LONG-TERM ENDOGENOUS ECONOMIC GROWTH AND ENERGY TRANSITIONS

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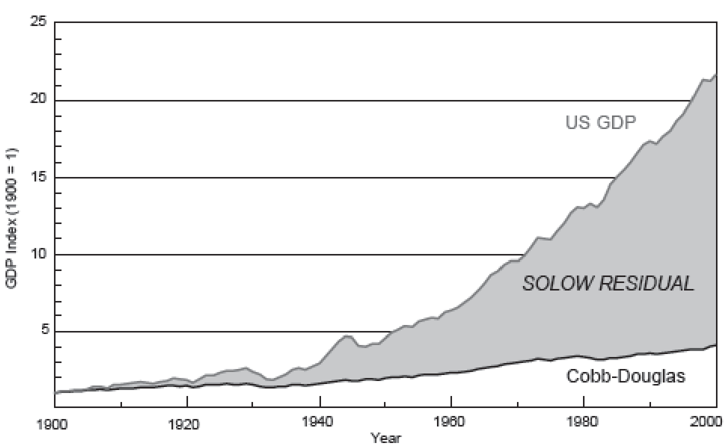
Neoclassical economic growth

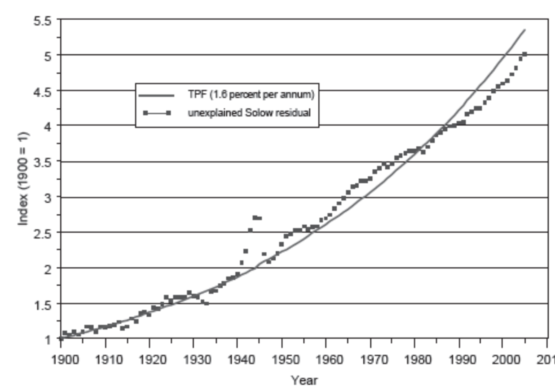
- In mainstream economics, the macroeconomic product Y_t (GDP) is the result of the aggregation of production factors which generally consist in physical capital K_t and labor L_t: $Y_t = F(K, L)$.

- Where F is for example the Cobb-Douglas production function: $Y_t = K^{\alpha}L^{1-\alpha}$. With α and $1-\alpha$ the output elasticities of capital and labor respectively corresponding to 0.3 and 0.7 (cost share theorem).

- But the increase of these production factors do not match the increase of GDP. The unexplained economic growth is supposed to comes from technological progress : increases of technological level A_t.



Increase of technological level A_t, (or Total Productivity Factor, TPF)



Source: Ayres and Warr, 2009

Neoclassical technological progress

- So the macroeconomic production function is now: $Y_t = A_t \, K^{\alpha} L^{1-\alpha}$
- Where this abstract representation of technological change (i.e. increases of A_t) aggregate very different production-augmenting factors such as: primary-to-final energy conversion efficiency, final-to-services energy conversion efficiency, labor division and organization, skill improvements, information and communication technologies contribution; but also the beneficial effects of inclusive institutions (that for example protect private property rights which incentivize innovation and R&D).
- In first economic growth models (Solow, 1956; Swan, 1956) technological change is exogenous.
- In the 90's the so-called "endogenous school" produced models in which technological progress is endogenized and explained by human capital accumulation (Lucas, 1988; Rebelo, 1991), directed physical capital and technology accumulation (Romer, 1986, 1990; Aghion and Howitt, 1992), public investment in education or research and development (Grossman and Helpman, 1991; Barro and Sala-i-Martin, 1995; Barro, 1996).

Neoclassical economics and energy

- Exogenous and endogenous growth models have suffered the same critic regarding the limits impose by Earth resources (Meadows et al., 1972).

- For economic growth to continue forever in a finite physical world, neoclassical authors had to postulate in their models that :
  - human-made capital would be a perfect substitute for the natural resource input, or that technological progress would have to be infinite in the future (Solow, 1974; Stiglitz, 1974; Dasgupta and Heal, 1974),
  - or that macroeconomic value added would have to become increasingly dematerialized and based on knowledge (Smulders, 1995).

- Work combining optimal economic growth and transition from fossil to renewable energy also exists (Tahvonen and Salo, 2001).

- The recent *Unified Growth Theory* of Galor (2011) takes no account of the broader environment (energy is not even mentioned).

Missing perspective

- These models suffer four drawbacks, namely that:
  - (i) they are essentially qualitative since their main variables (human capital, knowledge, skills) are not always readily quantifiable; and consequently,
  - (ii) they are mostly analyzed through static comparative equilibriums (or econometric analysis of a reduced equation) and hardly reproduce historical data with an accurate dynamics; this is because,
  - (iii) technological level is rather imprecisely defined in these models and most of the time stands as a time-dependent multiplier (or Total Factor Productivity) of the total macroeconomic production function; and more generally,
  - (iv) they do not take into account that the economic system must necessarily follows the natural laws of the broader biophysical system in which it is embedded, and in particular the laws of thermodynamics.

- In all these different studies, the biophysical perspective (exergy, EROI) is completely absent, and endogeneity is not straightforward.

- It is the purpose of the present article to propose (to neoclassical economics) a theoretical model of (very) long-term endogenous economic growth that takes into account the underlying physical essence of the economy system.

Introduction: theoretical positioning

Endogenous economic growth

- Human capital accumulation increases technological progress endogenously but underlying mechanism remains unclear.

Resource depletion and energy transtion

- Transition timing.
- Impact of fossil peak on economic growth.
- Climate change issue.

Biophysical economics

- EROI
- Net energy
- Exergy

Introduction (2/2)

Endogenous economic growth

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OUR PAPER

Biophysical economics

- EROI
- Net energy
- Exergy

Exergy as a production factor

- As repeatedly stressed by some authors (Ayres and Warr, 2009; Warr and Ayres, 2012), what is commonly named *energy* in economic studies and models is in fact *exergy*. Exergy is the part of energy that can perform actual work.

- As required by the first law of thermodynamics, energy is conserved in the economic process. On the other hand, the second law of thermodynamics stipulates that exergy is degraded through the functioning of the economy system since it is composed of multiples irreversible processes that imply some entropy creation.

- Energy enters the economy as a high quality (high exergy content) input in the forms of fossils fuels, nuclear energy, and concentrated solar energy (biomass and water/wind flows). Those energy forms are ultimately dissipated into a lower quality (lower exergy content) heat output that potentially contains zero exergy (and thus zero ability to generate useful work) if its temperature is the same as the broader environment.

- Hence, it is the exergy content of energy that constitutes a production factor used up in the economic process and not energy per se. In the following of the presentation we will sometimes stick to the familiar term of energy, even if strictly speaking it refers to exergy.

Overview of the model

- Discrete time. Time step between *t* and *t+1* is 20 years = capital services lifetime.

- Three productive sectors with profit maximizing representative firms:
  - Nonrenewable energy (NRE) sector using capital services as input,
  - Renewable energy (RE) sector using capital services as input,
  - Final good sector using capital services and total energy (NRE+RE) as inputs.

- NRE and RE sectors are price taking for capital cost and energy price. Unique energy price so energy inputs are fully substitutable.

- Representative household receives the whole macroeconomic income (capital services rents+sectors profits), saves for investment (capital construction in the following period) in priority and consumes what is left. No intertemporal utility maximization so capital cost is constant.

- Following Ayres and Warr (2009), the technological level is formally defined as the efficiency of primary-to-useful exergy conversion in the final good sector. Endogenous but strictly bounded from above.

Income, consumption, and investment

- The whole macroeconomic income is spent on consumption or investment. Investment at *t* depends on the level of capital at *t+1*:

$$C_t + I_t = vK_t + \Pi_t + \Omega_t + \Psi_t, \tag{1}$$

$$I_t = \frac{K_{t+1}}{\lambda}. \tag{2}$$

- 'Capital' is in fact 'labor activated effective capital services':
  - 'Labor activated' : capital services should be understood as the output result of the aggregation (in a production function that we do not explicit) of pure physical capital with routine labor provided by the population.
  - 'Effective' : the capital services output also contain some human capital in the form of skills and eye-hand coordination, to which the recent contribution of information and communication technologies should be added.

- v: constant cost of capital services, $v \equiv (1+\mu)^{t_{length}}/\lambda$, with t_{length}=20 years, μ=3% is the annual real interest rate.

- λ: productivity of the transformation of investments goods into productive capital.

Nonrenewable energy (NRE) sector

- NRE producer maximizes its profit in order to choose the quantity of gross primary NRE production R_t and the level of capital services requirement Z_t. p_t is the energy price, χ_{NRE} is self-consumed fraction. Hence, NRE producer seeks to solve:

$$\max_{X_t, Z_t} \Pi_t = (1 - \chi_{NRE})\, p_t R_t - v Z_t\,, \quad \forall\, t \in \{0, \ldots, T_e\}, \tag{3}$$

- under constraints

$$\sum_{t=1}^{T_e} t_{length} R_t \leq \mathcal{S},\ and \ \lim_{T_e \to +\infty} R_t = 0\,, \forall\, t \in \{0, \ldots, T_e\}, \tag{4}$$

$$Z_t = (R_t * D_t)^{\frac{1}{\theta}}\,, \qquad with\ 0 < \theta < 1\ \ \forall\, t \in \{0, \ldots, T_e\}. \tag{5}$$

- $\mathcal{S}$: Ultimately Recoverable Resource (URR).

- D_t : cost per NRE output unit. $\theta < 1$ means that NRE sector has decreasing returns-to-scale.

- After the injection of (5) into (3), first order condition with respect to R_t yields:

$$R_t = \left[\frac{p_t (1 - \chi_{NRE})\theta}{D_t^{\frac{1}{\theta}} v}\right]^{\frac{\theta}{1-\theta}}, \qquad \forall\, t \in \{0, \ldots, T_e\}. \tag{6}$$

Renewable energy (RE) sector

- RE flow (aggregation of solar radiant energy, geothermal and tidal energies) is suppose so large that it never constrains production. RE producer maximizes its profit in order to choose the quantity of gross primary RE production F_t and the level of capital services requirement G_t. p_t is the energy price, χ_{RE} is self-consumed fraction. Hence, RE producer seeks to solve:

$$\max_{F_t, G_t} \Omega_t = (1 - \chi_{RE})\, p_t F_t - v G_t\,, \quad \forall\, t \in \{0, \dots, T\}, \tag{7}$$

- under constraint

$$G_t = (F_t * B_t)^{\frac{1}{\gamma}}\,, \qquad with\ 0 < \gamma < 1\ \ \forall\, t \in \{0, \dots, T\}. \tag{8}$$

- B_t : cost per RE output unit. $\gamma < 1$ means that RE sector has decreasing returns-to-scale.

- After the injection of (8) into (7), first order condition with respect to F_t yields:

$$F_t = \left[\frac{p_t(1 - \ \chi_{RE})\gamma}{B_t{}^{\frac{1}{\gamma}} v}\right]^{\frac{\gamma}{1-\gamma}}, \qquad \forall\, t \in \{0, \dots, T\}. \tag{9}$$

Final good sector (1/2)

- Representative final good producer receives total available energy :

$$E_t = \begin{cases} R_t(1-\chi_{NRE}) + F_t(1-\chi_{RE}), & \forall\, t \in \{0, \dots, T_e\} \\ F_t(1-\chi_{RE}), & \forall\, t \in \{T_e+1, \dots, T\}. \end{cases} \quad (10)$$

- A_t is the efficiency of primary-to-useful exergy conversion, so final good Y_t (i.e. macroeconomic product, or GDP) comes from the aggregation of useful energy $A_t E_t$ with capital services H_t. We define the dimensionless variables $y_t \equiv \frac{Y_t}{Y_0}$, $a_t \equiv \frac{A_t}{A_0}$, $e_t \equiv \frac{E_t}{E_0}$, and, $h_t \equiv \frac{H_t}{H_0}$, where Y_0, A_0, E_0, and H_0 are given quantities in the reference initial period.

- Hence, the final good producer solves:

$$\max_{E_t, H_t} \Psi_t = Y_t - p_t E_t - v H_t, \qquad \forall\, t \in \{0, \dots, T\} \quad (11)$$

- under constraints,

$$y[a,e,h]_t = (a_t e_t)^{\alpha} {h_t}^{1-\alpha}, \qquad \forall\, t \in \{0, \dots, T\}, \quad (12)$$

$$Y_t = y[a,e,h]_t \, Y_0, \qquad \forall\, t \in \{0, \dots, T\}. \quad (13)$$

  - α: the constant output elasticity of useful energy.

Final good sector (2/2)

- The resolution of this problem implies to combine the first order conditions with respect to E_t and H_t in order to find:

$$H_t = \left[\frac{1-\alpha}{\alpha}\frac{p_t}{v}\right] E_t, \qquad \forall\, t \in \{0, \dots, T\}, \tag{14}$$

- Combining (14) with (12)-(13) in the first order condition with respect to E_t gives (after mathematical arrangements):

$$p_t = \left[\alpha \frac{Y_0}{H_0}\left(\frac{A_t H_0}{A_0 E_0}\right)^{\alpha}\left(\frac{1-\alpha}{\alpha v}\right)^{1-\alpha}\right]^{\frac{1}{\alpha}}, \qquad \forall\, t \in \{0, \dots, T\}. \tag{15}$$

- We define the saving rate of the economy as:

$$S_t = \frac{I_t}{Y_t}, \qquad \forall\, t \in \{0, \dots, T\}. \tag{16}$$

Endogenous technological progress

- The technological level A_t is necessarily bounded from above by a strictly positive constant $\overline{A} < 1$ representing the maximum efficiency of primary-to-useful exergy conversion that the economy will ultimately reach in the future.

$$A_t = \underline{A} + \frac{\overline{A} - \underline{A}}{1 + \exp\left(-\xi_t(t - t_{\Delta A_t\, max})\right)}, \qquad \forall\, t \in \{0, \dots, T\}, \tag{17}$$

- The speed of convergence ξ_t between the initial technological level $\underline{A}$ and its asymptotic value $\overline{A}$ depends on the variation of the knowledge stock of the economy. This knowledge stock depends on the effort deployed in the R&D sector in previous periods, which is a function of the saving rate of the economy. In addition, the more recent the saving rate the higher its influence on ξ_t. Hence, we define the growth rate ξ_t of the technological level as the first order exponential smooth of the saving rate of the economy during the *N* previous periods (where *N* is defined through calibration). With σ as the share of the macroeconomic investment going to R&D, we have:

$$\xi_t = \begin{cases} \sigma S_0 & for\ t = 0 \\ \sigma\left[\left(\frac{2}{N+1}\right)S_{t-1} + \left(1 - \frac{2}{N+1}\right)\xi_{t-1}\right], & \forall\, t \in \{1, \dots, T\}. \end{cases} \tag{18}$$

D_t: cost per nonrenewable energy output unit

- Must necessarily increases with cumulative production because easier-to-exploit resources are used up first before attention turns to deeper and more remote resources.

- Must be influenced by learning processes and R&D.

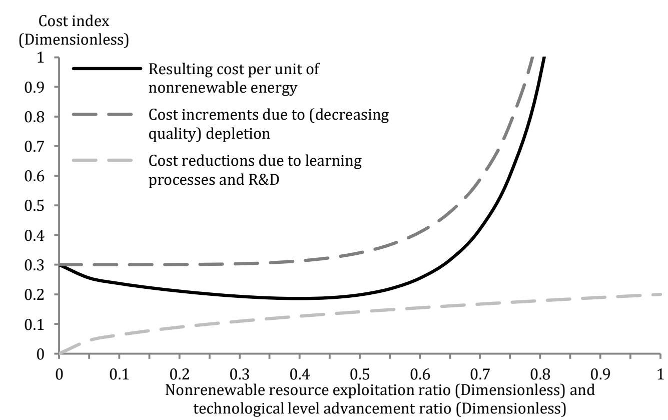
- ϕ_t is the exploited resource ratio : $\phi_t = \frac{t_{length} \sum_{i=0}^{t-1} R_i}{\mathcal{R}} \in [0,1], \quad \forall\, t \in \{0, \dots, T_e\}.$ (19)

- D_0 is the initial cost, $\widetilde{D}$ is the maximum capital cost reduction thanks to learning and R&D processes.

- ω_1 and ω_2 are positive constants determined when calibrating the model on historical global data.

- δ is the rate of quality degradation of the NRE resource.

$$D_t(\phi_t, A_t) = D_0 exp^{\delta {\phi_t}^{\omega_1}} - \widetilde{D}\left(\frac{A_t - \underline{A}}{\overline{A} - \underline{A}}\right)^{\omega_2}, \forall\, t \in \{0, \dots, T_e\}. \quad (20)$$



B_t: cost per renewable energy output unit

- Decreasing function since less capital is necessary to capture the same amount of primary renewable energy over time thanks to learning processes and R&D.

- We postulate that the RE sector is also 'technologically consistent' with the rest of the economy, so that B_t is a function of A_t.

- $\overline{B}$ is the initial cost, $\underline{B}$ is the final cost, $\tau > 0$ is the constant growth rate, $A_{\Delta B_t max}$ is the particular technological level at which the function B_t presents an inflexion point (i.e. the rate of degrowth of B_t is maximum when $A_t = A_{\Delta B_t max}$).

$$B_t(A_t) = \overline{B} - \frac{\overline{B} - \underline{B}}{1 + \exp\left(-\tau\left(A_t - A_{\Delta B_t max}\right)\right)}, \qquad \forall\, t \in \{0, \dots, T\}. \tag{21}$$

- The higher the ratio of technological level gain $\overline{A}/\underline{A}$, the lower the final unitary cost of RE production $\underline{B}$ should be compared to its initial value $\overline{B}$. Hence,

$$\underline{B} = \frac{\overline{B}}{\left(\overline{A}/\underline{A}\right)^{\eta}}, \qquad with\; 0 < \eta < 1 \quad \forall\, t \in \{0, \dots, T\}. \tag{22}$$

EROI of energy sectors

- The saving rate S_t can be decomposed in three parts $S_{H,t}$, $S_{Z,t}$ and $S_{G,t}$:

$$S_t = S_{H,t} + S_{Z,t} + S_{G,t}, \qquad with \;\; S_{H,t} = \frac{H_{t+1}}{\lambda Y_t}, \qquad S_{Z,t} = \frac{Z_{t+1}}{\lambda Y_t}, and \;\; S_{G,t} = \frac{G_{t+1}}{\lambda Y_t}. \tag{23}$$

- This helps to define the EROI (in our model GPR=GER=EROI) of:
  - the NRE sector

$$EROI_{NRE,t} = \frac{R_t}{R_t \chi_{NRE} + S_{Z,t-1} E_{t-1}}. \tag{24}$$

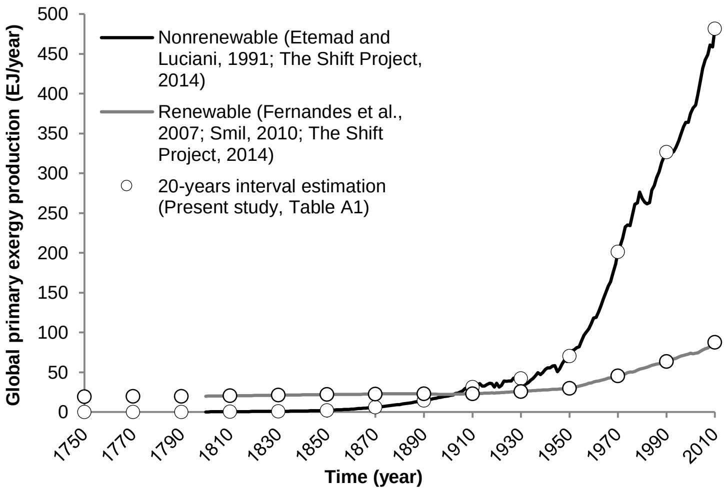
  - the RE sector

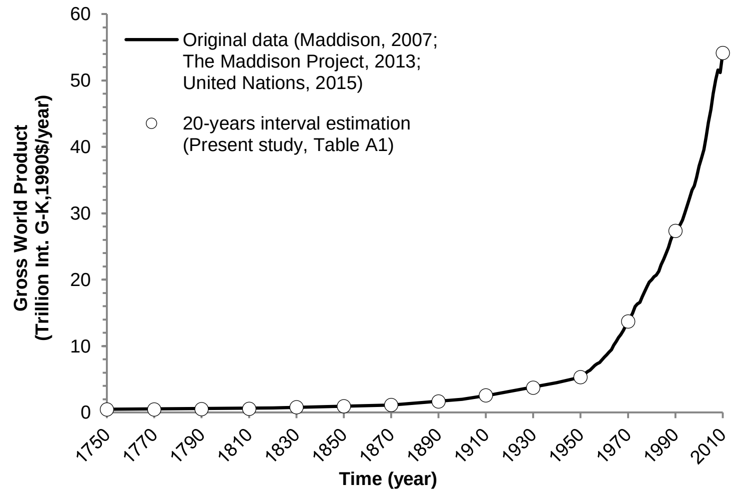
$$EROI_{RE,t} = \frac{F_t}{F_t \chi_{RE} + S_{G,t-1} E_{t-1}}. \tag{25}$$

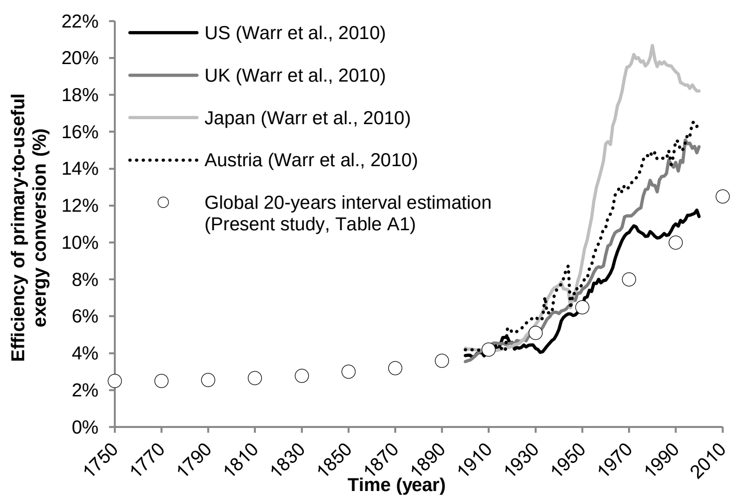
  - the whole energy sector

$$EROI_t = \frac{R_t + F_t}{R_t \chi_{NRE} + F_t \chi_{RE} + (S_{Z,t-1} + S_{G,t-1}) E_{t-1}}. \tag{26}$$

Global historical data: graphs







Global historical data: table

Time period (actual year)	Nonrenewable primary exergy production (EJ/year)	Renewable primary exergy production (EJ/year)	Efficiency of primary-to-useful exergy conversion (dimensionless)	Gross World Product (Billion Int. GK 1990$/year)
0 (1750)	0.00	19.55	0.0250	435
1 (1770)	0.05	19.65	0.0250	465
2 (1790)	0.20	19.85	0.0255	495
3 (1810)	0.55	20.50	0.0265	530
4 (1830)	1.00	21.25	0.0278	765
5 (1850)	2.20	22.05	0.0300	920
6 (1870)	6.00	22.75	0.0320	1115
7 (1890)	14.70	22.95	0.0360	1675
8 (1910)	31.50	23.20	0.0420	2550
9 (1930)	42.50	26.00	0.0510	3720
10 (1950)	70.50	30.00	0.0650	5315
11 (1970)	201.5	45.50	0.0800	13720
12 (1990)	326.5	63.75	0.1000	27350
13 (2010)	481.5	87.50	0.1250	54150

Scenarios

- Two prerogatives:
  - (i) the calibration must remain robust to the different scenarios that are tested,
  - (ii) the scenarios must differ by the least possible number of parameter values.

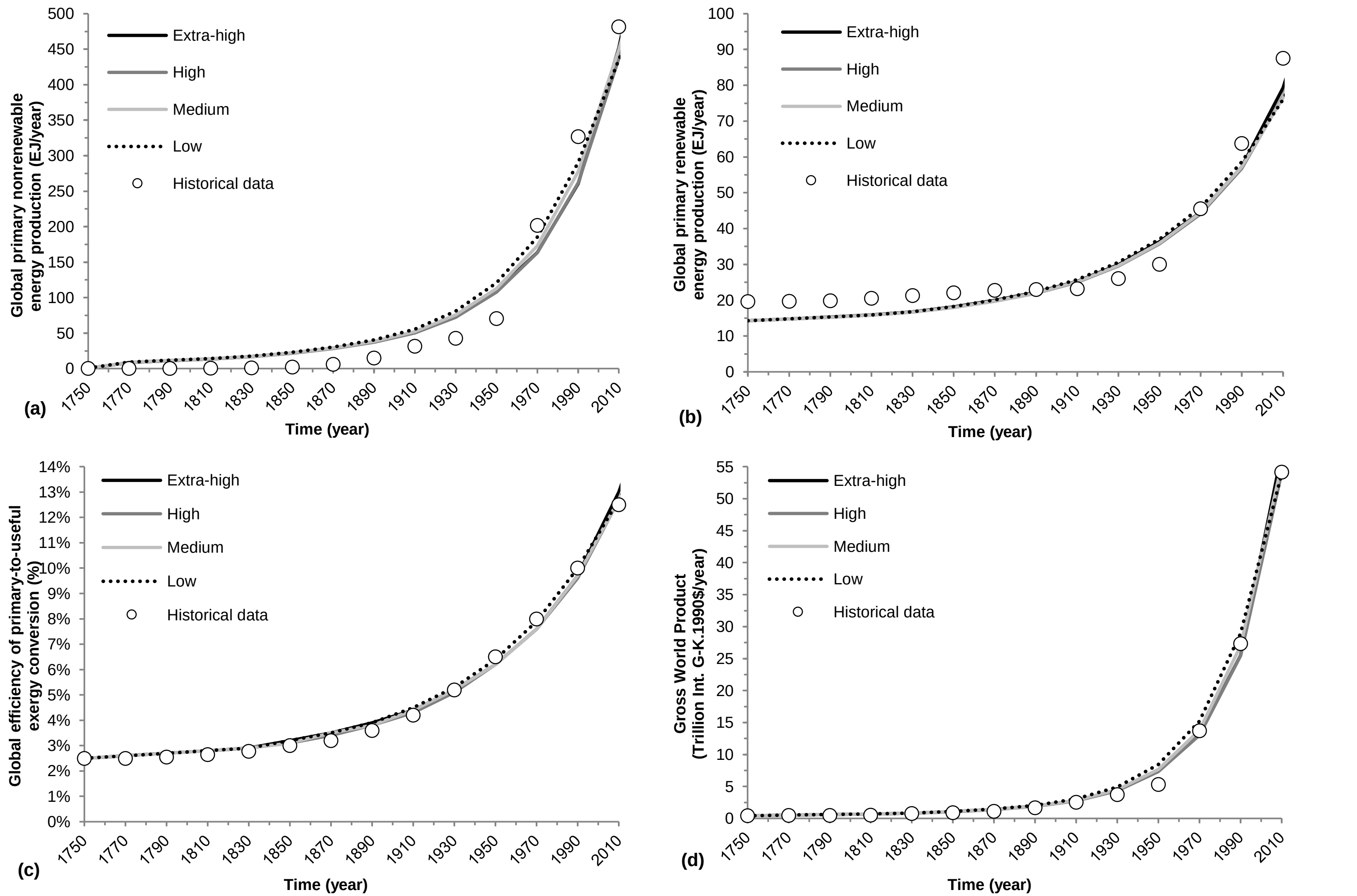
- Logically the main determinant of a given scenario is the ultimate value $\overline{A}$ towards which technological level A_t converges. Hence, after testing values from 0,15 to 0,95 we define four scenarios:

Parameter	Definition (unit)	*Low*	*Medium*	*High*	*Extra-High*
$\overline{A}$	Final technological level of the economy, i.e. final efficiency of primary-to-useful exergy conversion in the final good sector (dmnl).	0.25	0.35	0.45	0.65
$t_{\Delta A_t\, max}$	Time of maximum technological progress (model time period/*actual year*).	13.35 *(2017)*	14.45 *(2039)*	15.15 *(2053)*	16.0 *(2070)*
$\widetilde{D}$	Maximum capital cost reduction per unit of nonrenewable energy thanks to learning processes and R&D (B$/EJ).	6.180	6.295	6.365	6.458

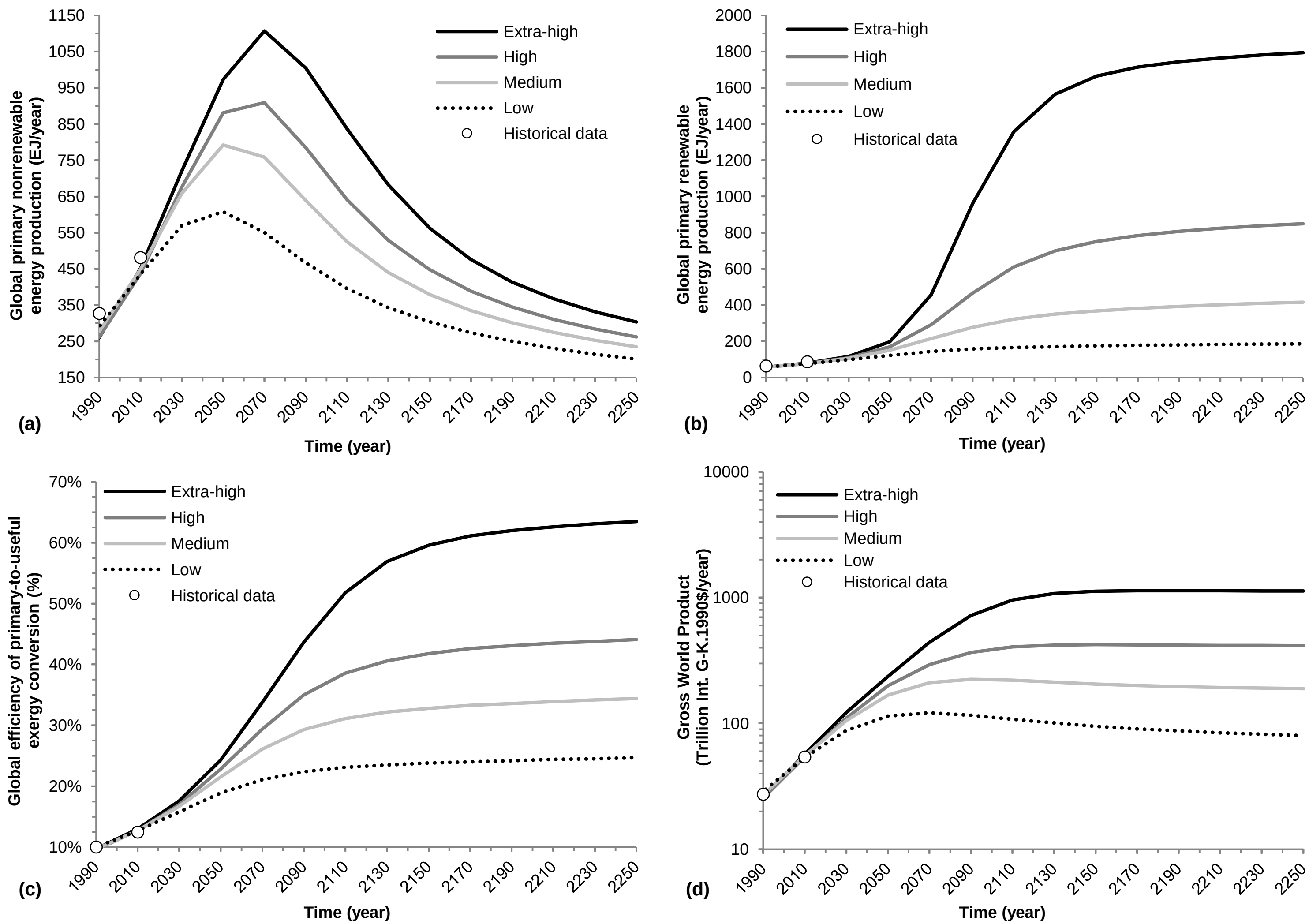
Common parameters

Parameter	Definition (unit)	Value	Units
T	Time horizon of the model.	25	dmnl
t_{length}	Time period length in real years between t and $t+1$.	20	years
λ	Transformation productivity of investment goods.	7.25	dmnl
μ	Annual real interest rate of the economy.	0.03	dmnl
v	Constant capital cost (dmnl), with $v \equiv (1+\mu)^{t_{length}}/\lambda$	0.249	dmnl
α	Share of energy services inputs in the CES final good production function.	0.6	dmnl
σ	Share of the macroeconomic investment going to R&D.	0.9	dmnl
N	Number of time periods used to smooth the saving rate of the economy in ξ_t.	4.0	dmnl
$\underline{A}, A_0$	Initial technological level.	0.025	dmnl
$\mathcal{R}$	Ultimately Recoverable Resource of nonrenewable energy.	177,500	EJ
D_0	Initial unitary capital cost of NRE production.	6.35	B$/EJ
δ	Rate of quality degradation of the NRE resource.	0.225	dmnl
ω_1	Power exponent of the ratio of exploited resource $\phi_{NRE,t}$ in the cost increasing part.	1.05	dmnl
ω_2	Power exponent of the ratio of exploited resource $\phi_{NRE,t}$ in the cost decreasing part.	0.05	dmnl
$\overline{B}$	Initial production cost per unit of renewable energy output.	1.35	B$/EJ
τ	Growth rate of B_t towards B_2.	15	dmnl
η	Constant used to link the final capital cost of RE production B_2 to its initial value B_1, and to the technological level gain ratio $\overline{A}/\underline{A}$.	0.25	dmnl
θ	Returns to scale in the NRE sector.	0.5	dmnl
γ	Returns to scale in the RE sector.	0.5	dmnl
χ_{NRE}	Share of gross primary energy production self-consumed by the NRE sector.	0.05	dmnl
χ_{RE}	Share of gross primary energy production self-consumed by the RE sector.	0.05	dmnl
H_0	Initial (1750) capital in the final sector.	745	B$
Y_0	Initial (1750) Gross World Product.	435	B$/yr
S_0	Initial (1750) saving rate of the economy.	0.5	dmnl

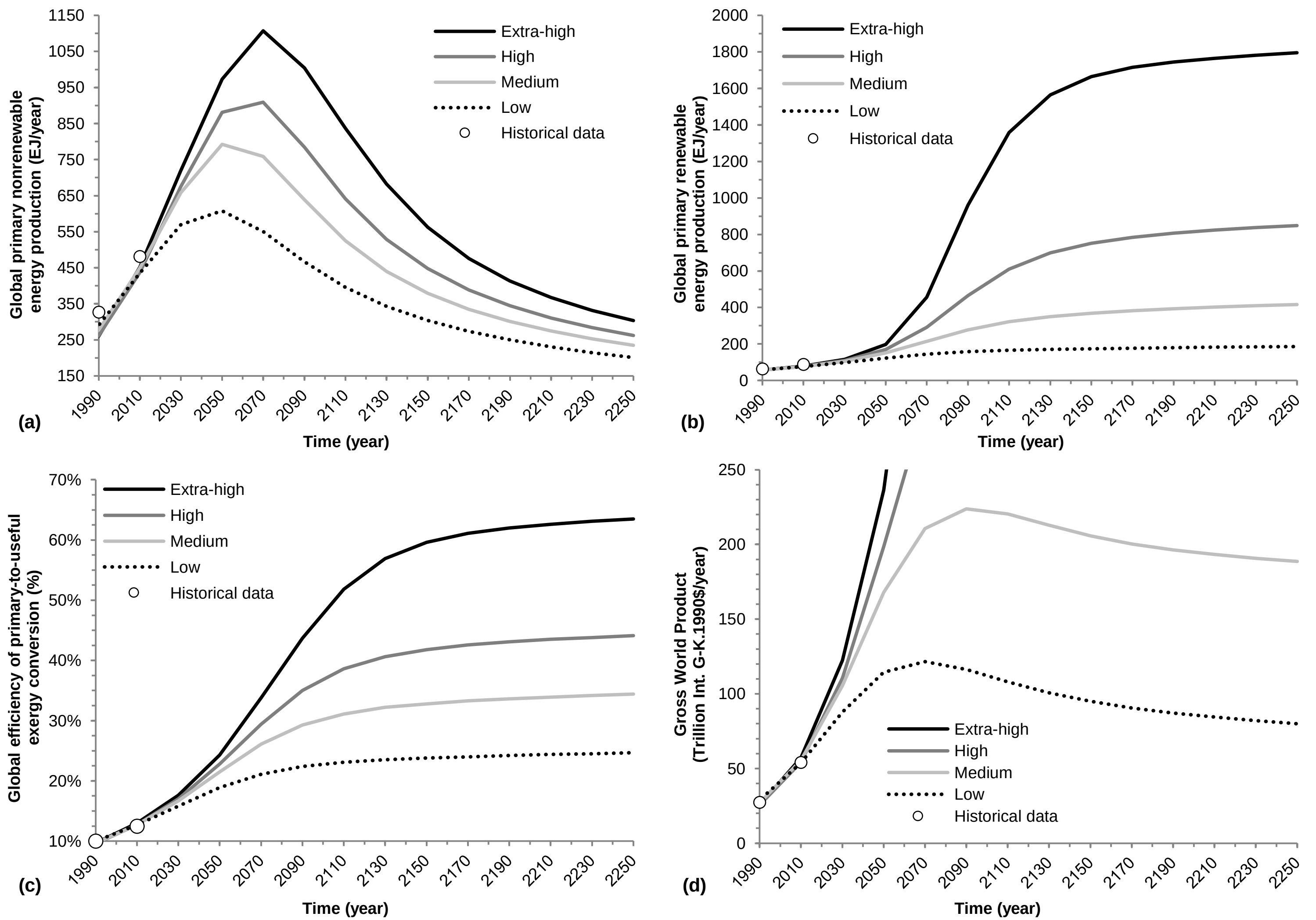
Calibration results



Prospective results (1/2)



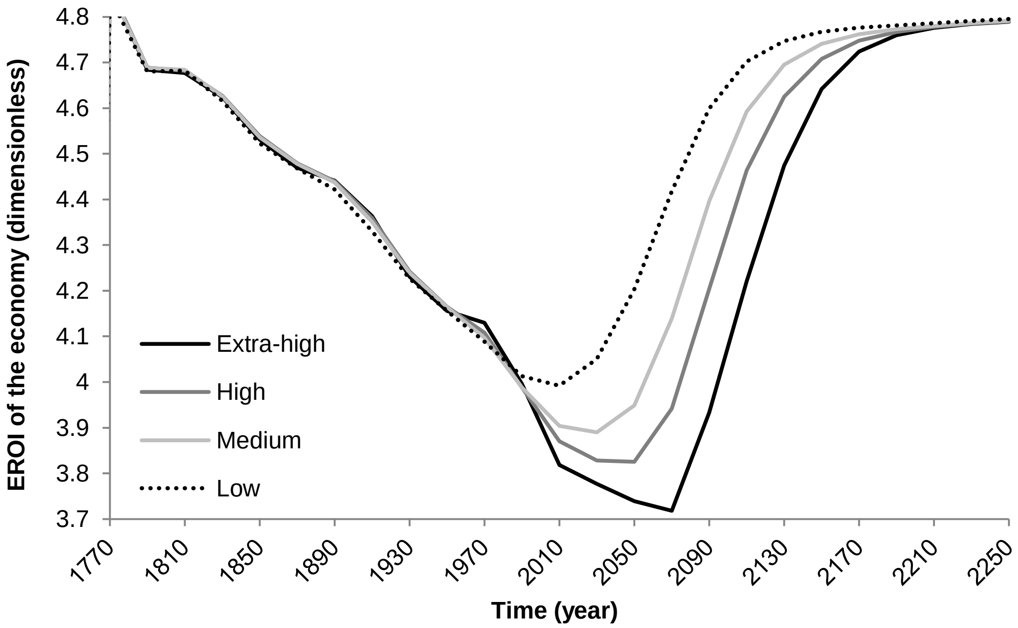
Prospective results (2/2)



EROI (strange) results (1/3)

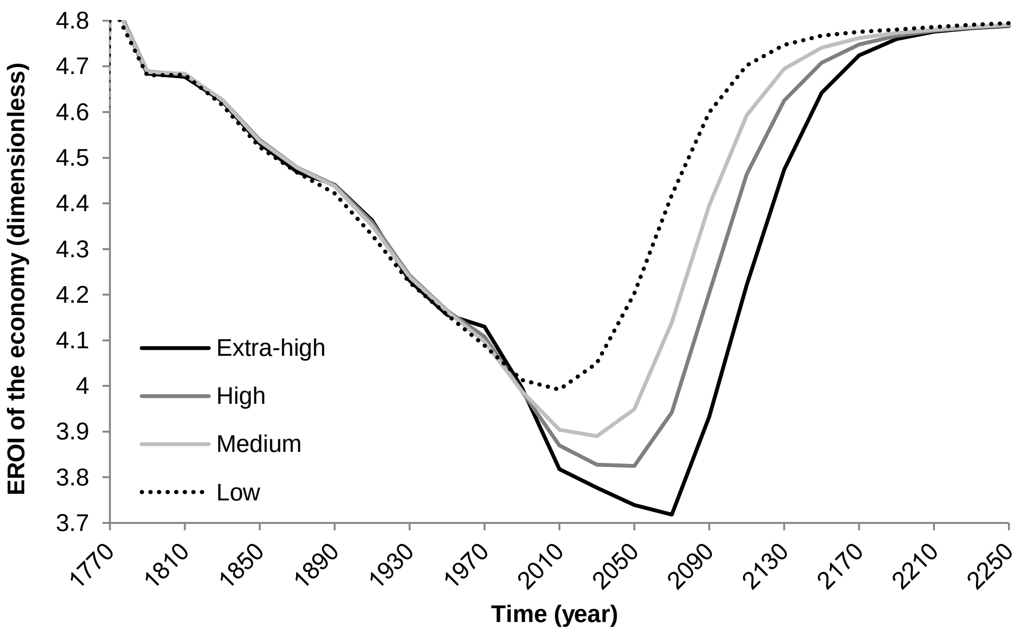
- For a given scenario EROIs of nonrenewable and renewable energy are the same…?!

- This is because in our model:
  - (i) NRE and RE productions are perfect substitutes since they are sold at the same price,
  - (ii) Both productions have the same level of self-consumption since we have assumed $\chi_{NRE} = \chi_{RE}$ in the absence of reliable data to choose otherwise.



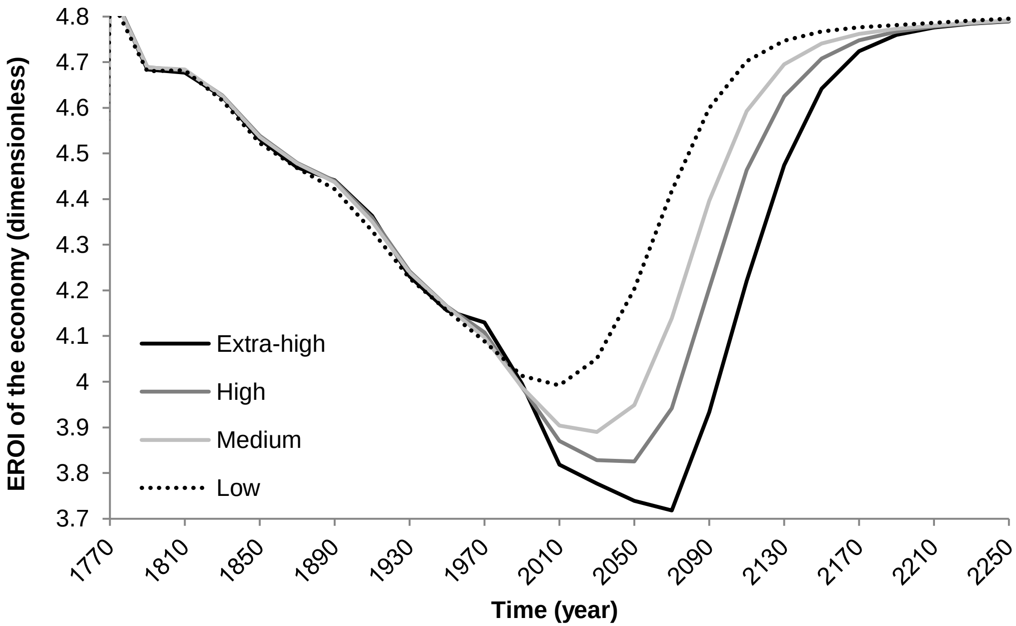
EROI (strange) results (2/3)

- EROIs of the economy are ‘low’ and do not vary much (always between 3,7 and 4,8): ‘capital services’ include physical capital, routine labor and human capital. As a consequence, the EROIs of the model represent full life cycle energy ratios of primary energy production with extended input boundary and are thus necessarily quite low compared to conventional values found in the literature.



EROI (strange) results (3/3)

- EROI pattern is U-shaped: once the technological level A_t takes off, it cost less and less primary energy to produce the final output good Y_t, in other word the energy embodied in capital services decreases.



Main results

- The final *level* of renewable energy production primarily determines the final GWP *level*. But more interestingly the combined dynamics of the nonrenewable and renewable energy productions, i.e. the time path of the energy transition, determine the more or less smoothed course of the GWP.

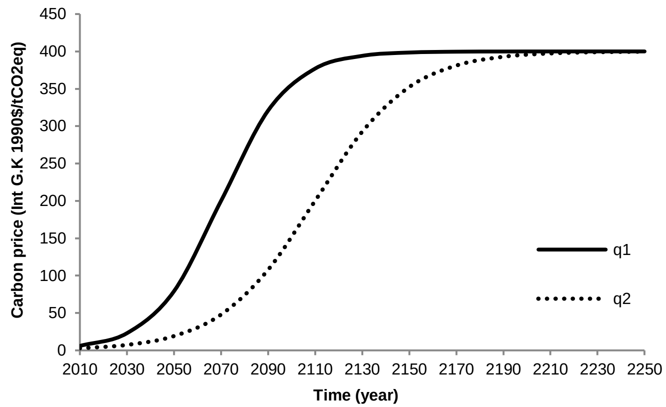
- If the nonrenewable energy peak is too high compared to the final combination of renewable production and technological level (as in the *Low* and *Medium* scenarios), the GWP can peak and then decreases before stabilizing.

- The negative GWP pattern (overshoot before degrowth) of the *Low* and *Medium* scenarios *do not* arise *solely* because their final technological levels $\overline{A}$ (respectively at 0.25 and 0.35) are too low in absolute terms. Rather, the negative impact of the energy transition on economic growth is due in our model to the final value of the technological level *and* the way this variable influences the production cost of the two energy forms (cf. 'technological consistency' between sectors).

=> In such case, is it possible to avoid the energy lock-in and smooth the GWP dynamics?

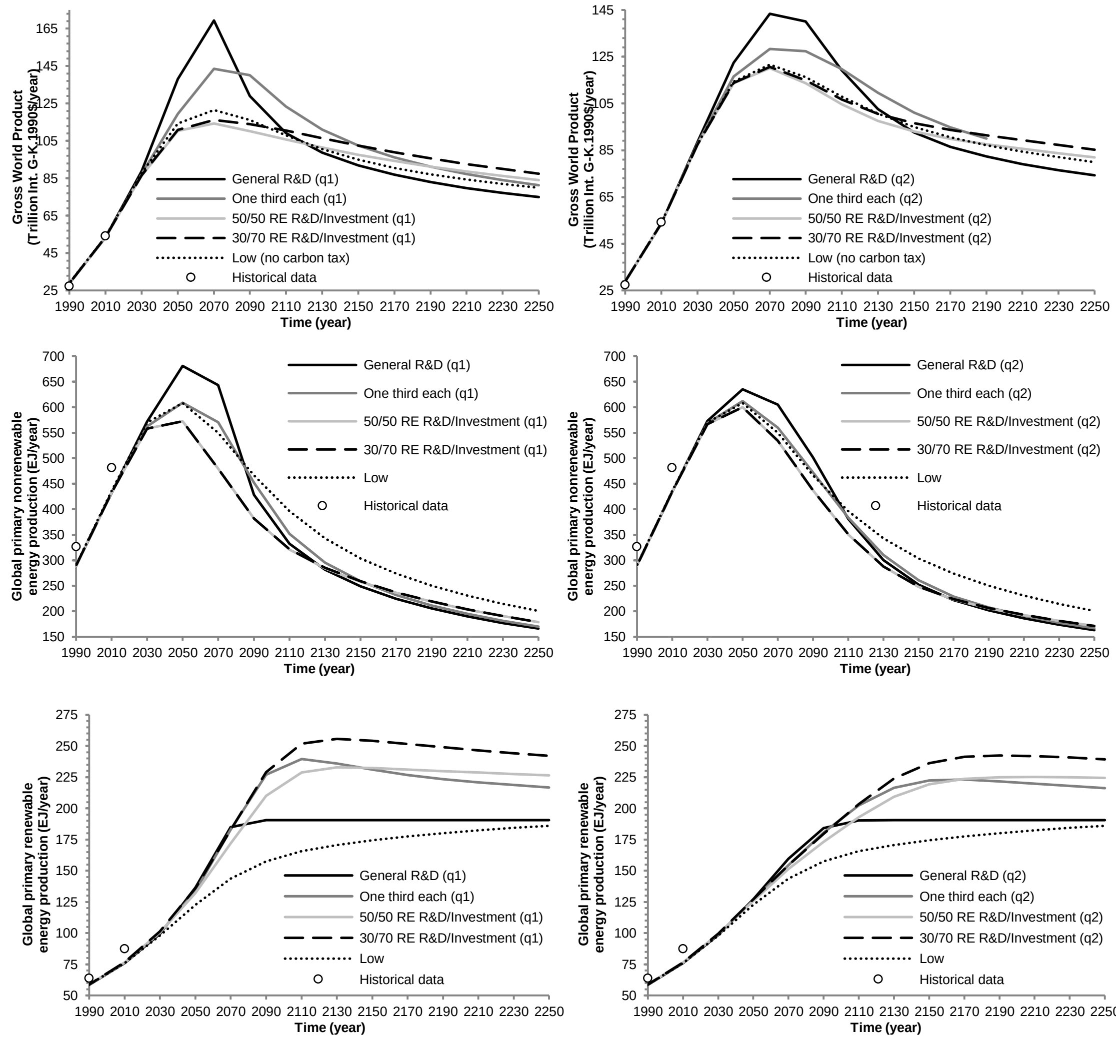
Implementing a carbon price in the worst case (i.e. *Low*) scenario to smooth the GWP dynamics

- We test two carbon price profiles:



- And four scenarios of carbon price income recycling:
  - *General R&D* scenario: the totality of the carbon tax income is allocated to the general R&D sector.
  - *One third each* scenario: the income from the carbon tax is split equally between the general R&D sector, the specific R&D of the RE sector and the direct capital investment in the RE sector.
  - *50/50 RE R&D/Investment* scenario: the carbon tax income is split equally between the specific R&D of the RE sector and the direct capital investment in the RE sector, there is no additional subsidy to the general R&D sector.
  - *30/70 RE R&D/Investment* scenario: 30% of the income from the carbon tax goes to the specific R&D of the RE sector, whereas 70% is used as a direct capital investment in the RE sector. In this scenario also there is no additional subsidy to the general R&D sector.

Results of carbon price simulations



Conclusion

- First simple theoretical model able to reproduce long-term global historical trends for nonrenewable and renewable primary energy supply, aggregated technological progress, and GWP.

- For an economy in which energy-producing and energy-using sectors are technologically consistent, and in the absence of any correction of the price system, the final efficiency of primary-to-useful exergy conversion of the economy must be sufficiently high (above 0.35) in order to have a smooth transition between nonrenewable and renewable energy productions that does not negatively impact economic growth.

- Avoiding such lock-in behavior of the economic system can be (at least partially) done through the implementation of a carbon price, which has also the benefit of decreasing GHG emissions from fossil fuels use and hence mitigates climate change.

- Research perspectives: Including food production, population, land-use change and climate change to account for multiples feedbacks in the economy-energy-climate system => in progress in a pure biophysical model (no price, no representative agent, only energy and carbon flows).