Financing the energy transition: a biophysical, stock-flow consistent approach at a global scale - WORKING PAPER

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Abstract

The abundance of cheap energy, in the form of fossil fuels, has been a key driver of the economic development of modern societies. Hence, the transition towards renewable energies at a global scale – mainly solar and wind – will be one of the most powerful forces that will shape the globalized economy of the 21st century. In order to understand the dynamics at hand, we construct a Stock-Flow Consistent model combining the insights from (i) EROI curves for global wind and solar potential [1][2], (ii) a simple energy-economy model assessing the feasibility and implications of the energy transition [3] and (iii) a global model incorporating the interactions between the economy, finance and climate dynamics [4]. The model is a system dynamics model of the global economy treating explicitly the interactions between sectors (energy, banking, households, public and rest of the economy) and the feedback loops between flow dynamics and accumulation or depletion of stocks. Our simulation results underline the challenge related to the high capital intensity of renewable energies: the investments required to transition to a 100% renewable energy system necessitate a temporary stagnation or degrowth of consumption, depending on the speed of the transition.

1 Introduction

[TO DO]

2 State of the art

[TO DO]

3 The model

Our model represents a closed, world economy. It combines the general structure from Dupont *et al.* [5] with dynamical equations similar to the ones of Bovary *et al.* [4]. Figure 1 gives a general overview of the model. The different sectors are presented as well as the flows of matter, energy and workers. On the other hand, Figure 2 depicts the economic and financial flows between the different sectors, which mirror the physical flows of Figure 1. As illustrated, the private sector is divided into energy firms and "other firms". The former produce energy for the entire economy while the latter produce a homogeneous general-purpose good, named final good, for consumption and investment. Furthermore, a distinction is made between the households (who receive their earning from their work) and capitalists (whose revenues depend on their capital investments). This distinction is of course a purely logical one, since a person can perceive both a salary and earnings from financial investments. The banking sector, which grants loans and receives deposits, is also presented in Figure 2, as well as the state. The state is modeled through its intervention (taxes, subsidies and regulations) on the different sectors of the economy.

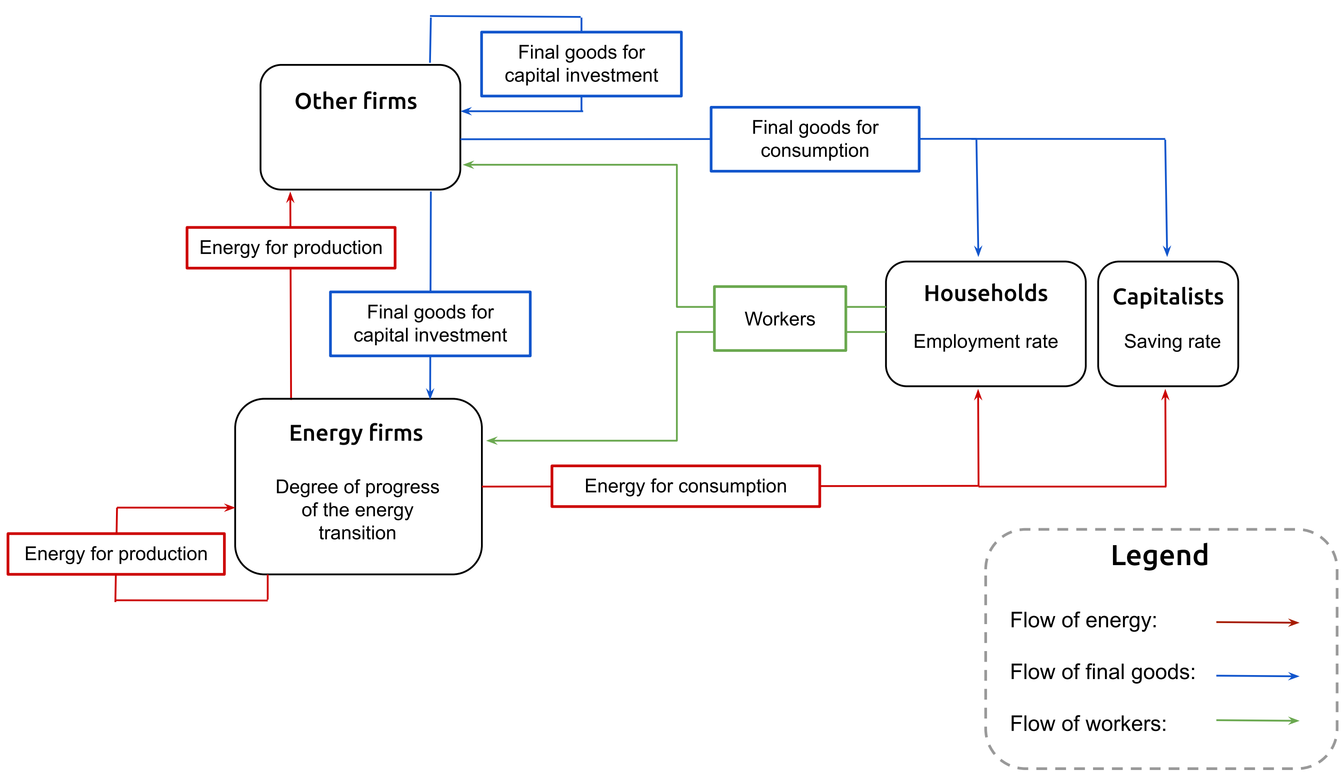

Figure 1: Overall structure of our model - physical flows

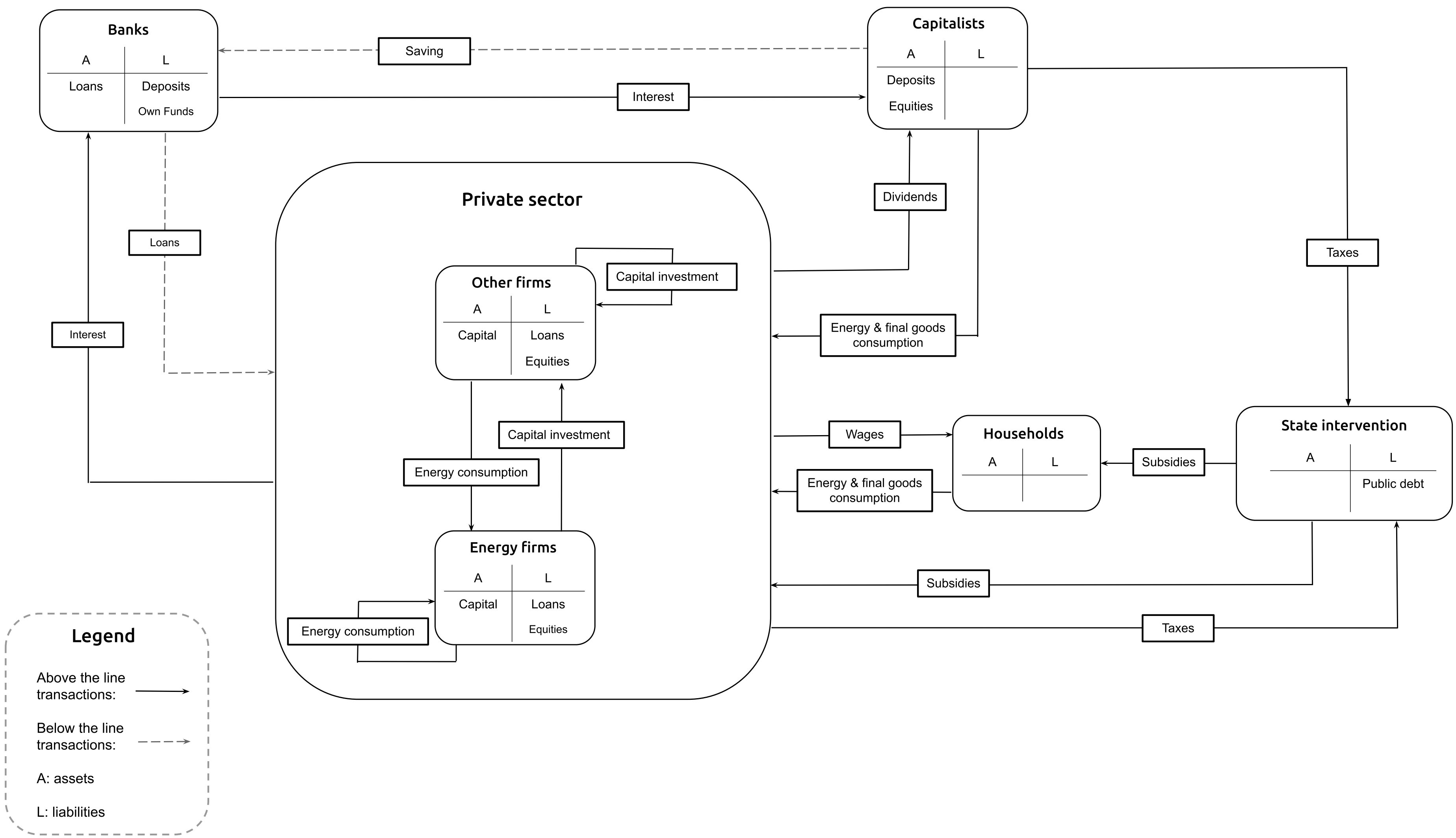

Figure 2: Overall structure of our model - economic and financial flows

For the sake of clarity, we will be using the conventions that follow throughout the paper:

- The two productive subsectors are referred to by the subscripts "e" (energy sector) and "f" (final goods sector).
- Households, capitalists and banks are respectively referred to by the subscripts "h", "c" and "b".
- Energy quantities are expressed in SI units and final goods quantities are expressed in monetary units. All quantities are denoted by uppercase letters when they are in nominal monetary terms and by lowercase letters when they are in real terms (i.e. either in energy units or in monetary units corrected for inflation).
- For a given variable α, we define $\hat{\alpha} := \frac{\frac{d\alpha}{dt}}{\alpha}$

3.1 Balance sheet and Transaction Flow Matrix

Figure 2 can be expressed more formally in the form of a Transaction Flow Matrix (TFM, Table 1) and a balance sheet (Table 2). A TFM shows the various flows taking place in an economy. Following a strict accounting framework, each flow has an origin - and is thus expressed as an outflow for that sector, showed with a minus sign '-' in the table hereunder - and a destination - an inflow for that sector, showed with a plus sign '+'. This is why the sum of all items in a row have to be equal to 0, as highlighted in the 'Total' column. The first part of the TFM concerns all non-financial transactions, i.e. all transactions regarding the real economy as well as the redistribution of income through wages or dividends. The lower part of the TFM is the Flow-of-Funds (FOF) table which shows how savings are allocated across the different financial assets of the economy. The corresponding balance sheet (i.e. how all stocks are allocated across sectors) is shown in Table 2.

	Households	Capitalists	Energy firms		Final goods firms		Banks	Σ
			Current	Capital	Current	Capital		
Consumption	$-C_{h,e} - C_{h,f}$	$-C_{c,e} - C_{c,f}$	$+C_{h,e} + C_{c,e}$		$+C_{h,f} + C_{c,f}$			0
Investment				$-I_e$	$+I_e + I_f$	$-I_f$		0
Intermediary consumption			$+E_f$		$-E_f$			0
Wages	$+W\,(L_e + L_f)$		$-W\,L_e$		$-W\,L_f$			0
Government intervention			$-T_e\,y_e$					$-T_e\,y_e$
Interests on loans			$-r\,D_e$		$-r\,D_f$		$+r\,(D_e + D_f)$	0
Interests on deposits		$+\iota_c$					$-\iota_c$	0
Firms dividends		$+\Pi_{e,d} + \Pi_{f,d}$	$-\Pi_{e,d}$		$-\Pi_{f,d}$			0
Retained earnings			$-\Pi_{e,u}$	$+\Pi_{e,u}$	$-\Pi_{f,u}$	$+\Pi_{f,u}$		0
Σ (=Financial balance)	0	$\dot{M}$	0	$-\dot{D}_e$	0	$-\dot{D}_f$	$\dot{OF}_b$	0
Change in capital stock				$\dot{K}_e$		$\dot{K}_f$		$\dot{K}_e + \dot{K}_f$
Change in deposits		$\dot{M}$					$-\dot{M}$	0
Change in loans				$-\dot{D}_e$		$-\dot{D}_f$	$+\dot{D}_e + \dot{D}_f$	0
Change in own funds							$-\dot{OF}_b$	$-\dot{OF}_b$
Change in equities		$+\dot{\mathcal{E}}_e + \dot{\mathcal{E}}_e$		$-\dot{\mathcal{E}}_e$		$-\dot{\mathcal{E}}_f$		0
Σ (=Change in net worth)		$\dot{M} + \dot{\mathcal{E}}_e + \dot{\mathcal{E}}_e$		0		0	0	$\dot{X}$

Table 1: Transaction Flow Matrix

	Households	Capitalists	Energy firms	Final goods firms	Banks	Σ
Capital stock			K_e	K_f		$K_e + K_f$
Deposits		M			$-M$	0
Loans			$-D_e$	$-D_f$	$D_e + D_f$	0
Banks' own funds					$-OF_b$	$-OF_b$
Equity		$\mathcal{E}_e + \mathcal{E}_f$	$-\mathcal{E}_e$	$-\mathcal{E}_f$		0
Σ (=Net worth)		$M + \mathcal{E}_e + \mathcal{E}_f$	0	0	0	X

Table 2: Balance sheet

3.2 Production

Production takes place in the private sector, which is subdivided into the energy sector and the final goods sector. Both subsectors require three factors of production: capital (expressed in final goods units), energy and workers. Furthermore, both subectors produce following a Leontief production function. Let us call y_x the yearly production of sector x, e_x the yearly energy required for this production, L_x the required number of workers and k_x the capital stock of sector x ($x \in \{e, f\}$). We thus have the following production equations:

$$y_f = \alpha_f \, L_f = \frac{e_f}{\epsilon_f} = \frac{k_f}{\gamma_f} \tag{1}$$

$$y_e = \frac{e_e}{\epsilon_e} \leq \frac{k_e}{\gamma_e} \tag{2}$$

$$k_e = \alpha_e \, L_e \tag{3}$$

in which α_x, ϵ_x and γ_x denote respectively the labour, energy and capital intensity of the production in sector x. Note that here, y_x and k_x are noted as lowercase letters, hence they are in real terms ($x \in \{e, f\}$). Besides, the equation for energy production slightly differs from the classical Leontief production equation. First, there is an inequality between y_e and $\frac{k_e}{\gamma_e}$. This expresses the fact that the energy capital is rarely used to its full capacity and that a strategic reserve is kept for periods of particularly tight energy supply. We can thus define the utilization rate of energy capital as $u_e := \frac{y_e \, \gamma_e}{k_e}$, which must always stay below unity. Second, we assume that the number of workers L_e in the energy sector is proportional to k_e instead of y_e. Indeed, as will made clear later, the number of workers in the energy sector is negligible before the energy transition and then increases as the energy sector becomes renewable. We then make the assumption that in a renewable energy system, the number of jobs is proportional to the capital stock of the system and not to its energy production. In other words, it is the installation of wind turbines and solar panels which create jobs, not their operation.

3.3 Demand

Our model is a supply model. It means that production and demand are supposed equal to each other at all times for the two subsectors. Production and demand hence share the same notation y_x ($x \in \{e, f\}$). As suggested by Figures 1 and 2, final goods are required for (i) investment i_f in the capital of final goods firms; (ii) investment i_e in the capital of energy firms; (iii) households consumption $c_{h,f}$ and (iv) capitalists consumption $c_{c,f}$. Similarly, energy demand can be split up in four components: (i) energy inputs for final goods production e_f; (ii) energy inputs for energy production e_e; (iii) households energy consumption $c_{h,e}$ and (iv) capitalists energy consumption $c_{c,e}$. We thus have the following demand equations:

$$y_f = i_f + i_e + c_{h,f} + c_{c,f} \tag{4}$$

$$y_e = e_f + e_e + c_{h,e} + c_{c,e} \tag{5}$$

Let us further define p_f the price of final goods and p_e the price of energy. Note that following the convention described above, we have $C_{h,f} = p_f \, c_{h,f}$ and $C_{e,f} = p_e \, c_{e,f}$. We then make the assumption that the final goods consumption and the energy consumption of households and capitalists are related by the equation:

$$c_{x,e} = \epsilon_f \, f(\frac{p_e}{p_f}) \, c_{x,f} \qquad (x \in \{h, c\}) \tag{6}$$

where ϵ_f is the energy intensity of final goods production (see equ.1) and $f(\cdot)$ is a monotonously decreasing function. This equation amounts to saying that the energy consumption of citizens decreases with technological progress (ϵ_f) and is sensitive to the real energy price.

3.4 Inflation

Let us call W_f and W_e the nominal wages of workers in the energy and final goods subsectors, respectively. We make the assumption that:

$$W_f = W_e = W \tag{7}$$

Let us also call δ_x the depreciation rate of capital and UC_x, the firms' unit cost of production in sector x ($x \in \{e, f\}$). We have the following equation:

$$UC_x = \frac{W \cdot L_x + p_e\, e_x + p_f\, \delta_x\, k_x}{y_x} \qquad (x \in \{e, f\}) \tag{8}$$

Inflation in the price of final goods, in turn, is determined by the following equation:

$$\dot{p}_f = \beta_{p_f}\,(\mu_f\, UC_f - p_f) \tag{9}$$

This equation indicates that final goods firms adjust their price p_f with a speed β_{p_f}, such that p_f tends towards their unit cost of production multiplied by a certain markup μ_f. μ_f is strictly superior to one in order to ensure positive profits.

The equation for the inflation in the price of energy is very similar. The only difference is that the quantity $\mu_e\, UC_e$ is increased by a government tax T_e, which energy firms transfer to the consumers.

$$\dot{p}_e = \beta_{p_e}\,(\mu_e\, UC_e + T_e - p_e) \tag{10}$$

3.5 Workers

Let us call the world population POP. The growth of POP is based on the 2014 IIASA projections, approximated by the equations and parameter values advised by Rozell [6]:

$$\dot{POP} = POP\, \tau\, (1 - \theta\, t) \tag{11}$$
$$\dot{\tau} = -\theta\, \tau \tag{12}$$

With the values of θ and τ described in Appendix B, these equations produce the population curve depicted in Figure 3. The curve indicates a peak of the world population at 9.7 billion around 2080, followed by a slow decline.

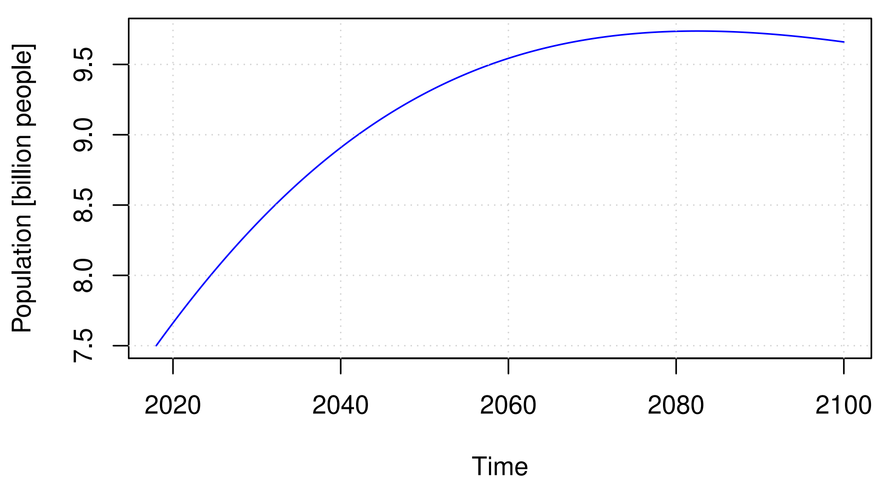

Figure 3: Evolution of the world population in our model, approximated from the 2014 IIASA projections

Let us further define the employment rate in sector x as

$$\lambda_x = \frac{L_x}{POP} \qquad (x \in \{e, f\}) \tag{13}$$

We then define the global employment rate as:

$$\lambda = \lambda_f + \lambda_e \tag{14}$$

As already stated above, workers exchange their labour force for a nominal wage W. This wage is determined following the Goodwinian process depending on the global employment rate λ and the price of final goods p_f. This allows us to capture the behaviour of the Phillips Curve as well as a certain degree of money illusion:

$$\widehat{W} = \omega_0 + \omega_1 \lambda + (1 - \omega_2)\, \hat{p}_f \tag{15}$$

where $0 < \omega_2 < 1$ and $(1 - \omega_2)$ is the money illusion of workers.

Regarding to the growth of labour productivity, we assume that it is the same for workers in the final goods and energy sectors:

$$\hat{\alpha}_f = \hat{\alpha}_e = \hat{\alpha} \tag{16}$$

This labour productivity growth is defined according to a linear Kaldor-Verdoorn dynamics:

$$\hat{\alpha} = \alpha_0 + \alpha_1 \lambda \tag{17}$$

Finally, we assume that households consume all of their wages:

$$p_f\, c_{h,f} + p_e\, c_{h,e} = W \cdot L \tag{18}$$

Profits, investment and debt

Let us define D_x, the aggregated debt of firms in sector x ($x \in \{e, f\}$) and r, the interest rate that they have to pay on this debt. The firms' profits in both producing sectors can be respectively written as:

$$\Pi_f = y_f\, (p_f - UC_f) - r\, D_f \tag{19}$$

$$\Pi_e = y_e\, (p_e - UC_e - T_e) - r\, D_e \tag{20}$$

A constant fraction Δ of these profits is paid as dividends to the shareholders (that is, the capitalists):

$$\Pi_{x,d} = \Delta\, \Pi_x \qquad (x \in \{e, f\}) \tag{21}$$

with the subscript d standing for "dividends".

The profits are also used for investment in new capital. Regarding to the energy firms, we assume that they have a certain target utilization rate of their capital stock u_e^T (in other words, they want to maintain a certain level of strategic reserve) and that they invest into new capital such that u_e stays close to u_e^T. For a given value of y_e, u_e^T corresponds to a target level of energy capital stock k_e^T:

$$k_e^T = \frac{\gamma_e\, y_e}{u_e^T} \tag{22}$$

The investment i_e of the energy firms into new capital is thus given by:

$$i_e = \beta_{i_e} \left(k_e^T - k_e\right) + \delta_e\, k_e \tag{23}$$

where β_{i_e} is a constant adjustment speed and $\delta_e\, k_e$ serves to compensate for the depreciation of the existing energy capital stock. Note that this investment behaviour is independent of the energy firms' profits. Indeed, we assume that these firms simply try to fulfill the energy demand, independently of their gains (nonetheless, the energy price is set such that these profits remain mainly positive, see above).

We thus have an equation for i_e. Moreover, equations 6 and 18 determine the value of $c_{h,f}$, and the value of $c_{c,f}$ will be later deduced from equation 34. The investment in capital stock of final goods firms is therefore the residual of equation 4 and is given by:

$$i_f = y_f - i_e - c_{h,f} - c_{c,f} \tag{24}$$

Let us define $\Pi_{x,u}$, the retained earnings of firms in sector x. We have:

$$\Pi_{x,u} = \Pi_x + p_f\, \delta_x\, k_x - \Pi_{x,d} \qquad (x \in \{e, f\}) \tag{25}$$

In both producing sectors, the firms bridge the gap between retained earnings and investment by issuing debt:

$$\dot{D}_x = p_f\, i_x - \Pi_{x,u} \qquad (x \in \{e, f\}) \tag{26}$$

Finally, the capital accumulation equation is as usual:

$$\dot{k}_x = i_x - \delta_x\, k_x \qquad (x \in \{e, f\}) \tag{27}$$

3.6 Banks and capitalists

The interest rate of the central bank r_{CB} is set according to Taylor's rule:

$$r_{CB} = r^* + \hat{p}_f + \varphi \left(\hat{p}_f - \hat{p}_f^T\right) \tag{28}$$

where r^* is the constant "natural" rate of interest, φ is a parameter and $\hat{p}_f^T$ is the inflation target of the central bank.

We define μ_b as the banks' prudential ratio. Banks' required level of own funds OF_b^T is then given by:

$$OF_b^T = \mu_b\,(D_f + D_e) \tag{29}$$

The banks' retained earnings $\Pi_{b,u}$ are thus computed such that their own funds OF_b converge towards their required level, with a convergence speed β_b:

$$\Pi_{b,u} = \beta_b \left(OF_b^T - OF_b\right) \tag{30}$$

$$\dot{OF}_b = \Pi_{b,u} \tag{31}$$

The banks' ability to retain earnings depends on their revenues, which are themselves directly determined by the interest rate's level. The banks' target rate of interest is therefore computed in a similar way to their retained earnings, but with the addition of the central bank's rate of interest:

$$r^T = r_{CB} + \lambda_{r^T}\, \frac{OF_b^T - OF_b}{OF_b^T} \tag{32}$$

where λ_{r^T} is a constant parameter. Once they have determined their target interest rate, banks then progressively adjust their interest rate towards this target, with speed β_r:

$$\dot{r} = \beta_r \left(r^T - r\right) \tag{33}$$

The capitalists' revenues are composed of the dividends they perceive from firms and of the interest they receive from their deposits. This interest is equal to the banks' total earnings $r\,(D_f + D_e)$ minus the banks' retained earnings. If we assume that capitalists consume a fraction $(1 - s_c)$ of their revenues, then their final goods consumption (in nominal terms) is given by:

$$C_{c,f} = (1 - s_c)\,(\Pi_{f,d} + \Pi_{e,d} + r\,(D_f + D_e) - \Pi_{b,u}) \tag{34}$$

3.7 Reduced form model

Let us define the following set of variables:

$$K_e := \frac{k_e}{k_f} \qquad \mathcal{P}_e := \frac{p_e}{p_f} \qquad \omega_x := \frac{W}{\alpha_x\, p_x} \qquad d_x := \frac{D_x}{p_f\, k_x} \tag{35}$$

$$\pi_x := \frac{\Pi_x}{p_f\, k_x} \qquad \pi_{x,d} := \frac{\Pi_{x,d}}{p_f\, k_x} \qquad \pi_{b,u} := \frac{\Pi_{b,u}}{p_f\, k_f} \qquad of_b := \frac{OF_b}{p_f\, k_f} \tag{36}$$

$$uc_x := \frac{UC_x}{p_x} \qquad \kappa_{h,f} := \frac{c_{h,f}}{k_f} \qquad \kappa_{c,f} := \frac{c_{c,f}}{k_f} \qquad \mathcal{T}_e := \frac{T_e}{p_e} \tag{37}$$

where ($x \in \{e, f\}$). After performing the computations described in Appendix A, all equations described in the previous subsections become summarized in the reduced form model on next page.

Besides, using the new set of variables described above, equation 6 and the equations from the reduced form model, the GDP of the global economy can be expressed as follows:

$$GDP = I_e + I_f + C_{h,f} + C_{c,f} + C_{h,e} + C_{c,e} \tag{38}$$

$$\frac{GDP}{p_f} = i_e + i_f + c_{h,f} + c_{c,f} + (c_{h,e} + c_{c,e})\, \mathcal{P}_e \tag{39}$$

$$\frac{GDP}{p_f\, k_f} = \mathcal{K}_e\, (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e\, \epsilon_f\, f(\mathcal{P}_e))\, (\kappa_{h,f} + \kappa_{c,f}) \tag{40}$$

$$\tag{41}$$

We also have, when combining equations 6 and 18:

$$W \cdot L = c_{h,f}\, (p_f + p_e\, \epsilon_f\, f(\mathcal{P}_e)) \tag{42}$$

$$\frac{W \cdot L}{p_f\, k_f} = \kappa_{h,f}\, (1 + \mathcal{P}_e\, \epsilon_f\, f(\mathcal{P}_e)) \tag{43}$$

The wage share Ω is defined as the wage bill over GDP in nominal terms:

$$\Omega = \frac{W \cdot L}{GDP} \tag{44}$$

$$= \frac{\kappa_{h,f}\, (1 + \mathcal{P}_e\, \epsilon_f\, f(\mathcal{P}_e))}{\mathcal{K}_e\, (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e\, \epsilon_f\, f(\mathcal{P}_e))\, (\kappa_{h,f} + \kappa_{c,f})} \tag{45}$$

$$\tag{46}$$

Finally, the saving rate s is the fraction of GDP that is devoted to capital investment:

$$s = \frac{I_e + I_f}{GDP} \tag{47}$$

$$= \frac{\mathcal{K}_e\, (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f}{\mathcal{K}_e\, (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e\, \epsilon_f\, f(\mathcal{P}_e))\, (\kappa_{h,f} + \kappa_{c,f})} \tag{48}$$

Reduced form model:

$$\dot{POP} = POP\,\tau\,(1-\theta\,t)$$
$$\dot{\tau} = -\theta\,\tau$$
$$\dot{\mathcal{K}}_e = \mathcal{K}_e\,(\hat{k}_e - \hat{k}_f)$$
$$\dot{\mathcal{P}}_e = \mathcal{P}_e\,(\hat{p}_e - \hat{p}_f)$$
$$\dot{\omega}_f = \omega_f\,(\omega_0 + \omega_1\,\lambda - \omega_2\,\hat{p}_f - \alpha_0 - \alpha_1\,\lambda)$$
$$\dot{\omega}_e = \omega_e\,(\omega_0 + \omega_1\,\lambda - \omega_2\,\hat{p}_f + (\hat{p}_f - \hat{p}_e) - \alpha_0 - \alpha_1\,\lambda)$$
$$\dot{\lambda}_x = \lambda_x\left(\hat{k}_x - \alpha_0 - \alpha_1\,\lambda - \tau\,(1-\theta\,t)\right) \qquad (x \in \{e,f\})$$
$$\dot{d}_x = \hat{k}_x - (1-\Delta)\,\pi_x - d_x\left(\hat{p}_f + \hat{k}_x\right) \qquad (x \in \{e,f\})$$
$$\dot{r} = \beta_r\left(r^T - r\right)$$
$$\dot{of}_b = \pi_{b,u} - of_b\left(\hat{p}_f + \hat{k}_f\right)$$

with the following intermediate variables:

$$\pi_{b,u} = \beta_b\,(\mu_b\,(d_f + \mathcal{K}_e\,d_e) - of_b)$$
$$uc_f = \omega_f + \epsilon_f \mathcal{P}_e + \gamma_f\,\delta_f$$
$$\pi_f = \frac{1}{\gamma_f}\,(1 - uc_f) - r\,d_f$$
$$\kappa_{h,f} = \frac{\omega_f}{\mathcal{P}_e\,\epsilon_f\,f(\mathcal{P}_e)+1}\left(\frac{1}{\gamma_f} + \frac{\alpha_f}{\alpha_e}\,\mathcal{K}_e\right)$$
$$\kappa_{c,f} = (1-s_c)\,(\pi_{f,d} + \mathcal{K}_e\,\pi_{e,d} + r\,(d_f + \mathcal{K}_e\,d_e) - \pi_{b,u})$$
$$u_e = \frac{\gamma_e}{(1-\epsilon_e)\,\mathcal{K}_e}\left(\frac{\epsilon_f}{\gamma_f} + \epsilon_f\,f(\mathcal{P}_e)\,(\kappa_{h,f} + \kappa_{c,f})\right)$$
$$uc_e = \frac{\gamma_e}{u_e}\,\omega_e + \epsilon_e + \frac{\gamma_e\,\delta_e}{\mathcal{P}_e\,u_e}$$
$$\hat{p}_e = \beta_{p_e}\,(\mu_e\,uc_e + \mathcal{T}_e - 1)$$
$$\pi_e = \frac{\mathcal{P}_e\,u_e}{\gamma_e}\,(1 - uc_e - \mathcal{T}_e) - r\,d_e$$
$$\hat{k}_e = \beta_{i_e}\left(\frac{u_e}{u_e^T} - 1\right)$$
$$\hat{k}_f = \frac{1}{\gamma_f} - \left(\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \delta_f + \kappa_{h,f} + \kappa_{c,f}\right)$$
$$\lambda = \lambda_f + \lambda_e$$
$$\hat{p}_f = \beta_{p_f}\,(\mu_f\,uc_f - 1)$$
$$r_{CB} = r^* + \hat{p}_f + \varphi\left(\hat{p}_f - \hat{p}_f^T\right)$$
$$r^T = r_{CB} + \lambda_{r^T}\,\frac{\mu_b\,(d_f + \mathcal{K}_e\,d_e) - of_b}{\mu_b\,(d_f + \mathcal{K}_e\,d_e)}$$

4 Scenario analysis

4.1 Assumptions and scenarios definition

The main parameters which, in our model, drive the evolution of the world economy are:

- the intensities of the three factors of production for final goods: α_f, γ_f and ϵ_f;
- the intensities of the three factors of production for energy: α_e, γ_e and ϵ_e;
- the world population POP.

The evolution of the labour intensity in both producing sectors and of the world population have already been chosen (see equation 17 and Figure 3). Regarding the evolution of the capital intensity γ_f of final goods production and of the energy intensity ϵ_f of final goods production, we take the same assumptions as Dupont *et al.* [3]: we assume that γ_f stays constant through time (this parameter has indeed not changed since 1990) and we assume that ϵ_f evolves according to the global energy intensity of GDP in the business-as-usual scenario from the IEA's "World Energy Outlook" 2020 report [7]. This amounts to extrapolating until 2100 the evolution of the global energy intensity of GDP observed during last 30 years. The resulting curve for ϵ_f is plotted on Figure 4.

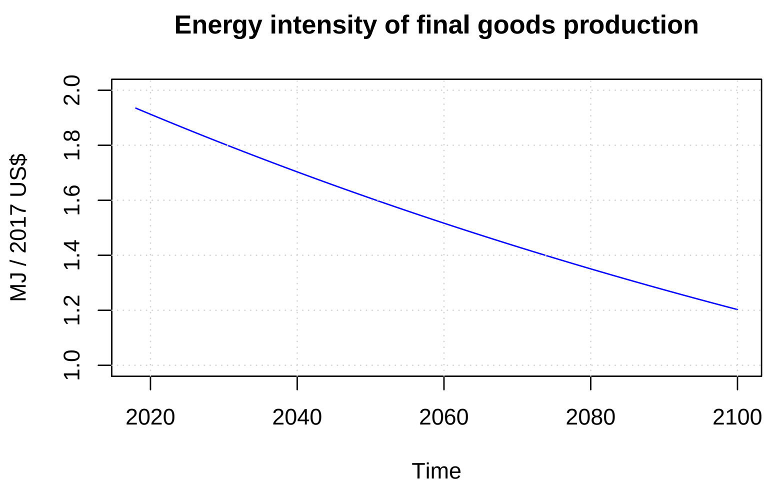

Figure 4: Evolution of ϵ_f in our model. ϵ_f gets reduced by 38% between 2018 and 2100.

The evolution of the last two parameters γ_e and ϵ_e is envisioned through different scenarios:

- There is no energy transition, γ_e and ϵ_e stay constant throughout the century (baseline scenario). This corresponds to an idealized world where there would be no climate change, thus no need to conduct an energy transition and where there would be infinite fossil resources of constant quality.
- A slow energy transition is taking place, which leads to an energy system based entirely on renewable energy by 2100 (slow transition scenario). As a consequence, γ_e and ϵ_e evolve as the production is moving from fossil fuels to renewable energy sources.
- A fast energy transition is taking place, compatible with the Paris Agreement. This transition leads to an energy system based entirely on renewables by 2050 (fast transition scenario). Again, γ_e and ϵ_e evolve as the production is moving from fossil fuels to renewable energy sources.

The evolution of γ_e and ϵ_e in the second and third scenario is described in the next subsection.

4.2 Modeling the energy transition

Adding the energy transition requires to perform some adaptations to the model. To do so, we proceed like Dupont *et al.* [3]. First, we split y_e into y_{nre}, the energy production from non-renewable sources and y_{re}, the energy production from renewable sources:

$$y_e = y_{nre} + y_{re} \tag{49}$$

Like Dupont *et al.* [3], we aggregate all non-renewable and all renewable energy sources into two blocs. Moreover, we assume that renewable energy sources are limited to wind and solar energy, since these two renewable sources are expected to clearly dominate all the others throughout the transition [7],[8],[9]. We then define the degree of progress of the energy transition χ as the fraction of total energy production which comes from renewable sources:

$$\chi = \frac{y_{re}}{y_e} \tag{50}$$

$\chi \simeq 0$ at the beginning of the energy transition; the transition is completed once $\chi = 1$. We can thus rewrite equation 49 as:

$$y_e = y_{nre} + y_{re} \tag{51}$$
$$= (1-\chi)\, y_e + \chi\, y_e \tag{52}$$

Similarly, if we define the capital and energy intensities of non-renewable (γ_{nre}, ϵ_{nre}) and renewable (γ_{re}, ϵ_{re}) energy production, we have:

$$\gamma_e = (1-\chi)\, \gamma_{nre} + \chi\, \gamma_{re} \tag{53}$$
$$\epsilon_e = (1-\chi)\, \epsilon_{nre} + \chi\, \epsilon_{re} \tag{54}$$

We make the very conservative assumption that γ_{nre} and ϵ_{nre} are constant through time i.e. the fossil fuels' quality does not decrease during the century. Regarding renewable parameters, we assume that ϵ_{re} has a low, constant value. For γ_{re}, we proceed like in [3]: we aggregate the global EROI curves for wind energy [1] and photovoltaic panels [2], then we transform this aggregated EROI curve into a curve of capital intensity via the equation:

$$\gamma_{re} = \frac{1}{EROI\, \epsilon_f\, \delta_e} \tag{55}$$

Indeed, $EROI = \frac{\text{Energy inputs}}{\text{Energy outputs}}$ and we slightly adapted the EROI curves from [1],[2] such that all energy inputs of renewable energies were capital energy inputs, excluding the small operational energy inputs. Thus $\frac{1}{EROI}$ gives the quantity of energy to be invested as capital per unit of energy output. By multiplying by $\frac{1}{\epsilon_f}$, we transform this quantity of energy into a quantity of capital stock expressed in final goods units. We then multiply by $\frac{1}{\delta_e}$ in order to have the capital stock required over the entire lifecycle of the renewable energy facility instead of a yearly value. The resulting curve for γ_{re} is plotted in Figure 5.

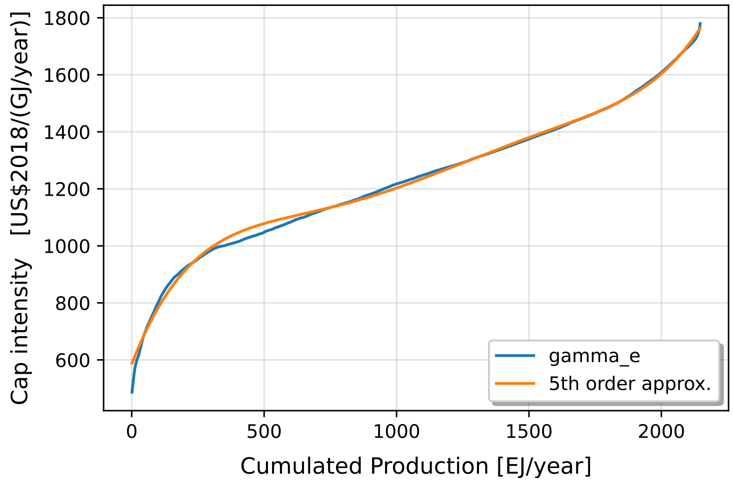

Figure 5: Capital intensity of renewable energy production as a function of the total energy production from renewable energies, computed based on the EROI curves from Dupont *et al.* [1][2]

We can observe that the capital intensity of renewable energy production increases as a function of the total production from renewable energies. In other words, a massive deployment of renewable energies will imply that the energy output per unit of capital decreases, since we will have to install renewable energy systems in places which do not display optimal characteristics (e.g. lower wind speed or less solar irradiation). Finally, Figure 5 displays the 5^{th} order polynomial approximation of the γ_e curve, which is used in the simulation code.

It is worth noting that the energy transition is modeled here in an extremely conservative way. Indeed, according to the model, doing the energy transition only implies replacing fossil fuel installations by wind turbines and solar panels, which have a higher capital intensity per unit of energy produced. Many important aspects of the energy transition are thus overlooked. More specifically, we make the very conservative assumptions that we can neglect:

- The issue related to the electrification of entire sectors. We simply assume that the technologies will evolve such that the economy becomes compatible with a 100% electrical energy production.
- The necessity to reinforce the electricity grid as the share of renewable energies increases. If it was included in the model, this reinforcement of the grid would lead to a further increase of the capital intensity of energy production.
- The necessary investments in energy storage systems as the energy system transitions towards 100% renewable production. Again, if it was included in the model, this would lead to a further increase of the capital intensity of energy production due to the transition.
- The probable increase in metals' energy extraction costs once wind turbines and solar panels become massively manufactured.
- The climate change damages on the global economy and on the energy system, both in the slow and fast transition scenarios.

The energy transition is included in the set of differential equations by exogenously imposing an increase in χ. The evolution of χ corresponding to both energy transition scenarios is modeled in Figure 6.

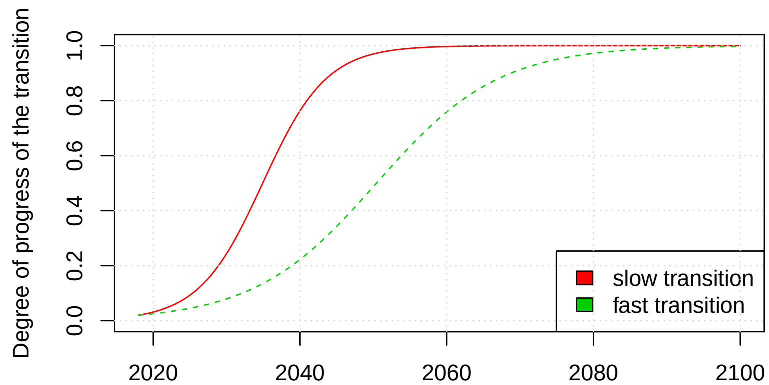

Figure 6: Degree of progress of the energy transition as a function of time in both transition scenarios

4.3 Results

We simulate the reduced form model for the three scenarios described above with R. The model equations are the ones of the reduced form model from subsection 3.7, completed by the energy transition equations. The simulation results run from year 2018 to 2100 like in Dupont *et al.*, so that we could reuse some of their data for calibration (see Appendix B) [3].

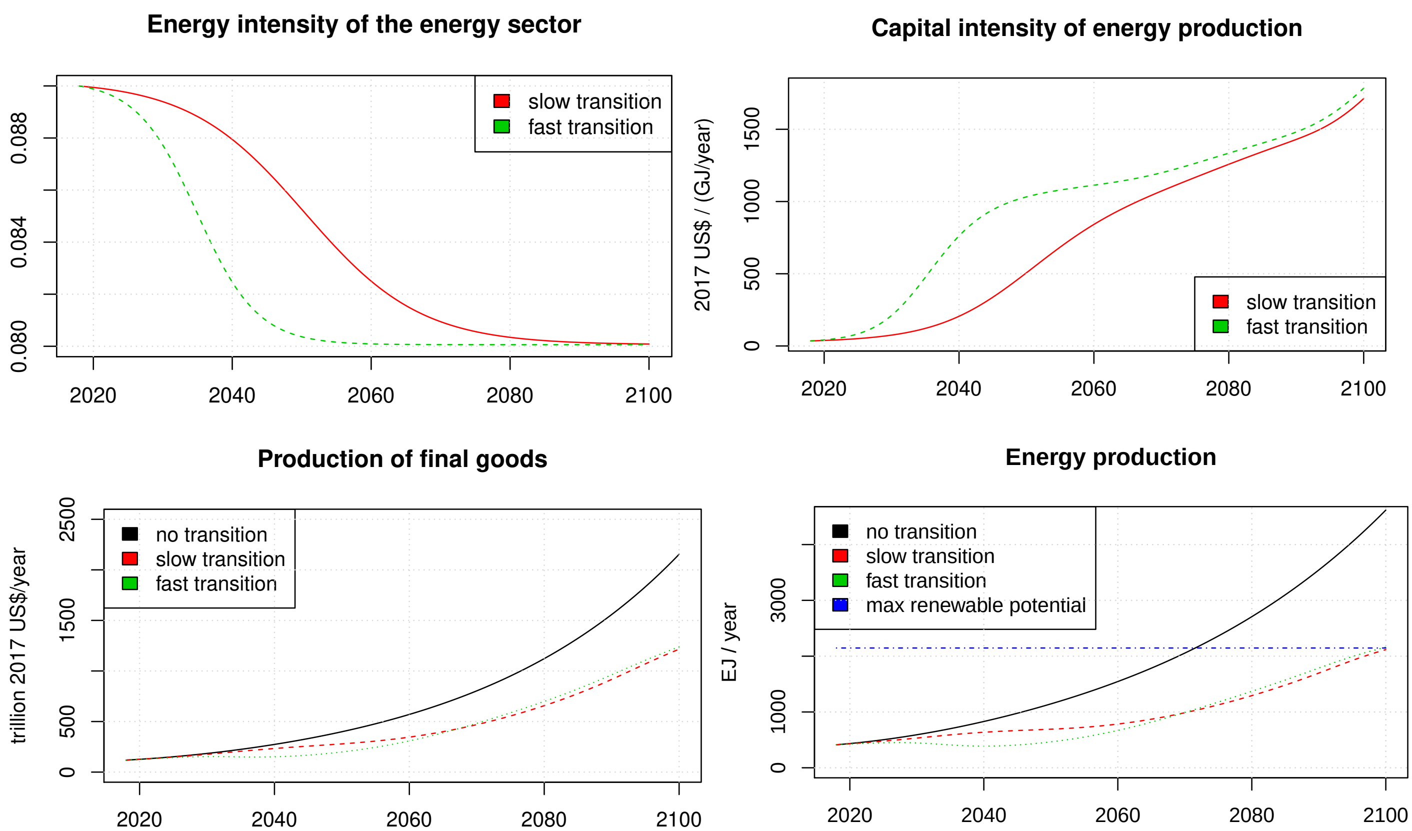

Figure 7: Simulation results - comparison of the three scenarios

Figure 7 displays a first series of simulation results. To begin with, we observe that the energy intensity of the energy sector ϵ_e diminishes as a consequence of the energy transition. Indeed, the extraction of fossil fuels requires a lot of direct energy inputs, unlike the operation of wind turbines and solar panels. The decrease in ϵ_e is however mitigated by the losses associated with electricity distribution and transport that are integrated into ϵ_{re} [3]. On the other hand, the capital intensity of the energy sector γ_e skyrockets as a consequence of the energy transition. It even continues to increase after the end of the transition, due to the decreasing quality of renewable energy sites (see Figure 5). Hence, γ_e becomes multiplied by 50 between 2018 and 2100.

For the production of final goods y_f and energy y_e, we observe that all three scenarios display a similar overall growth pattern, even if this growth is less strong in the two scenarios including an energy transition. Yet, it is worth noting that the "fast transition scenario" exhibits a slight degrowth in both y_f and y_e between around 2030 and 2045. Besides, in both energy transition scenarios, the total energy production, which is 100% renewable in 2100, reaches by the end of the century the world maximum potential for wind and solar energy as computed by Dupont *et al.* [1][2].

Let us rewrite equation 4 as follows:

$$y_f = i_f + i_e + c_{h,f} + c_{c,f} \tag{56}$$

$$\frac{y_f}{k_f} = \frac{i_f}{k_f} + \mathcal{K}_e \frac{i_e}{k_e} + \kappa_{h,f} + \kappa_{c,f} \tag{57}$$

$$\frac{1}{\gamma_f} = \hat{k}_f + \delta_f + \mathcal{K}_e \left(\hat{k}_e + \delta_e\right) + \kappa_{h,f} + \kappa_{c,f} \tag{58}$$

This equation indicates that the production $\frac{1}{\gamma_f}$ of final goods per unit of capital stock in the final goods sector has four competing uses: the investment in capital of the final goods sector, the investment in energy capital, the households' consumption of final goods and the capitalists' consumption of final goods. Figure 8 plots, for the three scenarios, these four quantities expressed as a fraction of $\frac{1}{\gamma_f}$:

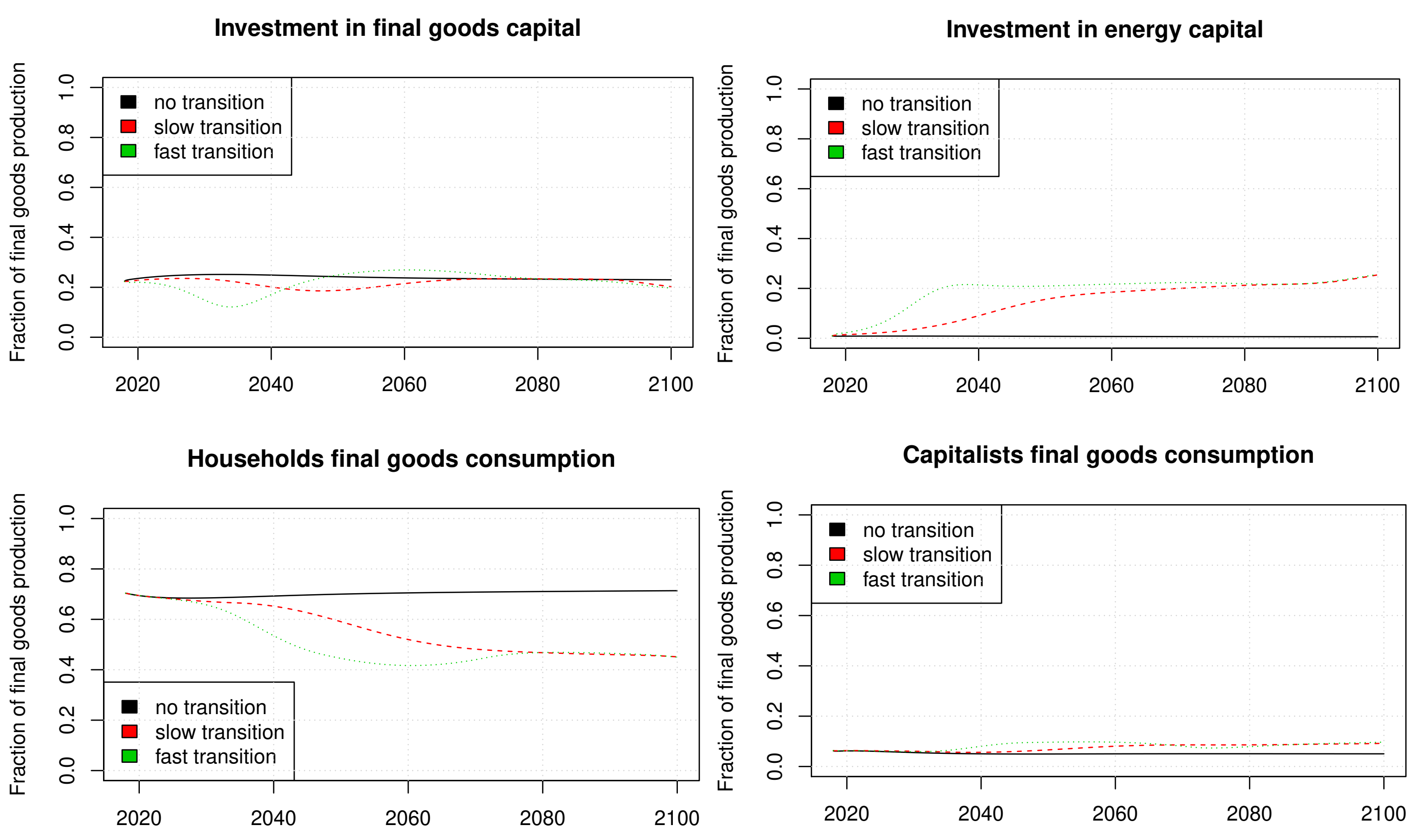

Figure 8: Simulation results - comparison of the three scenarios

All four quantities are more or less constant in the "no transition" scenario. In the two energy transition scenarios however, we observe that the investment in energy capital progressively increases a consequence of the rising capital intensity of the energy sector. This causes a temporary slump in the investment in final goods capital and a permanent, strong decrease in the fraction of final goods production dedicated to households consumption. Both effects are more pronounced in the "fast transition" scenario. Regarding the final goods consumption of capitalists, it benefits from the energy transition since the transition implies a rapid growth of the energy sector, hence a growth of dividends from that sector. Thus, $\kappa_{c,f}$ reaches higher levels in both transition scenarios compared to the baseline case.

Figure 9 further describes the simulation results in the three scenarios:

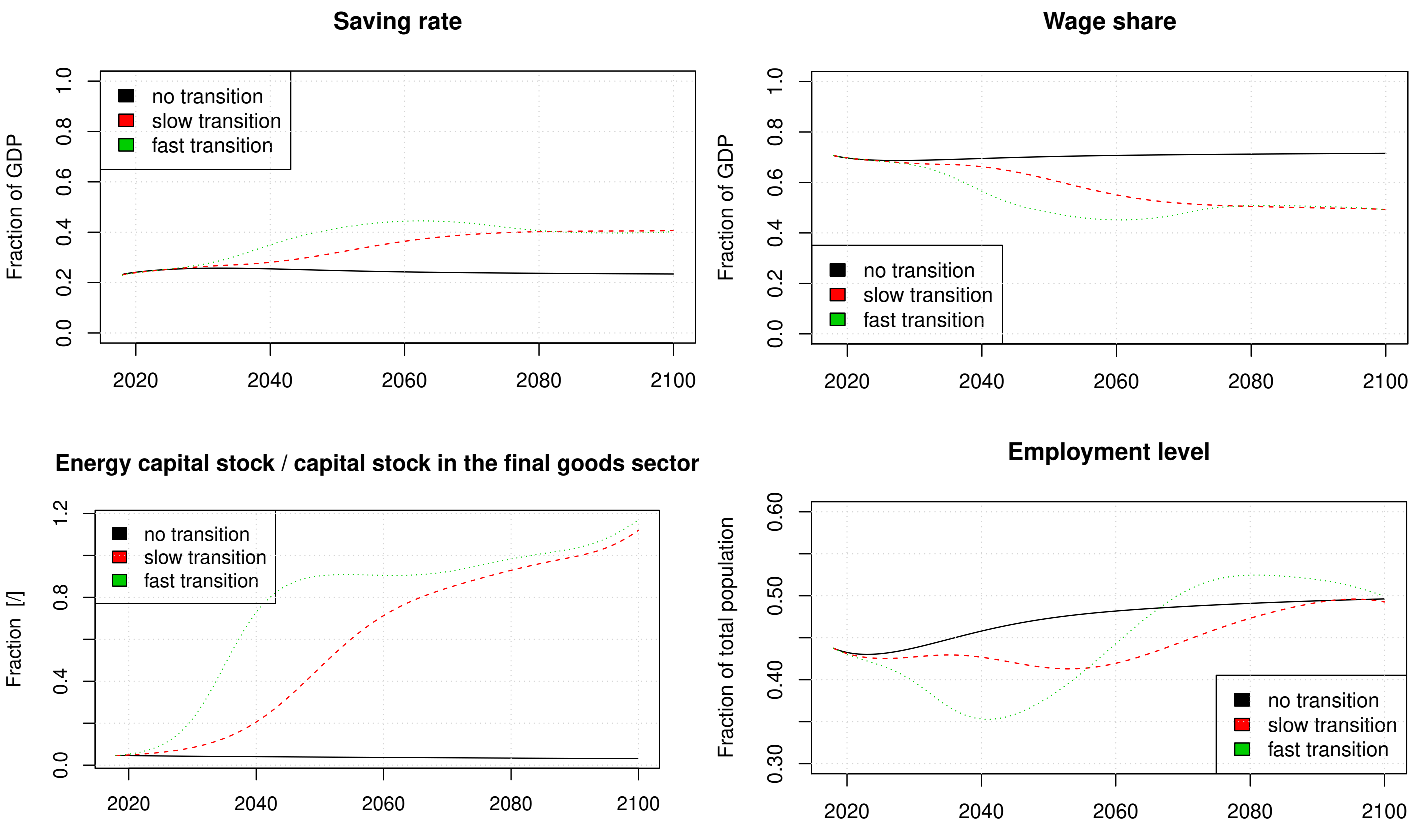

Figure 9: Simulation results - comparison of the three scenarios

As a result of the increasing investment in energy capital, the energy transition causes the saving rate of the economy to drastically increase, from 23% in 2018 to more than 40% during and after the transition. As put in perspective by Režný and Bureš, "*at the peak of the war effort, the US economy was able to devote over 40% of its output solely to defence spending*" [10]. In other words, in the energy transition scenarios displayed here, the global economy transitions to a permanent war economy.

Describe the evolutions of the wage share + K_e + employment level [TO DO]

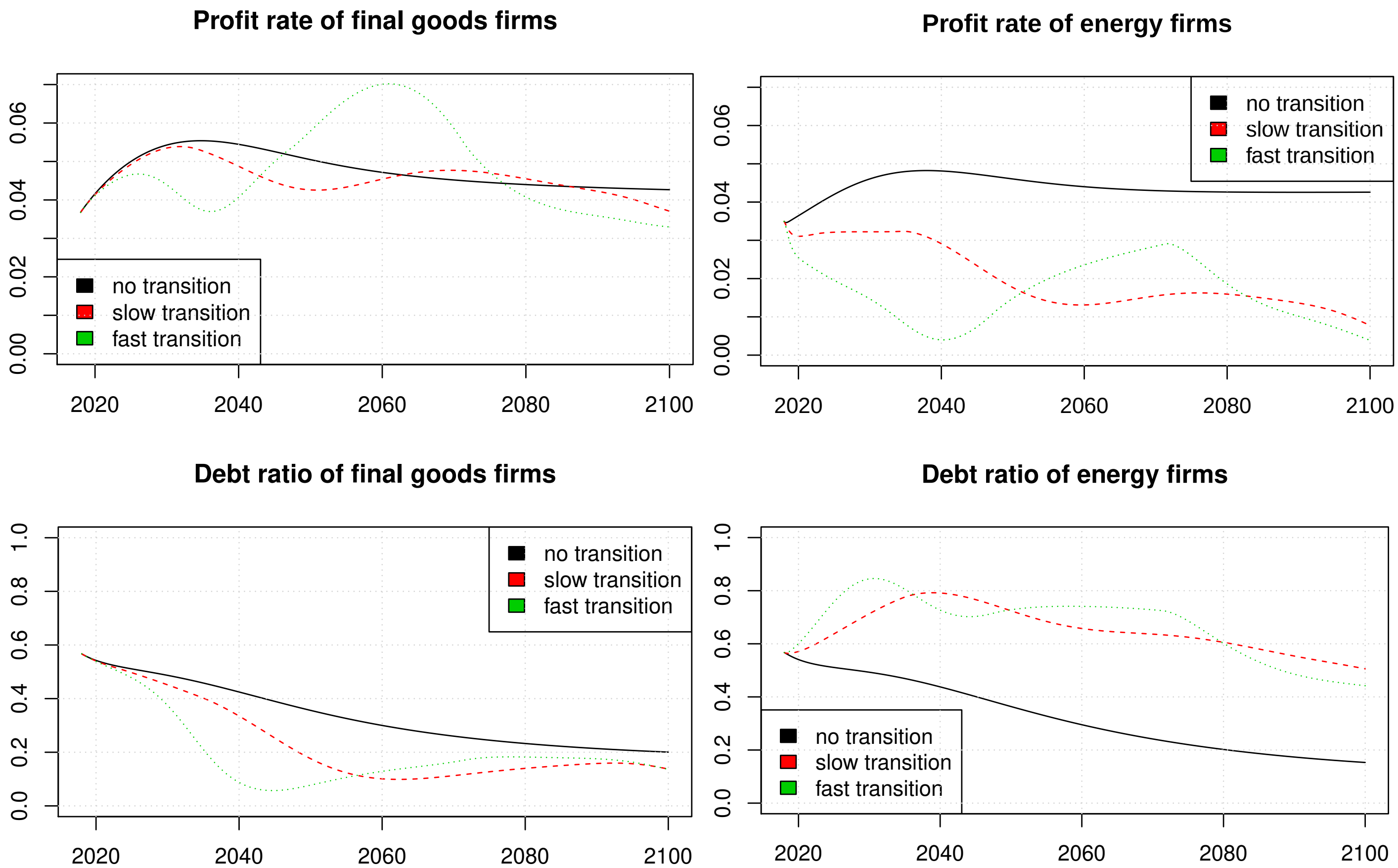

Figure 10: Simulation results - comparison of the three scenarios

Describe Figure 10 [TO DO]

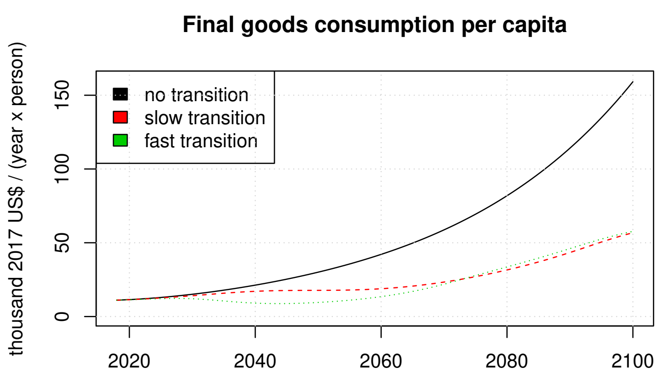

Figure 11: Simulation results - comparison of the three scenarios

Figure 11 informs us that in the fast transition scenario, even if consumption per capita is increasing overall, it decreases temporarily *by 29% in absolute terms* between 2027 and 2044.

This is due to the fall in employment level (see Figure 9) [TO DEVELOP FURTHER]

4.4 Discussion

We develop a fourth scenario consisting in a fast transition with strong state intervention in order to avoid the temporary fall in consumption per capita between 2027 and 2044:

- Tax capitalists (their consumption gets reduced up to 75%)
- Put a lower bound on the investment in k_f thanks to:
  - a forced reduction of the investment in k_e
  - subsidies coming from the revenues of the tax on capitalists
- Transfer the rest of the tax revenues to households to sustain their consumption
- Guarantee the debt of the energy firms so that they can benefit from low interest rates

Display results of the fast transition scenario after state intervention [TO DO]

Compare results with those of Dupont *et al.* [3] [TO DO]

Compare results with those of Bovari *et al.* [4][11] [TO DO]

Compare results with those of Jackson and Jackson [12] [TO DO]

Compare results (especially the saving rate) with those of Režný and Bureš [10] [TO DO]
Note that their model has a very different structure compared to ours.

Compare results with those of King, including those from his most recent articles [13] [TO DO]

5 Conclusion

We modelled the energy transition using detailed EROI curves and generally conservative/optimistic assumptions.

We showed that even with these conservative assumptions, the energy transition implied a profound socio-economic restructuration of our economies:

- The saving rate must permanently reach levels unseen since WWII [10]
- Acceptability of a fast transition will be an issue (decrease in consumption, even in the case of a strong state intervention)
- Fairness is key for acceptability of the transition
- A renewable-based energy system can theoretically sustain economic growth, but not on the long term since we quickly reach the maximum global potentials for wind and solar energy
- Jobs creation will be a key determinant for the transition's success

The state has a fundamental role to play to manage and compensate the disruptive effects of a rapid energy transition compatible with the Paris Agreement.

The falling profit rate of the energy sector questions the appropriateness of its privatization in the context of the transition

[TO IMPROVE]

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A Derivation of the reduced form model

Based on the definition of new variables (35-37), we can modify the equations from section 3 to obtain a reduced form model.

Given $\omega_x := \frac{W}{\alpha_x\, p_x}$, we have:

$$\hat{\omega}_x = \widehat{W} - \hat{\alpha}_x - \hat{p}_x \qquad (x \in \{e, f\}) \tag{59}$$

which becomes, when we insert equations 15 and 17:

$$\hat{\omega}_f = \omega_0 + \omega_1\,\lambda - \omega_2\,\hat{p}_f - \alpha_0 - \alpha_1\,\lambda \tag{60}$$

$$\hat{\omega}_e = \omega_0 + \omega_1\,\lambda - \omega_2\,\hat{p}_f + (\hat{p}_f - \hat{p}_e) - \alpha_0 - \alpha_1\,\lambda \tag{61}$$

We know from equations 1 and 3 that:

$$L_f = \frac{y_f}{\alpha_f} \tag{62}$$

$$L_e = \frac{k_e}{\alpha_e} \tag{63}$$

Thus, given $\lambda_x := \frac{L_x}{POP}$, we have:

$$\hat{\lambda}_x = \hat{L}_x - \widehat{POP} \qquad (x \in \{e, f\}) \tag{64}$$

$$\hat{\lambda}_f = \hat{y}_f - \alpha_0 - \alpha_1\,\lambda - \widehat{POP} \tag{65}$$

$$\hat{\lambda}_f = \hat{k}_f - \alpha_0 - \alpha_1\,\lambda - \widehat{POP} \tag{66}$$

$$\hat{\lambda}_e = \hat{k}_e - \alpha_0 - \alpha_1\,\lambda - \widehat{POP} \tag{67}$$

We also have $d_x := \frac{D_x}{p_f\, k_x}$ which becomes, when we take the derivative:

$$\dot{d_x} = \frac{\dot{D}_x}{p_f\, k_x} - d_x\left(\hat{p}_f + \hat{k}_x\right) \qquad (x \in \{e, f\}) \tag{68}$$

After inserting equations 25, 26, 27, 21 and the definition of π_x, we obtain:

$$\dot{d_x} = \frac{i_x}{k_x} - \frac{\Pi_{x,u}}{p_f\, k_x} - d_x\left(\hat{p}_f + \hat{k}_x\right) \tag{69}$$

$$= \frac{i_x}{k_x} - \frac{\Pi_x + p_f\,\delta_x\, k_x - \Pi_{x,d}}{p_f\, k_x} - d_x\left(\hat{p}_f + \hat{k}_x\right) \tag{70}$$

$$= \hat{k}_x - \frac{\Pi_x - \Pi_{x,d}}{p_f\, k_x} - d_x\left(\hat{p}_f + \hat{k}_x\right) \tag{71}$$

$$= \hat{k}_x - (1 - \Delta)\,\pi_x - d_x\left(\hat{p}_f + \hat{k}_x\right) \tag{72}$$

Moreover, given $of_b := \frac{OF_b}{p_f\, k_f}$ and equation 31, we have:

$$\dot{of}_b = \frac{\dot{OF}_b}{p_f\, k_f} - of_b\left(\hat{p}_f + \hat{k}_f\right) \tag{73}$$

$$= \pi_{bu} - of_b\left(\hat{p}_f + \hat{k}_f\right) \tag{74}$$

Given $uc_x := \frac{UC_x}{p_x}$ and equation 8, we further have:

$$UC_f = \frac{W}{\alpha_f} + \epsilon_f\, p_e + p_f\, \gamma_f\, \delta_f \tag{75}$$

$$uc_f = \omega_f + \epsilon_f \mathcal{P}_e + \gamma_f\, \delta_f \tag{76}$$

and

$$UC_e = \frac{\gamma_e\, W}{\alpha_e\, u_e} + \epsilon_e\, p_e + p_f \frac{\gamma_e\, \delta_e}{u_e} \tag{77}$$

$$uc_e = \frac{\gamma_e}{u_e}\, \omega_e + \epsilon_e + \frac{\gamma_e\, \delta_e}{\mathcal{P}_e\, u_e} \tag{78}$$

With $\pi_x := \frac{\Pi_x}{p_f\, k_x}$ and $\mathcal{T}_e := \frac{T_e}{p_e}$, equations 19 and 20 become:

$$\pi_f = \frac{1}{\gamma_f}\,(1 - uc_f) - r\, d_f \tag{79}$$

$$\pi_e = \frac{\mathcal{P}_e\, u_e}{\gamma_e}\,(1 - uc_e - \mathcal{T}_e) - r\, d_e \tag{80}$$

With $\kappa_{h,f} := \frac{c_{h,f}}{k_f}$, we obtain, when combining equations 6 and 18:

$$c_{h,f}\,(p_e\, \epsilon_f\, f(\mathcal{P}_e) + p_f) = W \cdot L \tag{81}$$

$$c_{h,f} = \frac{\omega_f}{\mathcal{P}_e\, \epsilon_f\, f(\mathcal{P}_e) + 1}\, \alpha_f\, (L_f + L_e) \tag{82}$$

$$c_{h,f} = \frac{\omega_f}{\mathcal{P}_e\, \epsilon_f\, f(\mathcal{P}_e) + 1} \left(y_f + \frac{\alpha_f}{\alpha_e}\, k_e \right) \tag{83}$$

$$\kappa_{h,f} = \frac{\omega_f}{\mathcal{P}_e\, \epsilon_f\, f(\mathcal{P}_e) + 1} \left(\frac{y_f}{k_f} + \frac{\alpha_f}{\alpha_e}\, \mathcal{K}_e \right) \tag{84}$$

$$\kappa_{h,f} = \frac{\omega_f}{\mathcal{P}_e\, \epsilon_f\, f(\mathcal{P}_e) + 1} \left(\frac{1}{\gamma_f} + \frac{\alpha_f}{\alpha_e}\, \mathcal{K}_e \right) \tag{85}$$

$$\tag{86}$$

Similarly, with $\kappa_{c,f} := \frac{c_{c,f}}{k_f}$, equation 34 becomes:

$$\kappa_{c,f} = (1 - s_c)\,(\pi_{f,d} + \mathcal{K}_e\, \pi_{e,d} + r\,(d_f + \mathcal{K}_e\, d_e) - \pi_{b,u}) \tag{87}$$

$$\tag{88}$$

Furthermore, by combining equations 5, 6 and the definition of u_e, we obtain:

$$u_e = \frac{\gamma_e}{(1 - \epsilon_e)} \left(\frac{e_f + c_{h,e} + c_{c,e}}{k_e} \right) \tag{89}$$

$$= \frac{\gamma_e}{(1 - \epsilon_e)\, \mathcal{K}_e} \left(\frac{\epsilon_f}{\gamma_f} + \frac{c_{h,e} + c_{c,e}}{k_f} \right) \tag{90}$$

$$= \frac{\gamma_e}{(1 - \epsilon_e)\, \mathcal{K}_e} \left(\frac{\epsilon_f}{\gamma_f} + \epsilon_f\, f(\mathcal{P}_e)\,(\kappa_{h,f} + \kappa_{c,f}) \right) \tag{91}$$

Let us divide both sides of equation 23 by k_e. It gives:

$$\frac{i_e}{k_e} = \beta_{i_e} \left(\frac{k_e^T}{k_e} - 1 \right) + \delta_e \tag{92}$$

$$\hat{k}_e = \beta_{i_e} \left(\frac{u_e}{u_e^T} - 1 \right) \tag{93}$$

We then combine equations 24 and 27 to get:

$$\frac{i_f}{k_f} = \frac{1}{\gamma_f} - \left(\mathcal{K}_e \, \frac{i_e}{k_e} + \kappa_{h,f} + \kappa_{c,f} \right) \tag{94}$$

$$\hat{k}_f = \frac{1}{\gamma_f} - \left(\mathcal{K}_e \, (\hat{k}_e + \delta_e) + \delta_f + \kappa_{h,f} + \kappa_{c,f} \right) \tag{95}$$

Finally, we combine equations 29 and 32 to have:

$$r^T = r_{CB} + \lambda_{r^T} \, \frac{\mu_b \, (D_f + D_e) - OF_b}{\mu_b \, (D_f + D_e)} \tag{96}$$

$$r^T = r_{CB} + \lambda_{r^T} \, \frac{\mu_b \, (d_f + \mathcal{K}_e \, d_e) - of_b}{\mu_b \, (d_f + \mathcal{K}_e \, d_e)} \tag{97}$$

B Calibration of the model

[TO DO]