$ (10)
- Capital stock: $K_t = K_{t-1} + I_t$ (11)
- Loans (identity): $L_t = L_{t-1} + I_t - RP_t$ (12)

Step 4: Put together all the equations of the model

Commercial banks

- Profits of banks (identity): $BP_t = int_L L_{t-1} - int_D D_{t-1}$ (13)
- Deposits (identity): $D_{redt} = L_t$ (14)

Auxiliary equations:

- Potential output: $Y_t^* = vK_t$ (15)
- Capacity utilisation: $u_t = Y_t / Y_t^*$ (16)
- Growth rate of output: $g_{Yt} = (Y_t - Y_{t-1}) / Y_{t-1}$ (17)
- Leverage ratio: $lev_t = L_t / K_t$ (18)

Outline

- SFC models can be simulated using various **software programmes** (e.g. EViews, R, Python, Excel or MATLAB).
- SFC models can be either **discrete-time** or **continuous-time** models.
- When SFC models are **small** we can solve them analytically and conduct stability analysis.
- When SFC models are **large** we typically use numerical simulations.

Steps in calibrating and simulating an SFC model:

- **Step 1**: Specify the steady-state equations.
- **Step 2**: Identify parameter values and initial values for the endogenous variables.
- **Step 3**: Check stock-flow consistency.
- **Step 4**: Design the simulation exercises.

Step 1: Specify the steady-state equations

- When the model is at a steady state, all variables grow at the same rate.
- Formally, for each variable x we have $x_t = x_{t-1}(1+g_K)$ where g_K is the growth rate.
- To get the steady-state equations for period 1 we replace all variables x_t with $x_{t=1}$ and all variables x_{t-1} with $x_{t=1}/(1+g_K)$.

Step 1: Specify the steady-state equations

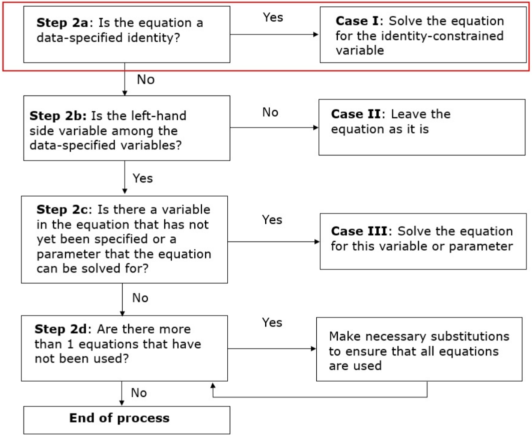
Steady-state equation	Case	Equation in the code
$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$ (1')	II	$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$
$W_{t=1} = s_W Y_{t=1}$ (2')	II	$W_{t=1} = s_W Y_{t=1}$
$C_{t=1} = c_1 \frac{Y_{Ht=1}}{1+g_K} + c_2 \frac{D_{t=1}}{1+g_K}$ (3')	III	$c_1 = \frac{C_{t=1}(1+g_K) - c_2 D_{t=1}}{Y_{Ht=1}}$
$D_t = D_{t-1} + Y_{Ht} - C_t$ (4')	-	-
$Y_{t=1} = C_{t=1} + I_{t=1}$ (5')	I	$C_{t=1} = Y_{t=1} - I_{t=1}$
$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$ (6')	II	$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$
$RP_{t=1} = s_F TP_{t=1}$ (7')	II	$RP_{t=1} = s_F TP_{t=1}$
$DP_{t=1} = TP_{t=1} - RP_{t=1}$ (8')	II	$DP_{t=1} = TP_{t=1} - RP_{t=1}$
$I_{t=1} = (\alpha_0 + \alpha_1 r_{t=1}) \frac{K_{t=1}}{1+g_K}$ (9')	III	$\alpha_0 = \frac{I_t}{K_{t=1}/(1+g_K)} - \alpha_1 r_{t=1}$
$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$ (10')	II	$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$
$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$* (11')	II	$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$
$L_t = \frac{L_{t=1}}{1+g_K} + I_{t=1} - RP_{t=1}$ (12')	III	$s_F = \frac{I_{t=1} - g_K L_{t=1}/(1+g_K)}{TP_{t=1}}$
$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$ (13')	II	$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$
$D_{redt=1} = L_{t=1}$ (14')	I	$D_{redt=1} = L_{t=1}$
$Y^*_{t=1} = vK_{t=1}$ (15')	II	$Y^*_{t=1} = vK_{t=1}$
$u_{t=1} = Y_{t=1}/Y^*_{t=1}$ (16')	III	$Y^*_{t=1} = Y_{t=1}/u_{t=1}$
$g_{Yt=1} = g_K$ (17')	II	$g_{Yt=1} = g_K$
$lev_{t=1} = L_{t=1}/K_{t=1}$ (18')	II	$lev_{t=1} = L_{t=1}/K_{t=1}$

* From $K_{t=1} = \frac{K_{t=1}}{1+g_K} + I_{t=1}$ we get $K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$

Step 2: Identify parameter values and initial values for the endogenous variables

- It is necessary to use a specific country as a reference.
- Based on the **GDP identity**, specify which variables of this identity will be calibrated using data and which variable will be used as a residual in the GDP identity.
- Identify all the **financial assets/liabilities** of the model and use real-world data for all of them, apart from one that should be specified via an accounting identity.
- Suppose that our **data-specified variables** are output, investment, loans and the rate of capacity utilisation.

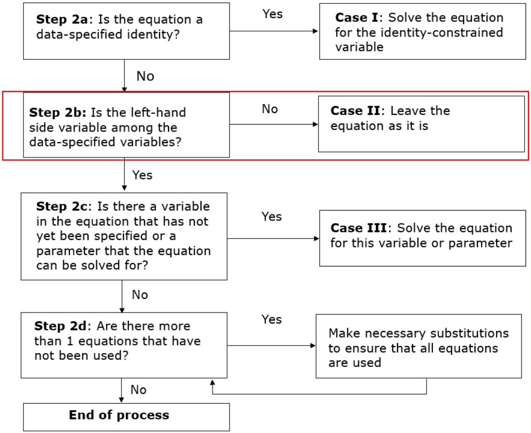
Step 2a: Identify parameter values and initial values for the endogenous variables



Step 2a: Identify parameter values and initial values for the endogenous variables

Steady-state equation	Case	Equation in the code
$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$ (1')	II	$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$
$W_{t=1} = s_W Y_{t=1}$ (2')	II	$W_{t=1} = s_W Y_{t=1}$
$C_{t=1} = c_1 \frac{Y_{Ht=1}}{1+g_K} + c_2 \frac{D_{t=1}}{1+g_K}$ (3')	III	$c_1 = \frac{C_{t=1}(1+g_K) - c_2 D_{t=1}}{Y_{Ht=1}}$
$D_t = D_{t-1} + Y_{Ht} - C_t$ (4')	-	-
$Y_{t=1} = C_{t=1} + I_{t=1}$ **(5')**	**I**	$C_{t=1} = Y_{t=1} - I_{t=1}$
$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$ (6')	II	$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$
$RP_{t=1} = s_F TP_{t=1}$ (7')	II	$RP_{t=1} = s_F TP_{t=1}$
$DP_{t=1} = TP_{t=1} - RP_{t=1}$ (8')	II	$DP_{t=1} = TP_{t=1} - RP_{t=1}$
$I_{t=1} = (\alpha_0 + \alpha_1 r_{t=1}) \frac{K_{t=1}}{1+g_K}$ (9')	III	$\alpha_0 = \frac{I_t}{K_{t=1}/(1+g_K)} - \alpha_1 r_{t=1}$
$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$ (10')	II	$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$
$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$ (11')	II	$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$
$L_t = \frac{L_{t=1}}{1+g_K} + I_{t=1} - RP_{t=1}$ (12')	III	$s_F = \frac{I_{t=1} - g_K L_{t=1}/(1+g_K)}{TP_{t=1}}$
$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$ (13')	II	$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$
$D_{redt=1} = L_{t=1}$ **(14')**	**I**	$D_{redt=1} = L_{t=1}$
$Y^*_{t=1} = vK_{t=1}$ (15')	II	$Y^*_{t=1} = vK_{t=1}$
$u_{t=1} = Y_{t=1}/Y^*_{t=1}$ (16')	III	$Y^*_{t=1} = Y_{t=1}/u_{t=1}$
$g_{Yt=1} = g_K$ (17')	II	$g_{Yt=1} = g_K$
$lev_{t=1} = L_{t=1}/K_{t=1}$ (18')	II	$lev_{t=1} = L_{t=1}/K_{t=1}$

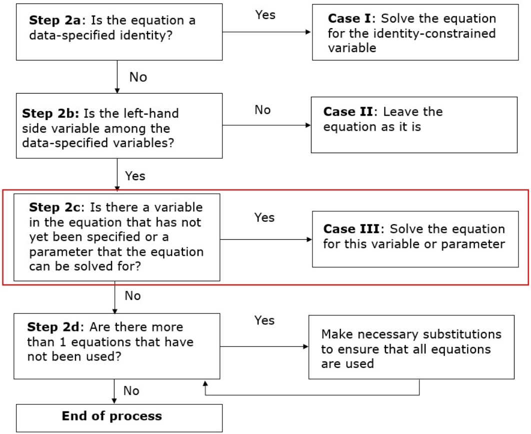
Step 2b: Identify parameter values and initial values for the endogenous variables



Step 2b: Identify parameter values and initial values for the endogenous variables

Steady-state equation	Case	Equation in the code
$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$ **(1')**	**II**	$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$
$W_{t=1} = s_W Y_{t=1}$ **(2')**	**II**	$W_{t=1} = s_W Y_{t=1}$
$C_{t=1} = c_1 \frac{Y_{Ht=1}}{1+g_K} + c_2 \frac{D_{t=1}}{1+g_K}$ (3')	III	$c_1 = \frac{C_{t=1}(1+g_K) - c_2 D_{t=1}}{Y_{Ht=1}}$
$D_t = D_{t-1} + Y_{Ht} - C_t$ (4')	-	-
$Y_{t=1} = C_{t=1} + I_{t=1}$ **(5')**	**I**	$C_{t=1} = Y_{t=1} - I_{t=1}$
$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$ **(6')**	**II**	$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$
$RP_{t=1} = s_F TP_{t=1}$ **(7')**	**II**	$RP_{t=1} = s_F TP_{t=1}$
$DP_{t=1} = TP_{t=1} - RP_{t=1}$ **(8')**	**II**	$DP_{t=1} = TP_{t=1} - RP_{t=1}$
$I_{t=1} = (\alpha_0 + \alpha_1 r_{t=1}) \frac{K_{t=1}}{1+g_K}$ (9')	III	$\alpha_0 = \frac{I_t}{K_{t=1}/(1+g_K)} - \alpha_1 r_{t=1}$
$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$ **(10')**	**II**	$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$
$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$ **(11')**	**II**	$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$
$L_t = \frac{L_{t=1}}{1+g_K} + I_{t=1} - RP_{t=1}$ (12')	III	$s_F = \frac{I_{t=1} - g_K L_{t=1}/(1+g_K)}{TP_{t=1}}$
$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$ **(13')**	**II**	$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$
$D_{redt=1} = L_{t=1}$ **(14')**	**I**	$D_{redt=1} = L_{t=1}$
$Y^*_{t=1} = vK_{t=1}$ **(15')**	**II**	$Y^*_{t=1} = vK_{t=1}$
$u_{t=1} = Y_{t=1}/Y^*_{t=1}$ (16')	III	$Y^*_{t=1} = Y_{t=1}/u_{t=1}$
$g_{Yt=1} = g_K$ **(17')**	**II**	$g_{Yt=1} = g_K$
$lev_{t=1} = L_{t=1}/K_{t=1}$ **(18')**	**II**	$lev_{t=1} = L_{t=1}/K_{t=1}$

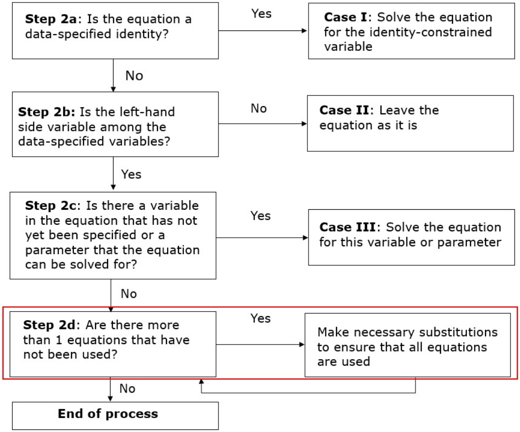
Step 2c: Identify parameter values and initial values for the endogenous variables



Step 2c: Identify parameter values and initial values for the endogenous variables

Steady-state equation	Case	Equation in the code
$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$ **(1')**	**II**	$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$
$W_{t=1} = s_W Y_{t=1}$ **(2')**	**II**	$W_{t=1} = s_W Y_{t=1}$
$C_{t=1} = c_1 \frac{Y_{Ht=1}}{1+g_K} + c_2 \frac{D_{t=1}}{1+g_K}$ **(3')**	**III**	$c_1 = \frac{C_{t=1}(1+g_K) - c_2 D_{t=1}}{Y_{Ht=1}}$
$D_t = D_{t-1} + Y_{Ht} - C_t$ (4')	-	-
$Y_{t=1} = C_{t=1} + I_{t=1}$ **(5')**	**I**	$C_{t=1} = Y_{t=1} - I_{t=1}$
$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$ **(6')**	**II**	$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$
$RP_{t=1} = s_F TP_{t=1}$ **(7')**	**II**	$RP_{t=1} = s_F TP_{t=1}$
$DP_{t=1} = TP_{t=1} - RP_{t=1}$ **(8')**	**II**	$DP_{t=1} = TP_{t=1} - RP_{t=1}$
$I_{t=1} = (\alpha_0 + \alpha_1 r_{t=1}) \frac{K_{t=1}}{1+g_K}$ **(9')**	**III**	$\alpha_0 = \frac{I_t}{K_{t=1}/(1+g_K)} - \alpha_1 r_{t=1}$
$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$ **(10')**	**II**	$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$
$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$ **(11')**	**II**	$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$
$L_t = \frac{L_{t=1}}{1+g_K} + I_{t=1} - RP_{t=1}$ (12')	III	$s_F = \frac{I_{t=1} - g_K L_{t=1}/(1+g_K)}{TP_{t=1}}$
$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$ **(13')**	**II**	$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$
$D_{redt=1} = L_{t=1}$ **(14')**	**I**	$D_{redt=1} = L_{t=1}$
$Y^*_{t=1} = vK_{t=1}$ **(15')**	**II**	$Y^*_{t=1} = vK_{t=1}$
$u_{t=1} = Y_{t=1}/Y^*_{t=1}$ **(16')**	**III**	$Y^*_{t=1} = Y_{t=1}/u_{t=1}$
$g_{Yt=1} = g_K$ **(17')**	**II**	$g_{Yt=1} = g_K$
$lev_{t=1} = L_{t=1}/K_{t=1}$ **(18')**	**II**	$lev_{t=1} = L_{t=1}/K_{t=1}$

Step 2d: Identify parameter values and initial values for the endogenous variables



Step 2d: Identify parameter values and initial values for the endogenous variables

Steady-state equation	Case	Equation in the code
$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$ **(1')**	**II**	$Y_{Ht=1} = W_{t=1} + DP_{t=1} + BP_{t=1} + int_D \frac{D_{t=1}}{1+g_K}$
$W_{t=1} = s_W Y_{t=1}$ **(2')**	**II**	$W_{t=1} = s_W Y_{t=1}$
$C_{t=1} = c_1 \frac{Y_{Ht=1}}{1+g_K} + c_2 \frac{D_{t=1}}{1+g_K}$ **(3')**	**III**	$c_1 = \frac{C_{t=1}(1+g_K) - c_2 D_{t=1}}{Y_{Ht=1}}$
$D_t = D_{t-1} + Y_{Ht} - C_t$ (4')	-	-
$Y_{t=1} = C_{t=1} + I_{t=1}$ **(5')**	**I**	$C_{t=1} = Y_{t=1} - I_{t=1}$
$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$ **(6')**	**II**	$TP_{t=1} = Y_{t=1} - W_{t=1} - int_L \frac{L_{t=1}}{1+g_K}$
$RP_{t=1} = s_F TP_{t=1}$ **(7')**	**II**	$RP_{t=1} = s_F TP_{t=1}$
$DP_{t=1} = TP_{t=1} - RP_{t=1}$ **(8')**	**II**	$DP_{t=1} = TP_{t=1} - RP_{t=1}$
$I_{t=1} = (\alpha_0 + \alpha_1 r_{t=1}) \frac{K_{t=1}}{1+g_K}$ **(9')**	**III**	$\alpha_0 = \frac{I_t}{K_{t=1}/(1+g_K)} - \alpha_1 r_{t=1}$
$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$ **(10')**	**II**	$r_{t=1} = \frac{TP_{t=1}}{K_{t=1}}$
$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$ **(11')**	**II**	$K_{t=1} = \frac{1+g_K}{g_K} I_{t=1}$
$L_t = \frac{L_{t=1}}{1+g_K} + I_{t=1} - RP_{t=1}$ **(12')**	**III**	$s_F = \frac{I_{t=1} - g_K L_{t=1}/(1+g_K)}{TP_{t=1}}$
$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$ **(13')**	**II**	$BP_{t=1} = int_L \frac{L_{t=1}}{1+g_K} - int_D \frac{D_{t=1}}{1+g_K}$
$D_{redt=1} = L_{t=1}$ **(14')**	**I**	$D_{redt=1} = L_{t=1}$
$Y^*_{t=1} = vK_{t=1}$ **(15')**	**III**	$v = Y^*_{t=1}/K_{t=1}$
$u_{t=1} = Y_{t=1}/Y^*_{t=1}$ **(16')**	**III**	$Y^*_{t=1} = Y_{t=1}/u_{t=1}$
$g_{Yt=1} = g_K$ **(17')**	**II**	$g_{Yt=1} = g_K$
$lev_{t=1} = L_{t=1}/K_{t=1}$ **(18')**	**II**	$lev_{t=1} = L_{t=1}/K_{t=1}$

Step 2e: Identify parameter values and initial values for the endogenous variables

For the parameters that have not been identified through the previous steps, options include:

- the use of reasonable values;
- the use of values from other studies;
- the use of values from real-world data;
- the econometric estimation of parameters.

Step 3: Check stock-flow consistency

- In order for your model to be consistent you need to ensure that:
    1. in the initial period all the stocks in the model satisfy the restrictions of the balance sheet matrix;
    2. the identities from the transactions flow matrix and balance sheet matrix are correctly written;
    3. the adding-up constraints are satisfied (if your model includes portfolio allocation).
- In the numerical simulations, consistency is checked by verifying that the redundant equation is satisfied.

Step 4: Design the simulation exercises

Some options:

- Start from the steady state and impose a shock (to an endogenous variable or a parameter). The **shock** can lead to a new steady state, instability or some sort of cyclical behaviour.
- Develop a **baseline scenario that does not correspond to the steady state**. This can be done for example by assuming that there is gradual decline in the investment rate or that climate damages occur.

Outline

- Traditional SFC models are inconsistent with the **biophysical limits of a finite planet**.
- They ignore the fact that production and consumption are not possible without using **energy** and **matter**.
- They do not take into account that economic activity creates various types of **waste** that can destabilise the ecosystem.
- They also neglect other types of **environmental problems**, like the loss of biodiversity, water scarcity and deforestation.

There are **two steps** for the incorporation of ecological aspects into SFC models:

1. Make a distinction between (i) carbon-intensive and green sectors, (ii) green and conventional (private and public) investment, (iii) green and conventional financial products (such as bonds and loans). This permits the analysis of transition risks and the macroeconomic implications of environmental policies.
2. Include **physical stocks and flows** (energy, matter, waste etc.) and their interactions with the economy. This permits the analysis of the harmful effects of economic activity on the environment and the implications of physical risks.

(1) Introducing green activities

How can green activities be included in an SFC model?

- By assuming that the firm sector can produce both green and conventional goods and can issue green financial instruments and take out green loans.
- By decomposing the firm sector, making a distinction between green and conventional firms.

(1) Introducing green activities

Balance sheet matrix

	Households	**Firms**	**Commercial banks**	**Total**
Deposits	$+D_t$		$-D_t$	0
Green loans		$-L_{Gt}$	$+L_{Gt}$	0
Conventional loans		$-L_{Ct}$	$+L_{Ct}$	0
Green capital		$+K_{Gt}$		$+K_{Gt}$
Conventional capital		$+K_{Ct}$		$+K_{Ct}$
Total (net worth)	$+D_t$	$+V_{Ft}$	0	$+K_t$

(1) Introducing green activities

Transactions flow matrix

	Households	Firms		Commercial banks		Total
		Current	Capital	Current	Capital	
Consumption	$-C_t$	$+C_t$				0
Green investment		$+I_{Gt}$	$-I_{Gt}$			0
Conventional investment		$+I_{Ct}$	$-I_{Ct}$			0
Wages	$+W_t$	$-W_t$				0
Firms' profits	$+DP_t$	$-TP_t$	$+RP_t$			0
Banks' profits	$+BP_t$			$-BP_t$		0
Interest on deposits	$+int_D D_{t-1}$			$-int_D D_{t-1}$		0
Interest on green loans		$-int_G L_{Gt-1}$		$+int_G L_{Gt-1}$		0
Interest on conventional loans		$-int_C L_{Ct-1}$		$+int_C L_{Ct-1}$		0
Change in deposits	$-\Delta D_t$				$+\Delta D_t$	0
Change in green loans			$+\Delta L_{Gt}$		$-\Delta L_{Gt}$	0
Change in conventional loans			$+\Delta L_{Ct}$		$-\Delta L_{Ct}$	0
Total	0	0	0	0	0	0

(1) Introducing green activities

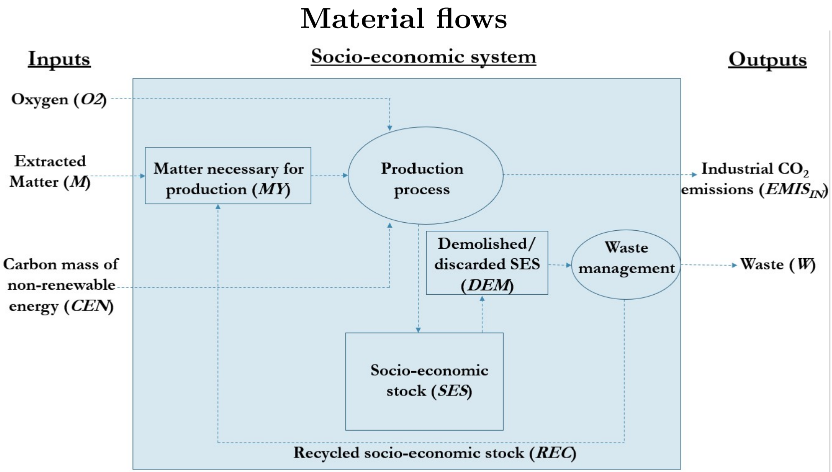
The introduction of green activities allows us to analyse **scenarios** like these ones:

- The **price of carbon** increases and, as a result, the cost for carbon-intensive activities goes up (Bovari et al., 2018; Monasterolo and Raberto, 2018; Dafermos and Nikolaidi, 2019).
- Financial investors increase the share of **green stocks** in their portfolio (Campiglio et al., 2017).
- Banks increase **credit rationing** on dirty loans or increase the availability of green credit (Dafermos and Nikolaidi, 2021; Dunz et al., 2021).

(2) Incorporating physical stocks and flows

- An integrated incorporation of environmental aspects into an SFC model requires the use of additional matrices, apart from the transactions and the balance sheet ones.
- The **physical flow matrix** captures the flows of energy and matter.
- The **physical stock-flow matrix** captures the interaction between physical stocks and flows.
- These matrices draw on the work of Georgescu-Roegen (1971) and rely on the laws of thermodynamics.

(2) Incorporating physical stocks and flows



(2) Incorporating physical stocks and flows

Physical flow matrix

	Material balance	Energy balance
Inputs		
Extracted matter	$+M_t$	
Non-fossil energy		$+E_{NFt}$
Fossil energy	$+CEN_t$	$+E_{Ft}$
Oxygen used for fossil fuel combustion	$+O2_t$	
Outputs		
Industrial CO_2 emissions	$-EMIS_{INt}$	
Waste	$-W_t$	
Dissipated energy		$-ED_t$
Change in socio-economic stock	$-\Delta SES_t$	
Total	0	0

- Material balance: $M_t + CEN_t + O2_t = EMIS_{INt} + W_t + \Delta SES_t$
- Energy balance: $E_{NFt} + E_{Ft} = ED_t$

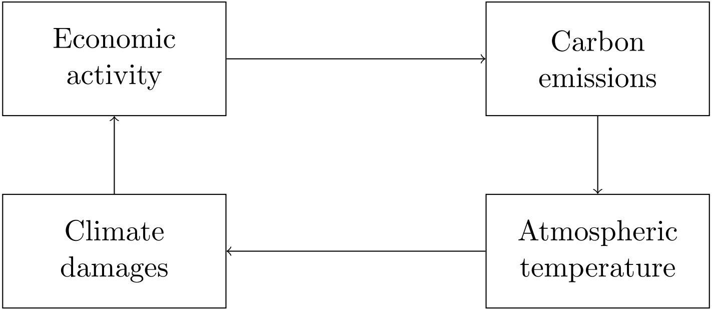
(2) Incorporating physical stocks and flows

Physical stock-flow matrix

	Material reserves	Fossil energy reserves	Cumulative CO_2 emissions	Socio-economic stock	Cumulative hazardous waste
Opening stock	REV_{Mt-1}	REV_{Et-1}	$CO2_{CUMt-1}$	SES_{t-1}	HW_{CUMt-1}
Additions to stock					
Resources converted into reserves	$+CON_{Mt}$	$+CON_{Et}$			
CO_2 emissions			$+EMIS_t$		
Production of material goods				$+MY_t$	
Non-recycled hazardous waste					$+hazW_t$
Reductions of stock					
Extraction/use of matter or energy	$-M_t$	$-E_{Ft}$			
Demolished/disposed socio-economic stock				$-DEM_t$	
Closing stock	REV_{Mt}	REV_{Et}	$CO2_{CUMt}$	SES_t	HW_{CUMt}

- Material reserves: $REV_{Mt-1}+CON_{Mt}-M_t=REV_{Mt}$
- Fossil energy reserves: $REV_{Et-1}+CON_{Et}-E_{Ft}=REV_{Et}$
- Cumulative CO_2 emissions: $CO2_{CUMtt-1}+EMIS_t=CO2_{CUMt}$
- Socio-economic stock: $SES_{t-1}+MY_t-DEM_t=SES_t$
- Cumualative hazardous waste: $HW_{CUMt-1}+\text{haz}W_t=HW_{CUMt}$

(2) Incorporating physical stocks and flows



(2) Incorporating physical stocks and flows

- **Industrial CO_2 emissions** ($EMIS_{INt}$) are generated when fossil fuels (E_{Ft}) are utilised to produce energy: $EMIS_{INt}=\omega_t(1\text{-}seq_t)E_{Ft}$
- **Atmospheric temperature** (T_{ATt}) is a positive function of cumulative carbon emissions ($CO2_{CUMt}$): $T_{ATt}=T_{ATt-1}+t_1(t_2\varphi CO2_{CUMt-1}\text{-}T_{ATt-1})$

where ω_t: CO_2 intensity; seq_t: proportion of sequestrated emissions; t_1: captures the timescale of the initial adjustment of the climate system to an increase in cumulative emissions; t_2: captures the global warming that stems from non-CO_2 greenhouse gas emissions; φ: Transient Climate Response to cumulative carbon Emissions (TCRE) ($^oC/GtCO_2$)

(2) Incorporating physical stocks and flows

Feedback effects of climate change on the economy

Type of shock		From gradual global warming	From extreme weather events
Demand	Investment	Uncertainty about future demand and climate risks	Uncertainty about climate risks
	Consumption	Changes in consumption patterns, e.g. more savings for hard times	Increased risk of flooding to residential property
	Trade	Changes in trade patterns due to changes in transport systems and economic activity	Disruption to import/export flows due to extreme weather events
Supply	Labour supply	Loss of hours worked due to extreme heat. Labour supply shock from migration	Loss of hours worked due to natural disasters, or mortality in an extreme case. Labour supply shock from migration
	Energy, food and other inputs	Decrease in agricultural productivity	Food and other input shortages
	Capital stock	Diversion of resources from productive investment to adaptation capital	Damage due to extreme weather
	Technology	Diversion of resources from innovation to adaptation capital	Diversion of resources from innovation to reconstruction and replacement

Source: NGFS (2019)

(2) Incorporating physical stocks and flows

- The feedback effects of the environment on the economy can be incorporated through **damage functions**.
- In **mainstream environmental models** the damages are confined to the supply side and tend to be optimistic.
- In **SFC models** damages refer both to the demand and the supply side and tend to be more pessimistic.
- The incorporation of damages remains a very challenging task and we are still far from formulating them properly.

Mainstream vs SFC models

Mainstream models	**SFC (and other post-Keynesian) models**
Supply-determined output (demand might matter only in the short run)	Demand-determined output (with supply-side constraints)
Banks are financial intermediaries (when they exist)	Money is endogenous
Utility and profit maximisation	Fundamental uncertainty/bounded rationality
Income distribution does not typically matter	Income distribution interacts with economic activity
Mitigation represents only a cost	Mitigation is both a cost and a source of income
Environmental problems as an externality/cost-benefit analysis	Economy as a subsystem of the ecosystem/Systems-based analysis

Outline

- The **DEFINE** (Dynamic Ecosystem-FINance-Economy) model is an **ecological SFC model** that analyses the complex interactions between the macroeconomy, the financial system and the ecosystem (Dafermos, Nikolaidi and Galanis, 2017, 2018; Dafermos and Nikolaidi, 2019, 2021).
- The model can be used for analysing the effects of a wide range of environmental policies.
- For more information, see: www.define-model.org

The model consists of two big blocks and various sub-blocks.

Ecosystem

- Matter, waste and recycling
- Energy
- Emissions and climate change
- Ecological efficiency and technology

Macroeconomy and financial system

- Output determination
- Firms
- Households
- Banks
- Government sector
- Central banks

DEFINE-SIMPLE

- DEFINE-SIMPLE is a simplified module of DEFINE that is used to illustrate how **green investment** can be incorporated in a simple way in an SFC model.
- The model assumes that a proportion of total private investment is green and that a part of bank loans is used to finance this type of investment.
- An increase in the proportion of green capital to total capital leads to a decline in **carbon intensity**.

DEFINE-SIMPLE

Key equations of the model:

- Green investment: $I_{Gt} = \beta_t I_t$
- Share of green investment in total investment: $\beta_t = \beta_0 - \beta_1 \left(int_G - int_C \right)$
- Industrial CO_2 emissions: $EMIS_{INt} = CI_t Y_t$
- Carbon intensity: $CI_t = CI_{\max} - \frac{CI_{\max} - CI_{\min}}{1 + ci_1 e^{-ci_2 \left(K_{Gt-1}/K_{Ct-1} \right)}}$

Policy analysis in DEFINE

Calibration of the model and econometric estimations:

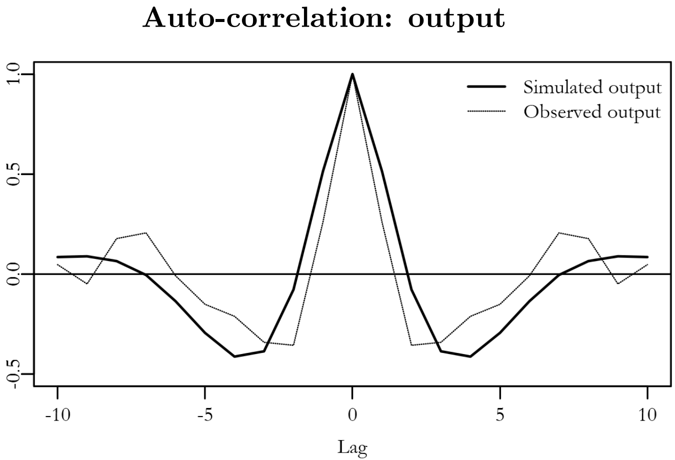
- We use a mix of calibration and estimation techniques.
- We econometrically estimate some functions (such as investment, consumption and loans) using panel data for the global economy.
- We calibrate some parameter values using data or other studies.
- We develop a baseline scenario for the period 2018-2100 and then conduct sensitivity and policy analysis.

Policy analysis in DEFINE

Baseline scenario:

- For the identification of the baseline scenario we draw on the Shared Socioeconomic Pathways (SSPs) framework (see Riahi et al., 2017).
- We use as a reference the SSP2 and SSP3 mitigation scenarios that correspond to radiative forcing levels of 6.0 W/m^2. These scenarios are close to the Hot House World scenario of NGFS.
- In both scenarios there is a transition to a low-carbon economy, but this transition is slow.

Policy analysis in DEFINE

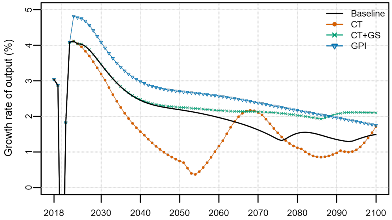


Green fiscal policies

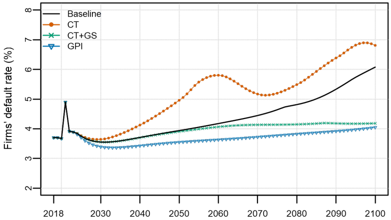
1. **Carbon Tax (CT)**: An increase in carbon taxes after 2023, without revenue recycling.
2. **Carbon Tax+Green Subsidies (CT+GS)**: Carbon taxes are recycled in the form of green subsidies that are provided to firms. The level of carbon taxes is the same as in the first scenario.
3. **Green Public Investment (GPI)**: Green public investment increases after 2023 from around 0.2% to 1% of GDP per year.

Green fiscal policies

Growth rate of output



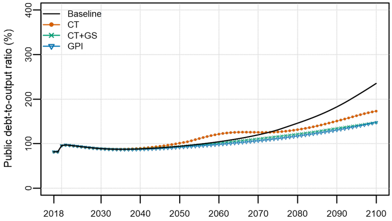
Default rate



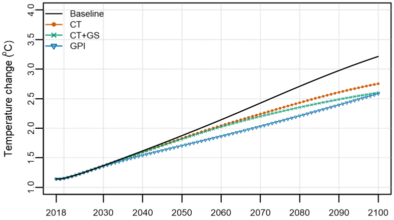
Source: Dafermos and Nikolaidi (in progress)
CT: Carbon Tax
CT+GS: Carbon Tax + Green Subsidy
GPI: Green Public Investment

Green fiscal policies

Public debt-to-GDP ratio



Atmospheric temperature



Source: Dafermos and Nikolaidi (in progress)
CT: Carbon Tax
CT+GS: Carbon Tax + Green Subsidy
GPI: Green Public Investment

Green fiscal policies

Category	Indicators	Carbon tax		Carbon tax+Green subsidy		Green public investment	
		Short run	Long run	Short run	Long run	Short run	Long run
Ecological	Atmospheric temperature	Moderately declines	Declines	Moderately declines	Declines	Moderately declines	Declines
	Material use and waste	Moderately decline	Decline	Moderately decline	Decline	Moderately decline	Increase
Macroeconomic/ social	Unemployment rate	Moderately increases	Increases	Moderately declines	Declines	Moderately declines	Declines
	Wage share	Moderately declines	Declines	Moderately increases	Increases	Moderately increases	Increases
Financial	Default rate	Moderately increases	Increases	Moderately declines	Declines	Moderately declines	Declines
	Banks' leverage ratio	Moderately increases	Increases	Moderately declines	Moderately declines	Moderately declines	Declines
	Public indebtedness	Increases	Declines	Declines	Declines	Declines	Declines

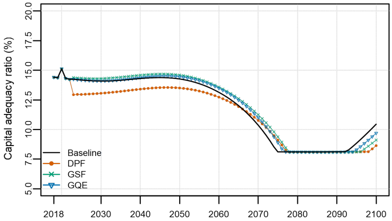
Source: Dafermos and Nikolaidi (in progress)

Green monetary/financial policies

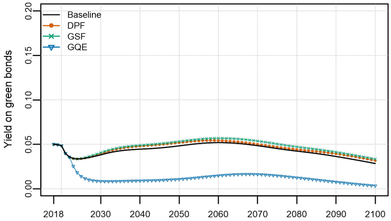
1. **Dirty Penalising Factor (DPF)**: the risk weight on dirty loans increases by 25 percentage points.
2. **Green Supporting Factor (GSF)**: the risk weight on green loans by 25 percentage points.
3. **Green QE (GQE)**: central banks increase the green corporate bonds that they hold under their QE programmes.

Green monetary/financial policies

Capital adequacy ratio



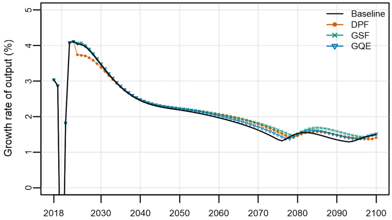
Yield on green bonds



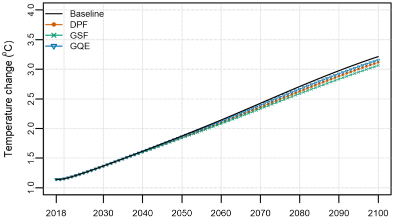
Source: Dafermos and Nikolaidi (in progress)
DPF: Dirty Penalising Factor
GSF: Green Supporting Factor
GQE: Green Quantitative Easing

Green monetary/financial policies

Growth rate of output



Atmospheric temperature



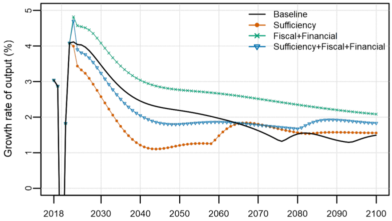
Source: Dafermos and Nikolaidi (in progress)
DPF: Dirty Penalising Factor
GSF: Green Supporting Factor
GQE: Green Quantitative Easing

Sufficiency policies and climate policy mixes

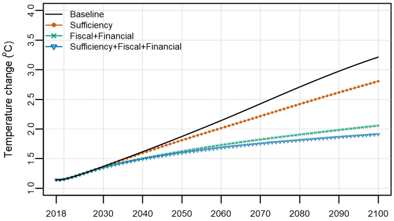
- **Sufficiency scenario**: Policies that reduce consumption are introduced gradually over the period 2023-2100 and lead to a reduction in the propensities to consume by 15% in 2100 compared to their 2023 levels (this is combined with a reduction in working hours).
- Two climate policy mixes:
  1. **Fiscal+Financial scenario**: We combine green fiscal policies and green monetary/financial policies.
  2. **Sufficiency+Fiscal+Financial scenario**: We combine the sufficiency policies with the macroeconomic and financial policies of the previous scenario.

Sufficiency policies and climate policy mixes

Growth rate of output



Atmospheric temperature



Sufficiency policies and climate policy mixes

Category	Indicators	Sufficiency policies		Fiscal+Financial policies		Sufficiency +Fiscal+Financial policies	
		Short run	Long run	Short run	Long run	Short run	Long run
Ecological	Atmospheric temperature	Moderately declines	Declines	Declines	Declines	Declines	Declines
	Material use and waste	Moderately decline	Decline	Decline	Decline	Decline	Decline
Macroeconomic/ social	Unemployment rate	Moderately increases	Declines	Moderately declines	Declines	Moderately declines	Declines
	Wage share	Moderately declines	Increases	Moderately increases	Increases	Moderately increases	Increases
Financial	Default rate	Increases	Declines	Moderately declines	Declines	Moderately increases	Declines
	Banks' leverage ratio	Moderately increases	Increases	Moderately declines	Declines	Moderately increases	Moderately increases
	Public indebtedness	Moderately increases	Increases	Moderately declines	Declines	Moderately increases	Moderately increases

Outline

- **Environmental Dynamic Stochastic General Equilibrium (E-DSGE)** models have been used to examine environmental issues in the context of business cycle analysis.
- A distinction can be made between: (i) **DSGE models without finance** and (ii) **DSGE models with finance**.
- In DSGE models without finance, a standard DSGE model is combined with a damage function and a carbon pricing framework. Main purpose: identify a carbon price that makes the business cycle smoother.
- In DSGE models with finance, environmental issues are examined in the context of a **financial accelerator framework**.

A DSGE model with fin. accelerator and carbon taxes

- Diluiso et al. (2021) have developed a model that combines the financial accelerator framework with carbon taxes and climate finance policies.
- Two types of **energy producers**: low-carbon and fossil energy producers.
- **Banks** lend funds to firms obtained from households. The model includes emissions but not environmental damages.

Journal of Environmental Economics and Management 110 (2021) 102545

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Climate actions and macro-financial stability: The role of central banks

Francesca Diluiso, Barbara Annicchiarico, Matthias Kalkuhl, Jan C. Minx

ARTICLE INFO

Keywords:
Climate policy
Green transition
Monetary policy
Capital requirements
Green quantitative easing
Euro area

ABSTRACT

Limiting global warming to well below 2 °C may pose threats to macroeconomic and financial stability. In an estimated Euro Area New Keynesian model with financial frictions and climate policy, we study the possible perils of a low-carbon transition and evaluate the role of monetary policy and financial regulation. We show that, even for very ambitious climate targets, transition costs are moderate along a timely and gradual mitigation pathway. Inflation volatility strongly increases for disorderly climate policy, demanding a strong monetary response by central banks. In reaction to an adverse financial shock originating in the fossil sector, a green quantitative easing policy can provide an effective stimulus to the economy, but its stabilising properties do not significantly differ from those of market neutral asset purchase programs. A financial regulation, encouraging the decarbonization of the banks' balance sheets via ad hoc capital requirements, can significantly reduce the severity of a financial crisis, but prolongs the recovery phase. Our results suggest that the involvement of central banks in climate actions must be carefully designed to be in compliance with their mandate and to avoid unintended trade-offs.

Through our strategy review, we will determine where and how the issue of climate change and the fight against climate change can actually have an impact on our policies.

[Christine Lagarde (2020), President of the ECB]

1. Introduction

By signing and ratifying the Paris Agreement countries agreed to limit global warming to well below 2 °C. Achieving this target requires to reach net-zero CO_2 emissions within the next 50-60 years (IPCC, 2018). According to recent estimates, this implies global emissions to decline by approximately 7% per year in a typical 1.5 °C scenario and by 3% per year in a 2 °C scenario (e.g. Höhne et al., 2020). Such strong emission reductions are historically unprecedented and partially the result of the past decade of political failure in contrasting climate change. In the absence of more stringent climate policies, global emissions are bound to keep rising (e.g. Friedlingstein et al., 2019; UNEP, 2019).[1] The current plans of expanding fossil fuel production will lead to emission levels in

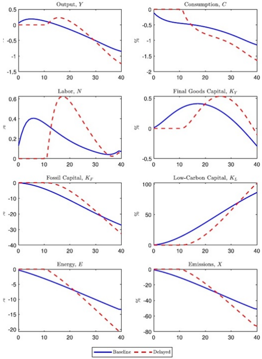
* Corresponding author.

[1] While the pandemic crisis has lead to a projected decrease of 7% in carbon emissions in 2020 (see Le Quéré et al., 2020, 2021), past recessions showed a quick rebound in emissions with even higher growth rates (e.g. Peters et al., 2020).

https://doi.org/10.1016/j.jeem.2021.102548
Received 29 July 2020
Available online 17 October 2021

A DSGE model with fin. accelerator and carbon taxes

- The figure shows the effects of an increase in carbon taxes.
- Due to rational expectations, the increase in the carbon tax leads **firms to increase production** in the first years.
- In their attempt to maximise their intertemporal utility, **workers also supply more labour and save more**.
- As a result of these developments, **inflation also declines**.



Source: Diluiso et al. (2021)
Note: Baseline is the orderly scenario and Delayed is the disorderly scenario in which the mitigation policy is implemented with a 3-year delay.

A DSGE model with green QE

- In Ferrari and Nispi Landi (2020) a distinction is made between **green** and **brown** firms both of which issue bonds bought by banks and the central bank.
- Green and brown bonds are not perfect substitutes.

Banks		Central Bank	
Assets	Liabilities	Assets	Liabilities
Green bonds b^G_{Ft}	Net worth n_t	Green bonds b^G_{Pt}	Pub. bonds d_{Pt}
Brown bonds b^B_{Ft}	Deposits d_t	Brown bonds b^B_{Pt}	


EUROPEAN CENTRAL BANK
EUROSYSTEM

Working Paper Series

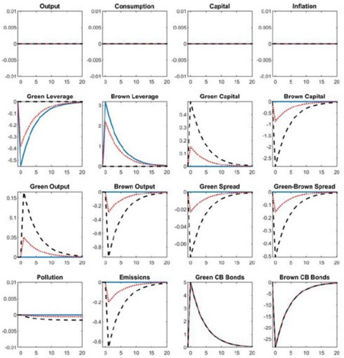
Alessandro Ferrari, Valerio Nispi Landi

Whatever it takes to save the planet? Central banks and unconventional green policy

No 2500 / December 2020

A DSGE model with green QE

- Only brown firms generate carbon emissions. The concentration of carbon affects a **damage function** which in turn affects **total factor productivity**.
- The figure shows the effects of a green QE that takes the form of an increase in green bonds bought by the central bank, accompanied by a decline in brown bonds.
- Ferrari and Nispi Landi (2022) have developed a similar model in which households face green-bond utility and brown-bond disutility.



Source: Ferrari and Nispi Landi (2020)

Outline

- SFC models constitute a flexible tool for analysing complex issues that involve an active role of **finance**.
- They have the capability of forming a solid alternative to DSGE models.
- More **progress** needs to be made in the way that these models are calibrated, validated and simulated.

Areas for future research in E-SFC modelling:

- Non-climate environmental problems, such as biodiversity and water scarcity
- Degrowth, consumption patterns and environmental regulation
- Links between environmental policies and balance of payments constraints
- Sectoral dynamics (e.g. through input-output tables) and inequality
- Country-specific E-SFC models
- Global North-Global South interactions and global climate justice