Stock-flow consistent modelling and ecological macroeconomics

Yannis Dafermos[1] Maria Nikolaidi[2]

[1]University of the West of England, [2]University of Greenwich

FMM Summer School
Berlin, 1 August 2019

- Over the last years, **stock-flow consistent** (SFC) modelling has become a very popular approach in heterodox macro modelling (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.
- 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 simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. Conclusion

Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. Conclusion

(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 (like consumption and investment function) are constructed following post-Keynesian theories.

(1) There are no black holes

Balance sheet matrix

	Households	Firms	Commercial banks	Central bank	Total
Deposits	+D		-D		0
Loans		-L	+L		0
Equities	$+p_e e$	$-p_e e$			0
Capital		+K			+K
High-powered money			+HPM	-HPM	0
Advances			-A	+A	0
Total (net worth)	$+V_H$	$+V_F$	0	$+V_{CB}$	+K

(1) There are no black holes

Transactions flow matrix

	Households	Firms		Commercial banks		Central bank		Total
		Current	Capital	Current	Capital	Current	Capital	
Consumption	-C	+C						0
Investment		+I	-I					0
Wages	+W	-W						0
Firms' profits	+DP	-TP	+RP					0
Banks' profits	+BP			-BP				0
Central bank's profits						-CBP	+CBP	0
Interest on deposits	$+int_D D_{-1}$			$-int_D D_{-1}$				0
Interest on loans		$-int_L L_{-1}$		$+int_L L_{-1}$				0
Interest on advances				$-int_A A_{-1}$		$+int_A A_{-1}$		0
Change in deposits	$-\Delta D$				$+\Delta D$			0
Change in loans			$+\Delta L$		$-\Delta L$			0
Change in equities	$-p_e \Delta e$		$+p_e \Delta e$					0
Change in high-powered money					$-\Delta HPM$		$+\Delta HPM$	0
Change in advances					$+\Delta A$		$-\Delta A$	0
Total	0	0	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 (e.g. by including a Phillips curve).

(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**.

DSGE vs SFC models: brief comparison

Key differences between SFC and DSGE models

DSGE models	Post-Keynesian SFC models
Supply-determined output	Demand-determined output (with supply-side constraints)
Banks are financial intermediaries	Money is endogenous
Utility and profit maximisation	Fundamental uncertainty/bounded rationality
Income distribution does not typically matter	Income distribution affects economic activity

Outline

1 Features of SFC models

2 Steps in developing an SFC model

3 Steps in simulating an SFC model

4 Incorporating ecological aspects into SFC models

5 The DEFINE model

6 Conclusion

Steps in developing an SFC model

- **Step 1**: Construct the balance sheet matrix.
- **Step 2**: Construct the transactions flow matrix.
- **Step 3**: Write down the identities from the transactions flow matrix. Use the columns (which reflect the budget constraints) and the rows with more than two entries. Identify the buffer variables in the identities.
- **Step 4**: Identify the variables that need to be determined based on behavioural equations. Select your behavioural equations.
- **Step 5**: Put together the identities and the behavioural equations.

Suppose that we have an economy with the following features:

- There are four sectors: firms, households, banks and a central bank.
- **Firms** make investment by using retained profits, loans and equity. A part of firms' profits is distributed to households.
- **Households** accumulate savings in the form of deposits and equity.
- **Banks** provide firm loans by creating deposits. Banks' profits are distributed to households.
- **Central bank** holds advances on the asset side of its balance sheet and high-powered money on the liability side.

This is a model with both private bank money and central bank money.

Step 1: Construct the balance sheet matrix.

	Households	Firms	Commercial banks	Central bank	Total
Deposits	+D		-D		0
Loans		-L	+L		0
Equities	$+p_e e$	$-p_e e$			0
Capital		+K			+K
High-powered money			+HPM	-HPM	0
Advances			-A	+A	0
Total (net worth)	$+V_H$	$+V_F$	0	$+V_{CB}$	+K

Step 1: Construct the balance sheet matrix.

	Households	Firms	Commercial banks	Central bank	Total
Deposits	+D		-D		0
Loans		-L	+L		0
Equities	$+p_e e$	$-p_e e$			0
Capital		+K			+K
High-powered money			+HPM	-HPM	0
Advances			-A	+A	0
Total (net worth)	$+V_H$	$+V_F$	0	$+V_{CB}$	+K

Question: How would you modify this balance sheet matrix in order to analyse (1) income distribution, (2) the housing market and (3) shadow banking?

- **Income distribution:** Zezza (2008), van Treeck (2009), Dafermos and Papatheodorou (2015), Kapeller et al. (2017)
- **Housing market:** Zezza (2008), Nikolaidi (2015), Ryoo (2016)
- **Shadow banking:** Eatwell et al. (2008), Lavoie (2014), Nikolaidi (2015), Botta et al. (2018, 2019)

Step 2: Construct the transactions flow matrix.

	Households	Firms		Commercial banks		Central bank		Total
		Current	Capital	Current	Capital	Current	Capital	
Consumption	-C	+C						0
Investment		+I	-I					0
Wages	+W	-W						0
Firms' profits	+DP	-TP	+RP					0
Banks' profits	+BP			-BP				0
Central bank's profits						-CBP	+CBP	0
Interest on deposits	$+int_D D_{-1}$			$-int_D D_{-1}$				0
Interest on loans		$-int_L L_{-1}$		$+int_L L_{-1}$				0
Interest on advances				$-int_A A_{-1}$		$+int_A A_{-1}$		0
Change in deposits	$-\Delta D$				$+\Delta D$			0
Change in loans			$+\Delta L$		$-\Delta L$			0
Change in equities	$-p_e \Delta e$		$+p_e \Delta e$					0
Change in high-powered money					$-\Delta HPM$		$+\Delta HPM$	0
Change in advances					$+\Delta A$		$-\Delta A$	0
Total	0	0	0	0	0	0	0	0

Step 3: Write down the identities from the transactions flow matrix. Use the columns (which reflect the budget constraints) and the rows with more than two entries. Identify the buffer variables in the identities.

	Households	Firms		Commercial banks		Central bank		Total
		Current	Capital	Current	Capital	Current	Capital	
Consumption	-C	+C						0
Investment		+I	-I					0
Wages	+W	-W						0
Firms' profits	+DP	-TP	+RP					0
Banks' profits	+BP			-BP				0
Central bank's profits						-CBP	+CBP	0
Interest on deposits	$+int_D D_{-1}$			$-int_D D_{-1}$				0
Interest on loans		$-int_L L_{-1}$		$+int_L L_{-1}$				0
Interest on advances				$-int_A A_{-1}$		$+int_A A_{-1}$		0
Change in deposits	-ΔD				+ΔD			0
Change in loans			+ΔL		-ΔL			0
Change in equities	$-p_e\Delta e$		$+p_e\Delta e$					0
Change in high-powered money					-ΔHPM		+ΔHPM	0
Change in advances					+ΔA		-ΔA	0
Total	0	0	0	0	0	0	0	0

- $\Delta D = Y_D - C - p_e \Delta e$
- $TP = Y - W - int_L L_{-1}$
- $\Delta L = I - RP - p_e \Delta e$
- $BP = int_L L_{-1} - int_D D_{-1} - int_A A_{-1}$
- $\Delta A = \Delta HPM + \Delta L - \Delta D$
- $CBP = int_A A_{-1}$
- $\Delta A = \Delta HPM + CBP$
- $DP = TP - RP$

Step 4: Identify the variables that need to be determined based on behavioural equations. Select your behavioural equations.

- Wage income of households: **W**
- Disposable income of households: Y_D
- Consumption expenditures: **C**
- Wealth (identity): V_H
- Deposits (identity): D
- Income: Y
- Total profits of firms (identity): TP
- Retained profits: **RP**
- Distributed profits (identity): DP
- Investment: **I**
- Capital stock: **K**
- Loans (identity): L
- Number of equities: **e**
- Price of equities: $\mathbf{p}_e$
- Profits of banks (identity): BP
- High-powered money: **HPM**
- Advances (identity): A
- Profits of central bank (identity): CBP

- Wage income of households: W=s_WY
- Consumption expenditures: C=$c_1 Y_{D-1} + c_2 V_{H-1}$
- Retained profits: RP=$s_F TP_{-1}$
- Investment: I=$g_K K_{-1}$
- Capital stock: K=K_{-1}+I
- Value of equity held by households: E=$(\lambda_0 + \lambda_1 r_{e-1} + \lambda_2 int_D + \lambda_3 (Y_{D-1}/V_{H-1}))V_{H-1}$
- Number of equities: e=$e_{-1} + \frac{xI_{-1}}{p_e}$
- Price of equities: $p_e = \frac{E}{e}$
- High-powered money: HPM=hD

Step 5: Put together the identities and the behavioural equations. **Households**

- Wage income of households: $W = s_W Y$
- Disposable income of households: $Y_D = W + DP + BP + int_D D_{-1}$
- Consumption expenditures: $C = c_1 Y_{D-1} + c_2 V_{H-1}$
- Wealth (identity): $V_H = D + p_e e$
- Value of equity held by households: $E = (\lambda_0 + \lambda_1 r_{e-1} + \lambda_2 int_D + \lambda_3 (Y_{D-1}/V_{H-1}))V_{H-1}$
- Deposits (identity): $D = D_{-1} + Y_D - C - p_e \Delta e$

Firms

- Income: Y=C+I
- Total profits of firms (identity): $\mathrm{TP=Y\text{-}W\text{-}int}_L \mathrm{L}_{-1}$
- Retained profits: $\mathrm{RP=s}_F\mathrm{TP}_{-1}$
- Distributed profits (identity): DP=TP-RP
- Investment: $\mathrm{I=g}_K\mathrm{K}_{-1}$
- Capital stock: $\mathrm{K=K}_{-1}\mathrm{+I}$
- Loans (identity): $\mathrm{L=L}_{-1}\mathrm{+I\text{-}RP\text{-}p}_e\Delta \mathrm{e}$
- Number of equities: $\mathrm{e=e}_{-1}+\frac{xI_{-1}}{p_e}$
- Price of equities: $\mathrm{p}_e=\frac{E}{e}$
- Rate of return of firms: $\mathrm{r}_e=\frac{DP}{p_{e-1}e_{-1}}+\frac{\Delta p_e}{p_{e-1}}$

Commercial banks

- Profits of banks (identity): $BP=int_L L_{-1}-int_D D_{-1}-int_A A_{-1}$
- High-powered money: $HPM=hD$
- Advances (identity): $A=HPM+L-D$

Central bank

- Profits of central bank (identity): $CBP=int_A A_{-1}$
- Advances (identity): $A_{red}=A_{-1}+\Delta HPM+CBP$

Useful tips - 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).

- If the model is consistent, the redundant equation is satisfied.

Useful tips - Wealth and capital gains

- **Deposits** are determined by the following identity:
  $D=D_{-1}+Y_D-C-p_e\Delta e$ (1)
- Equation (1) can be rewritten as follows:
  $\Delta D+p_e\Delta e=Y_D-C$ (2)
- We know from the balance sheet matrix that the **wealth of households** is:
  $V_H=D+p_e e$ (3)
- Therefore, the change in the wealth of households is:
  $\Delta V_H=\Delta D+p_e\Delta e+e_{-1}\Delta p_e$ (4)
- By combining equations (2) and (4) we get:
  $V_H=V_{H-1}+Y_D-C+e_{-1}\Delta p_e$ **(identity)**

Useful tips - Equity market

Equations of the **portfolio choice**:

$$E=(\lambda_{10}+\lambda_{11}r_{e-1}+\lambda_{12}r_b+\lambda_{13}int_D+\lambda_{14}(Y_{D-1}/V_{H-1}))V_{H-1}$$

$$B=(\lambda_{20}+\lambda_{21}r_{e-1}+\lambda_{22}r_b+\lambda_{23}int_D+\lambda_{24}(Y_{D-1}/V_{H-1}))V_{H-1}$$

$$D=(\lambda_{30}+\lambda_{31}r_{e-1}+\lambda_{32}r_b+\lambda_{33}int_D+\lambda_{34}(Y_{D-1}/V_{H-1}))V_{H-1}$$

where E is the value of equity, B are Treasury bills, D are deposits, V_H is wealth, Y_D is disposable income, r_e is the rate of return on equities, int_D is the interest rate on deposits and r_b is the interest on Treasury bills.

Useful tips - Equity market

- In the equity market we assume equilibrium:

$$e = \frac{E}{p_e}$$

- By using the equation for the number of equities in the previous equation we get:

$$e_{-1} + \frac{xI_{-1}}{p_e} = \frac{E}{p_e}$$

- By rearranging we have the following equation for the price of equities:

$$p_e = \frac{E - xI_{-1}}{e_{-1}}$$

Useful tips - Steady state of the model

At the steady state all flow-stock, stock-flow, flow-flow and stock-stock ratios (e.g. Y/K, L/K, M/Y) are constant.
For example:

$$\Delta(\frac{Y}{K})=\frac{Y}{K}-\frac{Y_{-1}}{K_{-1}}=\frac{Y}{K}-\frac{Y_{-1}(1+g_K)}{K}=\frac{\Delta Y-g_K Y_{-1}}{K}=\frac{\Delta Y}{K}-\frac{Y}{K}\frac{g_K}{(1+g_K)}$$

Since Y/K should be constant at the steady state, we need $\Delta(\frac{Y}{K})=0$.

Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. Conclusion

- SFC models can be simulated using various **software programmes** (e.g. EViews, R, Excel or MATLAB).
- SFC models can be either **discrete-time** or **continuous-time** models.
- When SFC models are **small** we can solve them analytically (e.g. by finding the steady-states and conducting stability analysis).
- When SFC models are **large** in most cases we use numerical simulations.

Steps in simulating an SFC model

- **Step 1**: Identify the endogenous variables of the model (as well as some auxiliary variables).
- **Step 2**: Identify the baseline scenario and select the parameter values (see the table below).

Category	Description
(A)	**Econometrically estimated parameters**
(B)	**Directly calibrated parameters**
(Bi)	Based on data
(Bii)	Based on previous studies
(Biii)	Selected from a reasonable range of values
(C)	**Indirectly calibrated parameters**
(Ci)	Calibrated such that the model matches the data
(Cii)	Calibrated such that the model generates the baseline scenario

Steps in simulating an SFC model

- **Step 3**: Select the initial values using the data for your economy or the equations of the model.
- **Step 4**: Write down the equations and run the model.
- **Step 5**: Report your results by using tables and graphs.
- **Step 6**: Validate the model by using your baseline scenario. Validation can be conducted, for example, by estimating the volatility, the auto-correlation and the cross-correlation for some key variables.
- **Step 7**: Re-run the simulations by changing key parameters (sensitivity analysis).
- **Step 8**: Re-run the simulations by changing parameters that correspond to policies/institutional structures.

Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. Conclusion

- Traditional SFC models are not in line with **ecological macroeconomics**.
- They ignore the fact that production and consumtpion 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 ways/steps** to incoporate ecological aspects in SFC models:

1. To make a distinction between 'green' and 'conventional' investment, products and financial instruments (e.g. loans, bonds).
2. To incroporate physical stocks and flows (energy, matter, waste etc.) and their interactions with the economy.

(1) Introducing green activities

How can green activities be included in an SFC model?

- **Way 1**: By assuming that the firm sector can produce both green and conventional goods and can issue green financial instruments and take out green loans.
- **Way 2**: 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		-D	0
Green loans		$-L_G$	$+L_G$	0
Conventional loans		$-L_C$	$+L_C$	0
Green capital		$+K_G$		$+K_G$
Conventional capital		$+K_C$		$+K_C$
Total (net worth)	+D	$+V_F$	0	+K

(1) Introducing green activities

Transactions flow matrix

	Households	Firms		Commercial banks		Total
		Current	Capital	Current	Capital	
Consumption	$-C$	$+C$				0
Green investment		$+I_G$	$-I_G$			0
Conventional investment		$+I_C$	$-I_C$			0
Wages	$+W$	$-W$				0
Firms' profits	$+DP$	$-TP$	$+RP$			0
Banks' profits	$+BP$			$-BP$		0
Interest on deposits	$+int_D D_{-1}$			$-int_D D_{-1}$		0
Interest on green loans		$-int_G L_{G-1}$		$+int_G L_{G-1}$		0
Interest on conventional loans		$-int_C L_{C-1}$		$+int_C L_{C-1}$		0
Change in deposits	$-\Delta D$				$+\Delta D$	0
Change in green loans			$+\Delta L_G$		$-\Delta L_G$	0
Change in conventional loans			$+\Delta L_C$		$-\Delta L_C$	0
Total	0	0	0	0	0	0

(1) Introducing green activities

- Green investment can be modelled as a proportion (β) of total investment: $\mathrm{I}_G=\beta\mathrm{I}$
- β can depend on a number of factors, like carbon prices, interest rates and regulation.
- **Credit conditions** for green and brown loans can be different.
- The accumulation of green capital compared to conventional capital can affect environmental variables, like **carbon emissions**.

(1) Introducing green activities

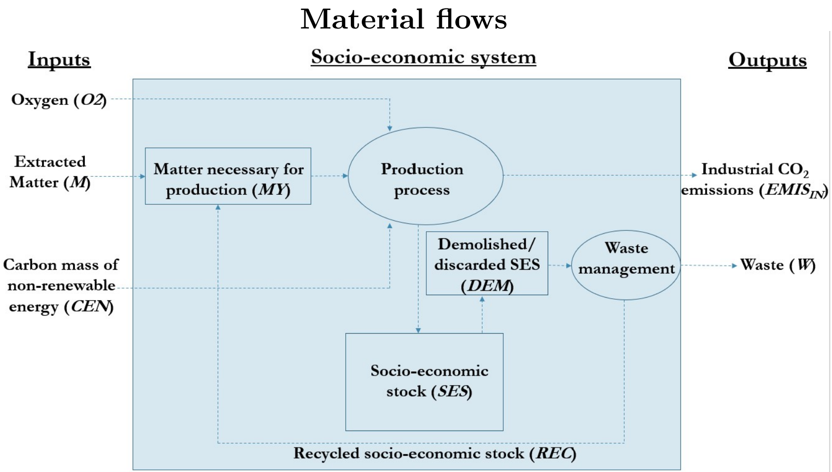
The introduction of green activities allows us to analyse **scenarios** like these ones:

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

(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	$+M$	
Renewable energy		$+ER$
Non-renewable energy	$+CEN$	$+EN$
Oxygen used for fossil fuel combustion	$+O2$	
Outputs		
Industrial CO_2 emissions	$-EMIS_{IN}$	
Waste	$-W$	
Dissipated energy		$-ED$
Change in socio-economic stock	$-\Delta SES$	
Total	0	0

- Material balance: $M+CEN+O2=EMIS_{IN}+W+\Delta SES$
- Energy balance: $ER+EN=ED$

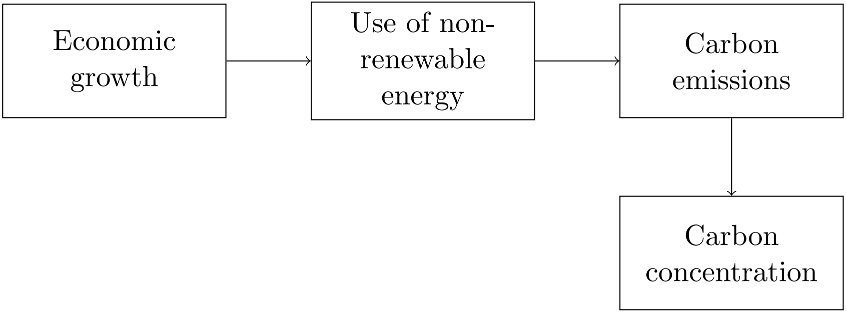
(2) Incorporating physical stocks and flows

Physical stock-flow matrix

	Material reserves	Non-renewable energy reserves	Atmospheric CO_2 concentration	Socio-economic stock	Hazardous waste
Opening stock	REV_{M-1}	REV_{E-1}	$CO2_{AT-1}$	SES_{-1}	HWS_{-1}
Additions to stock					
Resources converted into reserves	$+CON_M$	$+CON_E$			
CO_2 emissions			$+EMIS$		
Production of material goods				$+MY$	
Non-recycled hazardous waste					$+hazW$
Reductions of stock					
Extraction/use of matter or energy	$-M$	$-EN$			
Net transfer of CO_2 to oceans/biosphere			$+(\phi_{11}-1)CO2_{AT-1}+\phi_{21}CO2_{UP-1}$		
Demolished/disposed socio-economic stock				$-DEM$	
Closing stock	REV_M	REV_E	$CO2_{AT}$	SES	HWS

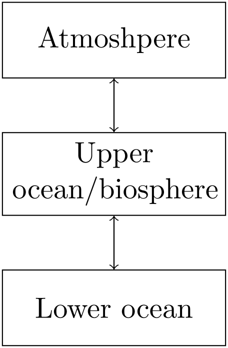
- Material reserves: $REV_{M-1}+CON_M-M=REV_M$
- Non-renewable energy reserves: $REV_{E-1}+CON_E-EN=REV_E$
- Atmospheric CO_2 concentration: $EMIS+\phi_{11}CO2_{AT-1}+\phi_{21}CO2_{UP-1}=CO2_{AT}$
- Socio-economic stock: $SES_{-1}+MY-DEM=SES$
- Hazardous waste: $HWS_{-1}+hazW=HWS$

(2) Incorporating physical stocks and flows



(2) Incorporating physical stocks and flows

The carbon cycle



(2) Incorporating physical stocks and flows

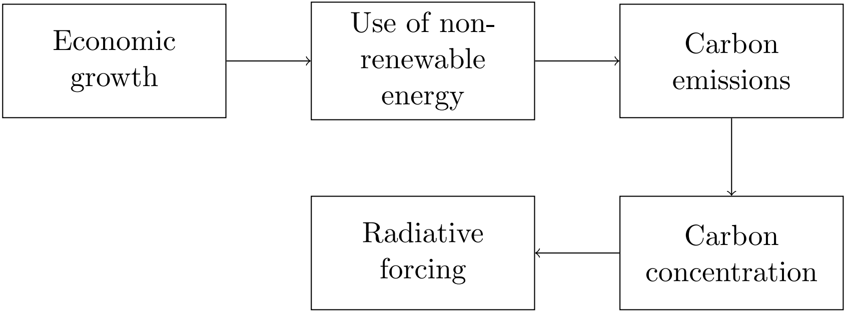
- Industrial CO_2 emissions ($EMIS_{IN}$) are generated when the non-renewable energy resources (EN) are used to produce energy: $EMIS_{IN}=\omega EN$
- The stock of carbon that remains in the atmosphere depends on the carbon cycle:

CO_2 concentration in the **atmosphere**:
$CO2_{AT}=EMIS+\phi_{11}CO2_{AT-1}+\phi_{21}CO2_{UP-1}$

CO_2 concentration in the **upper ocean/biosphere**:
$CO2_{UP}=\phi_{12}CO2_{AT-1}+\phi_{22}CO2_{UP-1}+\phi_{32}CO2_{LO-1}$

CO_2 concentration in the **lower ocean**:
$CO2_{LO}=\phi_{23}CO2_{UP-1}+\phi_{33}CO2_{LO-1}$

(2) Incorporating physical stocks and flows



(2) Incorporating physical stocks and flows

The atmospheric CO_2 concentration affects **radiative forcing** (F), which is the difference between the sunlight absorbed by the Earth and the energy radiated back to the space:

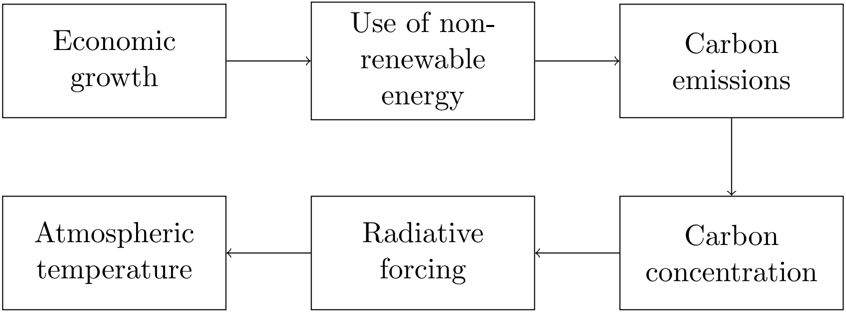
$$F = F_{2xCO2} \log_2 \frac{CO2_{AT}}{CO2_{AT-PRE}} + F_{EX}$$

F_{2xCO2}: Increase in radiative forcing (since the pre-industrial period) due to doubling of CO_2 concentration from pre-industrial levels (W/m^2)

$CO2_{AT-PRE}$: Pre-industrial atmospheric CO_2 concentration

F_{EX}: Radiative forcing, over pre-industrial levels, due to non-CO_2 greenhouse gases (W/m^2)

(2) Incorporating physical stocks and flows



(2) Incorporating physical stocks and flows

Radiative forcing affects **atmospheric temperature** (T_{AT}):

$T_{AT} = T_{AT-1} + t_1[F - \frac{F_{2CO2}}{S} T_{AT-1} - t_2(T_{AT-1} - T_{LO-1})]$

S: Equilibrium climate sensitivity, i.e. increase in equilibrium temperature due to doubling of CO_2 concentration from pre-industrial levels (^oC)

T_{LO}: Lower ocean temperature over pre-industrial levels (^oC)

(2) Incorporating physical stocks and flows

Question for discussion: What are the feedback effects of climate change on economic activity? Think about both demand-side and supply-side effects.

(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 incroporation of damages remains a very challenging task and we are still far from formulating them properly.

Mainstream vs ecol. macro SFC models

Key differences between IAMs/CGE and ecol. macro SFC models

IAMs/CGE models	SFC ecological macro models
Supply-determined output	Demand-determined output (with supply-side constraints)
Banks are financial intermediaries	Money is endogenous
Utility and profit maximisation	Fundamental uncertainty/bounded rationality
Income distribution does not typically matter	Income distribution affects economic activity
Mitigation represents only a cost	Mitigation is both a cost and a source of income
Environmental problems as externalities	Systems approach to the environmental issues

Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. Conclusion

- The **DEFINE** (Dynamic Ecosystem-FINance-Economy) model is an **SFC ecological macroeconomic model** that analyses the complex interactions between the macroeconomy, the financial system and the ecosystem (Dafermos, Nikolaidi and Galanis, 2017, 2018; Dafermos and Nikolaidi, 2019a, 2019b).
- The model can be used for analysing the effects of a wide range of envrionmental 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

Ecological macroeconomics

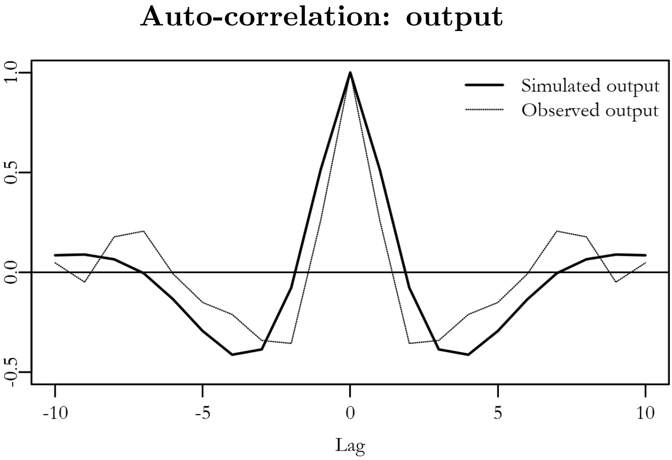
Calibration/estimation of the model:

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

Baseline scenario:

- Economic growth is, on average, slightly lower than 2.5% till 2050.
- Population becomes 9.77bn people in 2050.
- Very slow transition to a low-carbon economy.
- Share of renewable energy increases (from 14% in 2017) to 25% in 2050.
- Energy intensity improves by 30% till 2050.
- The default rate on corporate loans is around 4% till 2050.

Validation


Auto-correlation: output
Simulated output
Observed output
1.0
0.5
0.0
-0.5
-10
-5
0
5
10
Lag

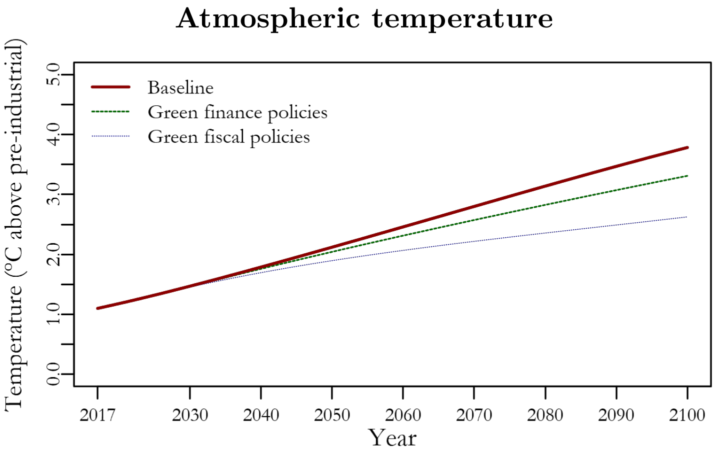
Green finance policies

- Suppose that in 2022 central banks around the globe announce that they will purchase 25% of the outstanding **green bonds** and they commit themselves that they will keep the same share of the green bond market over the next decades.
- Suppose also that in 2022 **green differentiated capital requirements** are introduced in two alternative forms:
    1. 'Green supporting factor': the risk weight on green loans declines by 25 percentage points
    2. 'Brown penalising factor': the risk weight on brown loans increases by 25 percentage points

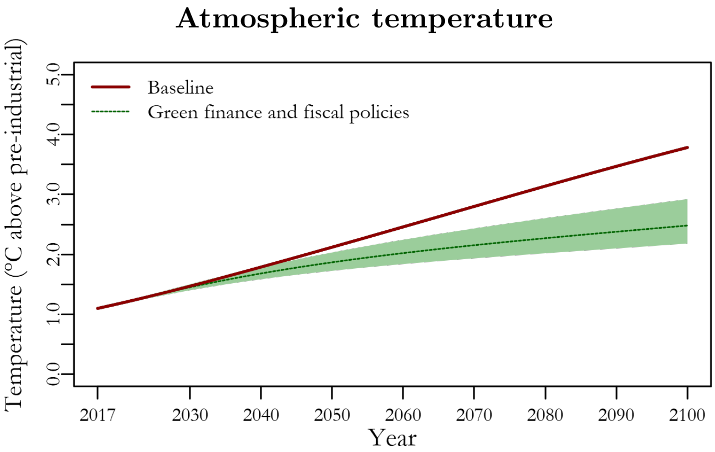
Green fiscal policies

- Suppose that in 2022 green fiscal policies are introduced in the following ways:
  1. **Carbon tax**: The carbon tax increases to 16 US dollars per tonne of CO_2 (this corresponds to 80 US dollars for the emissions currently covered by a carbon pricing scheme).
  2. **Green public subsidies**: The green public subsidies provided by the government increases from 28% to 60% (as a proportion of green investment)
  3. **Green public investment**: The green investment of the government increases from 0.25% to 1% (as a proportion of GDP)

Green finance and fiscal policies (isolated)



Green finance and fiscal policies (combined)



Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. Conclusion

- 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 the DSGE models.
- More **progress** needs to be made in the way that these models are calibrated, validated and simulated.

- Many important **ecological aspects** have not yet been incorporated into SFC models (e.g. biodiversity, water scarcity).
- The **distributional aspects** of environmental policies have only partially been investigated.
- The implications of the **circular economy** and **degrowth** are still under-researched.
- The role of **power** is basically taken into account only as an exogenous factor.