FARAWAY, SO CLOSE: AN AGENT-BASED MODEL FOR CLIMATE, ENERGY AND MACROECONOMIC POLICY ANALYSIS

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Outline

1. Complex Systems and Agent Based Modelling
2. Models of the Economy with Climate Change
3. The DSK model
    - DSK - The Model
    - Climate and Macroeconomic Dynamics
    - Transitions
    - Climate Damages
4. Conclusions and Future Developments

Complex Systems

A system is typically said to be **complex** if it exhibits the following two properties

- The system is composed of *interacting* units
- The system exhibits *emergent* properties,

that is, properties arising from the interactions of the units that are not properties of the individual units themselves.

(Flake, 1988; Tesfatsion and Judd, 2006)

Complex Systems in Economics

The economy, both in broad and strict sense, is a complex system!

Features of (Social) Complex Systems

- Many micro entities
  - relatively simple and routinised behaviour

- People decisions might be affected by
  - Inherent difficulty in dealing with uncertainty and probability (risk)
  - Framing and Context matters
  - Adaptive (Trial & Error) and Simple Behavioral Rules
  - Problem decomposition (Rubik's Cube)

Features of (Social) Complex Systems

- People exchange **locally** information, knowledge, goods

- Interaction Structures as **non-trivial networks**
  - Who owns who, boards of directors, …
  - Patent citations, collaboration citations, …
  - R&D joint-ventures, knowledge spillovers, …
  - Banks' liabilities

- Persistently heterogeneous economic agents

How to model complex systems

Agent Based Models

An Agent Based Model (ABM) is a computational tool used to study the behaviour of complex systems composed by multiple agents that are

- possibly heterogenous in all their characteristics
- boundedly rational (especially in economic applications)
- interacting among each other

Some technical issues

- ABMs are large computer programs (usually written in C, C++, Matlab or Java)
- ABMs usually include stochastic components
- Monte Carlo runs of size at least 50 are typically required
- Simulation time for a complete MC exercise varies from:
  - few seconds
  - more then a week

- Challenges with ABM
  - calibration
    - only small models are really calibrated/estimated (to the best of my knowledge)
    - larger models usually undergo an *indirect calibration* exercise (Windrum et al., 2007)
    - indirect calibration: search for parameter combinations replicating the largest number of stylized facts
    - as in other fields, "calibration is (still) more an art than a science"
  - validation (a lot of works in recent years)

Models of the Economy with Climate Change

- The majority of models in the literature are CGE based Integrated Assessment Models (IAMs)
    - DICE (Nordhaus, 1992, 2008; Nordhaus and Sztorc, 2013), FUND (Tol, 2002), PAGE (Hope, 2006), WiTCH (Bosetti et al., 2006; Emmerling et al., 2016)
    - Stern Review (Stern, 2007)
    - a plethora of ϵ-variations

- Issues and problems
    - **Equilibrium** models used to derive and study optimal policy schemes
    - ad hoc **welfare functions**: time preferences and risk aversion
    - ad hoc **damage functions**
    - difficulty in dealing with **catastrophes**
    - **heterogeneity** is mostly overlooked
    - **uncertainty** in the climate system: feedback loops and climate sensitivity

A Possible Gap in the Modelling Literature?

- Recent calls for the use of ABM within climate change economics
  - Farmer et al., 2015; Stern, 2016; Balint et al., 2016

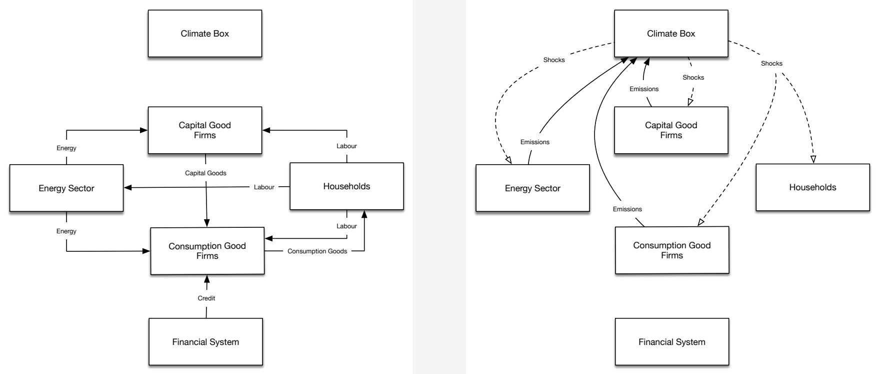
DSK - A Dystopian Schumpeter meeting Keynes model

- Fist attempt to build an integrated assessment agent based model
- A laboratory for coupled **climate/macroeconomic policy** analysis
- Macro oriented ABM with endogenous technical change
- Energy, financial, consumption good, capital good, public sectors
- Climate box with feedback loops and non-linear dynamics
- Stochastic damage generating function

What could the model be used for?

- The model can be used to
  - Study the effects of climate change on growth and volatility of the economy [**long run**]
  - Study the transition towards a *greener* economy and the policies that could favor it [**medium run**]
  - Study of ways-out from recessions through green oriented investments [**short run**]

The Basic Architecture



(a) Economic flows.

(b) Climate-related flows.

Figure: Schematic representation of the DSK model.

Capital and Consumption Good Sectors

Machines are produced in an upstream sector and sold in a downstream one.

- Machines (and production techniques) are characterized by 3 elements
    - labour productivity (L), Energy Efficiency (EE), Environmental Friendliness (EF)
    - technical change occurs along all the three dimensions

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- Unitary costs of production reflect the use of labour, energy and (eventually) carbon taxes
  - $c_i(t) = \frac{w(t)}{A^L_{i,\tau}} + \frac{c^{en}(t)}{A^{EE}_{i,\tau}} + t_{CO2}Em_i$

- Investment decisions are made on the basis of a payback rule
  - if $\frac{p^{new}}{\left[\frac{w(t)}{A^L_{i,\tau}} + \frac{c^{en}(t)}{A^{EE}_{i,\tau}}\right] - c^{new}_j} \leq b$ then machine of vintage τ is replaced

The Energy Module

- A vertically integrated monopolist employing *green* and *dirty* plants
- Plants are heterogeneous in terms of cost structures, thermal efficiencies and environmental friendliness
- Unit production cost of energy
  - *green*: $c_{ge}(t) = 0$
  - *dirty*: $c_{de}(t) = \frac{p_f(t)}{A^{TE}_{de,\tau}}$ where $p_f(t)$ is the price of fossil fuels (exogenous)

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- Total energy production cost depends on which plants are employed according to their unitary cost
- Price of energy is determined using a fixed-mark up rule
- The energy sector invest to expand production capacity
  - *green*: $IC_{ge,\tau} > 0$
  - *dirty*: $IC_{de,\tau} = 0$
- Innovations: either $\downarrow IC_{ge}$ or $\uparrow A^{TE}_{de,\tau}$ (up to the maximum of 1) and $\downarrow em_{de}$

The Climate Box

What does it do?

The Climate Box links carbon emissions to the dynamics of Earth's mean surface temperature through a core carbon cycle characterized by feedbacks loops. (Sterman et al., 2013)

Time-line in the climate box

1. Agents in the economy perform their activities, then CO_2 is expelled
2. Oceans' capacity to uptake CO_2 is modified
3. Exchanges with the atmosphere take place and a new equilibrium $C_a(t)$ is found
4. Radiative forcing is modified and temperature is affected
5. Idiosyncratic stochastic shocks hit the economy

CO2 Exchanges and Global Warming

- Emissions add to atmospheric CO_2 :
  $Em(t) = \sum_\tau \left(\sum_i Em^{cap}_{i,\tau}(t) + \sum_j Em^{con}_{i,\tau}(t) + Em^{en}_\tau(t)\right)$

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- CO_2 is exchanged with the biomass through net primary production
  - carbon concentrations reduces the (net) flux Atm → biomass
  - there is a fertilization feedback linked to warming
- CO_2 is exchanged with the oceans (simplifying Oeschger et al., 1975)
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  - oceans' marginal capacity to uptake CO_2 decreases with its atmospheric concentrations and temperature increases (climate-carbon feedback, see Sterman et al., 2013)
- The dynamics of the temperature is finally affected by CO_2 forcing
  $F_{CO_2}(t) = \gamma \log\left(\frac{C_a(t)}{C_a(0)}\right)$
- Temperature dynamics resembles those in the DICE model and are built on Schneider and Thompson (1981)

Modelling Damages and Disasters

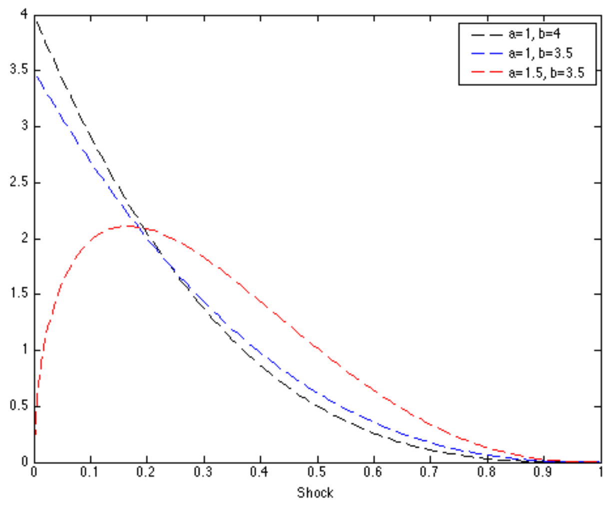
- Pindyck (2013): the choice of the **damage function** is the most speculative element of the analysis
  - Aggregating everything in a loss of final output misses the heterogeneity of possible damages and long run effects of disasters
  - Impossibility of catastrophes

Disaster Generating Function

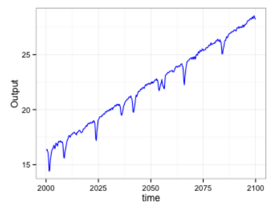
A parametric probability density function for dis-aggregated shocks that endogenously evolve according to the dynamics of the climate

- $f(s; a, b) = \frac{1}{B(a,b)} s^{a-1}(1-s)^{b-1}$
- (location) $a = a(t) = a_0[1 + \log[T_m(t)]$
- (scale) $b = b(t) = b_0 \frac{\sigma_{10y}(t-1)}{\sigma_{10y}(t)} + 1$
- (shock realization) $X_i(t) = X_i'(t)[1 - \hat{s}_i(t)]$
- where X could refer to labour productivity, capital stock, number of workers, consumption level of agent i

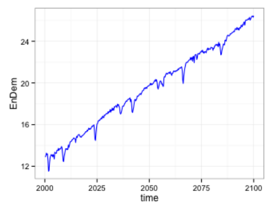
Disaster Generating Function - different parameters



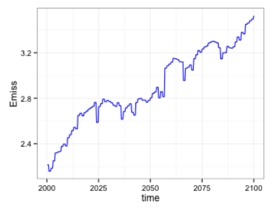
Model Dynamics



(a) Output.



(b) Energy demand.



(c) Emissions.

Model Dynamics - evidences from MC exercise

	MC average	MC median	MC st. dev.
Output growth	3.19%	3.19%	0.001
Likelihood of crises	12.1%	11.9%	0.076
Unemployment	12.0%	12.1%	0.022
Energy demand growth	2.15%	2.14%	0.002
Emissions growth	1.19%	1.17%	0.003
Volatility of output	0.268	0.270	0.022
Volatility of consumption	0.197	0.199	0.019
Volatility of investments	0.308	0.309	0.024
Volatility of total debt	0.677	0.683	0.085
Volatility of energy demand	0.215	0.215	0.034
Share of emissions from energy sector	61.4%	61.0%	0.201
Share of green energy	29.9%	24.5%	0.285
Periods green beyond 20%	33.0%	34.3%	0.103
Emissions at 2100	26.9	25.5	9.236
Temperature at 2100	4.54	4.65	0.509

Notes: All values refer to a Monte Carlo of size 50. Emissions are expressed in GtC, which can be converted in $GtCO_2$ using the following conversion factor: 1 GtC = 3.67 $GtCO_2$. Temperature is expressed in Celsius degrees above the preindustrial level, which is assumed to be 14 Celsius degrees. Volatilities are computed as square roots of longitudinal variances of Bandpass-filtered (6,32,12) series.

Business Cycle Properties

Is the model able to replicate major stylized facts at business cycle frequency?

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Should we care about business cycles frequency in a long run model of climate change?

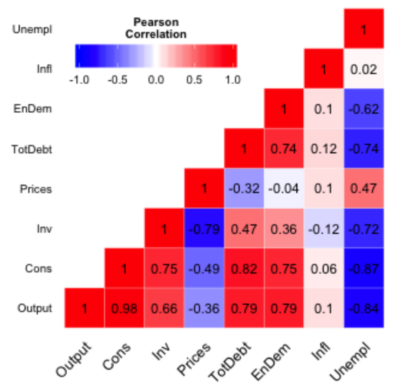
Until recently, the usual thinking among macroeconomists has been that short-term weather fluctuations don't matter much for economic activity. Construction hiring may be stronger than usual in a March when the weather is unseasonably mild, but there will be payback in April and May. If heavy rains discourage people from shopping in August, they will just spend more in September. But recent [events] prompted a rethink of this view. Extreme weather certainly throws a ringer into key short-term macroeconomic statistics. It can add or subtract 100,000 jobs to monthly US employment, the single most-watched economic statistic in the world, and generally thought to be one of the most accurate. The impact of El Niño related weather events [...] can be especially large because of their global reach. (Rogoff, 2016)

Micro and Macro Properties

Stylized facts	Empirical studies (among others)
Macroeconomic stylized facts	
SF1 Endogenous self-sustained growth with persistent fluctuations	Burns and Mitchell (1946); Stock and Watson (1999)
SF2 Fat-tailed GDP growth-rate distribution	Fagiolo et al (2008); Castaldi and Dosi (2008)
SF3 Recession duration exponentially distributed	Ausloos et al (2004); Wright (2005)
SF4 Relative volatility of GDP, consumption, investments and debt	Stock and Watson (1999); Napoletano et al (2006)
SF5 Cross-correlations of macro variables	Stock and Watson (1999); Napoletano et al (2006)
SF6 Pro-cyclical aggregate R&D investment	Walde and Woitek (2004)
SF7 Cross-correlations of credit-related variables	Lown and Morgan (2006); Leary (2009)
SF8 Cross-correlation between firm debt and loan losses	Mendoza and Terrones (2012); Foos et al (2010)
SF9 Pro-cyclical energy demand	Moosa (2000)
SF10 Syncronization of emissions dynamics and business cycles	Peters et al. (2012)
SF11 Co-integration of output, energy demand and emissions	Ozturk (2010); Triacca (2011); Attanasio et al. (2012)
Microeconomic stylized facts	
SF12 Firm (log) size distribution is right-skewed	Dosi (2007)
SF13 Fat-tailed firm growth-rate distribution	Bottazzi and Secchi (2003, 2006)
SF14 Productivity heterogeneity across firms	Bartelsman and Doms (2000); Dosi (2007)
SF15 Persistent productivity differential across firms	Bartelsman and Doms (2000); Dosi (2007)
SF16 Lumpy investment rates at firm-level	Doms and Dunne (1998)
SF17 Persistent energy and carbon efficiency heterogeneity across firms	DeCanio and Watkins (1998); Petrick (2013)

Business Cycle Properties

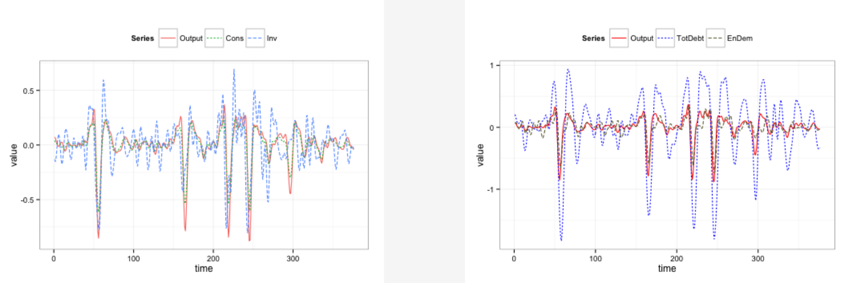
Figure: Contemporaneous cross-correlations.



	Output	Cons	Inv	Prices	TotDebt	EnDem	Infl	Unempl
Unempl								1
Infl							1	0.02
EnDem						1	0.1	-0.62
TotDebt					1	0.74	0.12	-0.74
Prices				1	-0.32	-0.04	0.1	0.47
Inv			1	-0.79	0.47	0.36	-0.12	-0.72
Cons		1	0.75	-0.49	0.82	0.75	0.06	-0.87
Output	1	0.98	0.66	-0.36	0.79	0.79	0.1	-0.84

Business Cycle Properties

Figure: Dynamics of filtered macroeconomic series

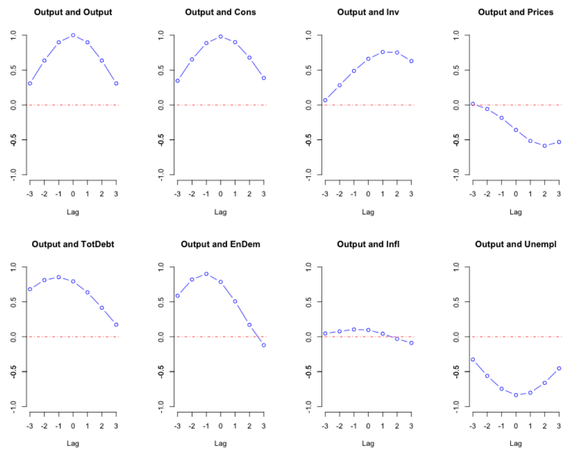


(a) Output, Consumption and Investments.

(b) Output, Total private debt, Energy demand.

Business cycle properties

Figure: Auto-cross correlations between output and main macroeconomic aggregates.



Long Run Facts

We have seen the model can reproduce a variety of stylized facts at business cycle frequency.

Can the model reproduce major facts about long run behaviour of economic and climate variables?

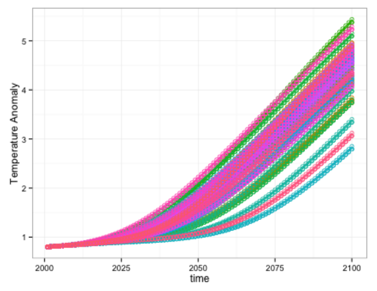
Long Run Facts

- Cointegrating relationships among output, energy demand and emissions

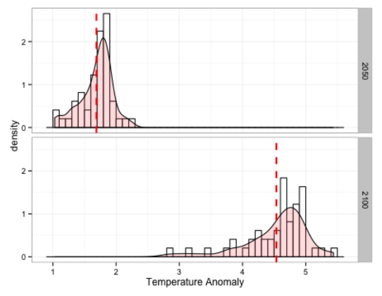
	Test statistic	5%-threshold	MC st. dev.	Runs passing test
		Engle-Granger Procedure		
Output-EnDem	-6.668	-2.58	2.557	96%
Emissions-Output	-3.877	-2.58	3.099	60%
Emissions-EnDem	-6.809	-2.58	3.410	90%
		Phillips-Ouliaris Procedure		
Output-EnDem	274.999	55.19	117.441	100%
Emissions-Output	134.381	55.19	130.312	100%
Emissions-EnDem	258.777	55.19	133.838	100%
		Johansen Procedure (three-variate VAR)		
r<=2	9.344	12.25	4.220	57% (null rejected)
r<=1	40.156	25.32	12.837	90% (null rejected)
r=0	98.003	42.44	17.962	100% (null rejected)

Long Run Facts

- Dynamics of temperature in the DSK model



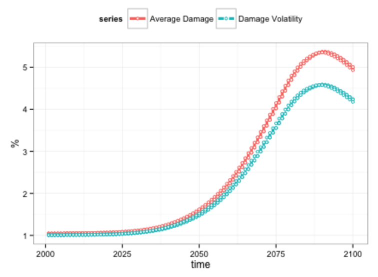
(a) Temperature projections.



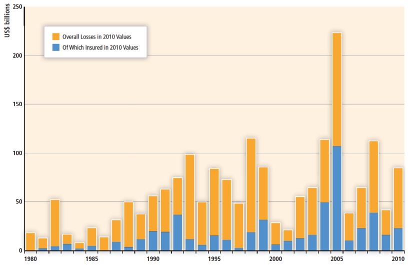
(b) Distribution of temperature.

Long Run Facts

- Climate damages in the DSK model



(a) Expected shocks according to DSK projections



(b) Estimates of actual damages. Source: IPCC (2012).

- The empirical distribution of actual damages is increasing both in mean and in variance. This feature is reproduced by the DSK model.

Transitions

If the model is good enough to guide us in the exploration of real world phenomena, we can start analyzing transitions to greener economies!

How likely is the transition towards a low carbon economy?

Additional assumptions

Let the $S_e(t)$ be the total revenues the energy monopolist gets at time t, where $S_e(t) = S_{de}(t) + S_{ge}(t)$. Assume:

$$RD_{ge}(t) = \xi S_{ge}(t-1)$$

and

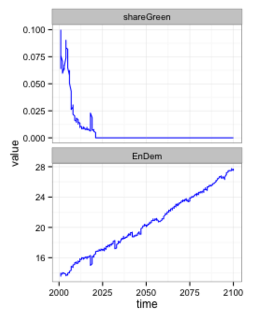
$$RD_{de}(t) = \xi S_{de}(t-1),$$

where $\xi > 0$ is the propensity to invest in R&D.

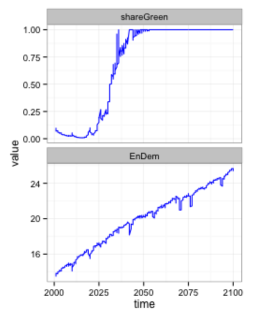
Transitions

The model endogenously generates two statistical equilibria:

- **Carbon intensive technology lock in.**



- **Transition to renewable energy technology.**



Transitions

	Carbon intensive lock in		Transition to green	
Likelihood	77%		23%	
	before 2025	after 2025	before 2075	after 2075
Likelihood	90%	10%	91%	9%
Output growth	3.16%	3.14%	3.27%	3.18%
	0.001	0.002	0.001	0.008
Unemployment	11.4%	12.1%	9.12%	10.0%
	0.016	0.020	0.019	0.012
Emission growth	1.22%	1.25%	0.77%	0.96%
	0.001	0.002	0.001	0.002
Emissions at 2100	28.64	30.12	18.22	23.13
	1.761	2.237	1.52	2.172
Temperature at 2100	4.59	4.82	1.75	2.68
	0.103	0.178	0.123	0.153

Notes: All values refer to the average computed on the sub-sample of runs from a Monte Carlo of size 100 that are classified in each scenario. Standard deviations in different sub-samples are reported below each coefficient. Given the low likelihood of some scenario, we invite the reader to be careful in the interpretation of results.

Climate Damages

What about the effects of climate change on the economy?

Climate Shocks

We consider different kinds of micro-level shocks

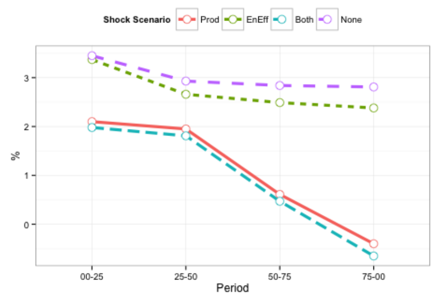
- productivity shocks
- energy efficiency shocks
- both
- inventories shocks (not reported here)
- consumption shocks (not reported here)
- labour force shocks (not reported here)
- capital stock shocks (not reported here)

Climate Damages

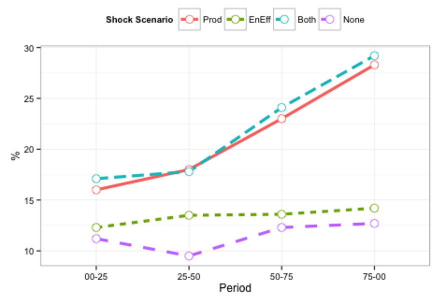
		Output growth	Likelihood of crises	Unemployment
Baseline (no Shocks)	MC average	3.19%	12.1%	12.0%
	MC median	3.19%	11.9%	12.1%
	MC st. dev.	0.001	0.076	0.022
Productivity Shocks	MC average	1.17%	25.6%	22.2%
	MC median	1.16%	27.2%	19.51%
	MC st. dev.	0.003	0.051	0.022
Energy Efficiency Shocks	MC average	3.02%	17.7%	13.8%
	MC median	3.04%	17.3%	13.7%
	MC st. dev.	0.001	0.034	0.015
Both	MC average	0.92%	26.8%	23.4%
	MC median	0.94%	29.4%	23.3%
	MC st. dev.	0.003	0.034	0.016

Notes: All values refer to a Monte Carlo of size 50. Average growth rates are obtained as longitudinal averages of period-to-period growth of the quantity of interest. Even though we are aware of the possible distortions implied by our choice we motivate it through the need of accounting for entire (non-smooth) dynamics rather than the initial and final points of the simulation, which might be affected by large drops due to shocks or endogenous crises.

Decomposition Over Time



(a) Output growth.



(b) Unemployment.

Policy

What policies can be tested?

Climate & Energy policy	**Macro policy**	**Industrial Policy**
Carbon tax	Fiscal Policy*	Standards
Command and Control	Green QE	Patent system
Fossil fuel tax	Green Bonds	
Minimum share of renewables		
Energy taxes and subsidies		

This will be another story!

Future developments

What we would like to do

- **(consumer) heterogeneity and inequality**
- **more details on energy technologies**
- **energy-finance link**
- **mission oriented “green” research**
- **introduce adaptation**
- **link to SSPs**

Many Thanks for Your Attention !!

Questions are welcomed!

Appendix

- Details on model structure (as in Dosi et al., 2010, 2013, 2015)

- **technical change**
- **firms' behaviour**
- **market structure**
- **energy sector**

Technical Change I

- **Capital-good firms search for better machines and for more efficient production techniques**
    - $A_{i,k}(t)$: feature of machine manufactured by firm i
    - $B_{i,k}(t)$: feature of production technique of firm i
    - $A_{i,k}(t)$ and $B_{i,k}(t)$ determine the technology of firm i at time t

- **R&D:**
    - R&D investment (RD) is a fraction of firm sales (S):

$$RD_i(t) = \upsilon S_i(t-1) \qquad \upsilon > 0$$

    - capital-good firms allocate R&D funds between innovation (IN) and imitation (IM):

$$IN_i(t) = \xi RD_i(t) \qquad IM_i(t) = (1-\xi)RD_i(t) \qquad \xi \epsilon [0,1]$$

Technical Change II

- **Innovation and imitation: two steps procedure**
- **Innovation:**
  1) firm successfully innovates or not through a draw from a Bernoulli($\theta_1(t)$), where $\theta_1(t)$ depends on $IN_i(t)$:

$$\theta_1(t) = 1 - e^{-o_1 IN_i(t)} \qquad o_1 > 0$$

  2) search space: the new technology is obtained multiplying the current technology by $(1 + x_i(t))$, where
     $x_i(t) \sim Beta$ over the support (x_0, x_1) with $x_0 < 0, x_1 > 0$

- **Imitation**
  1) firm successfully imitates or not through a draw from a Bernoulli($\theta_2(t)$), where $\theta_2(t)$ depends on $IM_i(t)$:

$$\theta_2(t) = 1 - e^{-o_2 IM_i(t)} \qquad o_2 > 0$$

  2) firms are more likely to imitate competitors with similar technologies (Euclidean distance)

Capital-Good Market

- **Capital-good firms:**
  - if they successfully innovate and/or imitate, they choose to manufacture the machine with the lowest $p_i + c_i^1 b$
    - p_i: machine price;
    - c_i^1: unit labor cost of production entailed by machine in consumption-good sector;
    - b: payback period parameter
  - fix prices applying a mark-up on unit cost of production
  - send a “brochure” with the price and the productivity of their machines to both their historical and some potential new customers
- **Consumption-good firms:**
  - choose as supplier the capital-good firm producing the machine with the lowest $p_i + c_i^1 b$ according to the information contained in the “brochures”
  - send their orders to their supplier according to their investment decisions

Investment

- **Expansion investment**
  - demand expectations (D^e) determine the desired level of production (Q^d) and the desired capital stock (K^d)
  - firm invests (EI) if the desired capital stock is higher than the current capital stock (K):

$$EI = K^d - K$$

- **Replacement investment**
  - payback period routine:
    - an incumbent machine is scrapped if

$$\frac{p^*}{c(\tau)-c^*} \leqslant b, \qquad b > 0$$

    - $c(\tau)$ unit labor cost of an incumbent machine;
    - p^*, c^* price and unit labor cost of new machines
  - also machine older than Λ periods are replaced

Financial Structure

- **Production and investment decisions of consumption-good firms may be constrained by their financial balances**
  - consumption-good firms first rely on their stock of liquid assets and then on more expensive external funds provided by the banking sector
  - credit ceiling: the stock of debt (*Deb*) of consumption-good firms is limited by their gross cash flows (= sales *S*):

$$Deb_j(t) \leqslant \kappa S_j(t-1), \quad \kappa \geqslant 1$$

Consumption-Good Markets

- **Supply:**
  - imperfect competition: prices (p_j) $\Rightarrow$ variable mark-up (mi_j) on unit cost of production (c_j)

$$p_j(t) = (1 + mi_j(t))c_j(t);$$

$$mi_j(t) = mi_j(t-1)\left(1 + \alpha \frac{f_j(t-1) - f_j(t-2)}{f_j(t-2)}\right);$$

    $\alpha > 0$; f_j: market share of firm j
  - firms first produce and then try to sell their production (inventories)

Consumption-Good Markets

- **Market dynamics:**
  - market shares evolve according to a “quasi” replicator dynamics:

$$f_j(t) = f_j(t-1)\left(1 + \chi \frac{E_j(t) - \overline{E}(t)}{\overline{E}(t)}\right); \quad \chi \geqslant 0$$

  E_j: competitiveness of firm j; $\overline{E}$: avg. competitiveness of consumption-good industry;

  - firm competitiveness depends on price and unfilled demand (l_j):

$$E_j(t) = -\omega_1 p_j(t) - \omega_2 l_j(t), \quad \omega_{1,2} > 0$$

Firm Bankruptcies and Banking Crisis

- **Firm failure:**
  - zero market share or negative stock of liquid assets
  - in that case, firm exits and defaults on its loans

- **Bank failure:**
  - firm's default (BD) has a negative effect on banks' profits:

$$\Pi^b_{k,t} = \sum_{cl=1}^{Cl_k} r_{deb,cl,t} L_{cl,t} + r_{res,t} Cash_{k,t} + r_{B,t} Bonds_{k,t} - r_D Dep_{k,t} - BD_{k,t}$$

  - banks fail whenever their net worth becomes negative

- **Full bail-out rule**
  - the Government always steps in and save the failing bank
  - bank bail-out has a negative impact on public budget

Energy Sector

Profits of the energy monopolist at the end of period t are equal to

$$\Pi_e(t) = S_e(t) - PC_e(t) - EI_e(t) - RD_e(t)$$

where

- $S_e(t)$ are revenues
- $PC_e(t) = \sum_{\tau \in IM} g_{de}(\tau, t) c_{de}(\tau, t) A_{de}^{\tau}$ are production costs
- $EI_e(t) = K_e^d(t) - K_e(t)$ are expansion investments
- $RD_e(t)$ are R&D expenditures

To obtain **revenues**, the energy producer adds a fixed mark-up $\mu_e \geq 0$ on the average cost of the more expensive infra-marginal plant. Hence the selling price reads

$$p_e(t) = \mu_e$$

if $D_e(t) \leq K_{ge}(t)$, and

$$p_e(t) = \overline{c}_{de}(\tau, t) + \mu_e$$

if $D_e(t) > K_{ge}(t)$, where $\overline{c}_{de}(\tau, t) = \max_{\tau \in IM} c_{de}(\tau, t)$.

The **expansion investment** is made up of new green capacity is added whenever the cheapest vintage of green plants must be below the discounted production cost of the cheapest dirty plant:

$$\underline{IC}_{ge} \leq b\underline{c}_{de}$$

where b is a discount factor, $\underline{IC}_{ge} = \min_\tau IC^\tau_{ge}$, and $\underline{c}_{de} = \min_\tau c^\tau_{de}$.

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