Climate policy and endogenous economic growth with poor substitution possibilities

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Abstract

We study the implications of climate policy in a world where fossil and renewable energy supply is bounded, strict thermodynamic limits to substituting energy apply and economic growth is endogenous through increasing product varieties. We show that for constant energy intensity of new products, economic growth rates are sensitive to the level of energy prices and growth rates become negative if energy prices increase at a constant rate. When energy intensity of new products declines at a constant rate, energy use can be decoupled from economic growth. We model climate policy effects on the economy via three channels: (1) mitigating climate change increases the price of energy by switching from cheap fossil to more expensive renewable energy; (2) global warming shifts the energy intensity of the economy through changes in demand for cooling/heating; (3) global warming affects total factor productivity. We show that (1) and (2) can influence the level of GDP of the economy and temporarily affect the growth rate of the economy; only channel (3) can affect growth rates in the long-run. Calibrating our model to key macroeconomic data, we find that conservative estimates on climate damages imply reductions of long-run growth rates by 12%. With respect to social welfare, positive growth effects of climate policy dominate reductions in consumption levels through higher energy prices for our base calibration. This dominance is, however, very sensitive to normative parameters as well as the estimated impacts of mitigation on energy prices and TFP.

Key words: global warming; exhaustible resources; renewable energy; product variety; thermodynamic laws

JEL codes: O44, Q54, Q55, Q49, O31

Once one starts to think about economic growth, it is hard to think about anything else.
Robert E. Lucas, 1988

1 Introduction

This paper addresses two questions of environmental economics and growth. The first – and older – question is concerned with the possibility for de-coupling economic growth from energy use. The second – more recent – question is related to the growth implications of climate change and climate policy that affect energy use, among others.

The question of sustained economic growth and limited or exhaustible resources was intensively studies in the wake of the oil crisis in the 1970s. Based on a quantitative Malthusian model of the global economy, the Club of Rome (Meadows et al., 1972) warned that depletion of natural resources and increasing environmental pollution will lead to a collapse of the global economy. Using a neoclassical growth model, Dasgupta and Heal (1974) showed that the role of the elasticity of substitution between natural resources and capital is decisive for positive long-term growth with exhaustible or limited natural resources. When the elasticity of substitution exceeds unity, finite resources can be substituted by reproducible capital and decoupling of economic growth and resource use is possible. If the elasticity of substitution is below one, long-term consumption will converge to zero as natural resources get exhausted. Stiglitz (1974) and Solow (1974) studied the particular case of unity elasticity. They showed that a constant consumption path can be maintained for a sufficiently high rate of technological progress or a sufficiently low income share to natural resources.

These works proved that decoupling of natural resource use from economic growth is possible if either reproducible capital is a substitute to natural resources, or resource efficiency grows sufficiently large. Both conditions, however, likely violate crucial thermodynamic laws when applied to the use of energy as an input for specific goods or services (Ockwell, 2008; Ayres, 1998). Consider, e.g. electricity production. The first law of thermodynamics implies that the energy contained in electricity cannot exceed the energy used for creating electricity – be it the energy content of the fossil or nuclear fuel or the energy content of the influx of solar radiation. The ratio between the energy contained in electricity and the energy contained in the input is also denoted as conversion efficiency. Technological progress and application of more capital-intensive technologies can increase this conversion efficiency. The first law of thermodynamics implies that conversion efficiency cannot exceed one. Hence, increased capital use and technological progress can ensure sustained increases in electricity production when the energy contained in inputs is bounded.

This line of argumentation can be expanded to various machines and services that create (physical) work. Cullen and Allwood (2010) provide an overview on the theoretical energy efficiency limits for various devices like lightning devices, engines for creating motion, combustion devices for heat etc. While there exists a large potential of energy efficiency increases – these increases are strictly bounded level effects and cannot help decoupling energy input from physical work. As creation of consumption goods and services is an entropy decreasing process which requires physical work, the limits to substitutability and energy efficiency increases apply as well (Daly, 1987). If all energy were exhaustible, positive consumption would therefore not be conceivable in the long run.

While renewable energy could ensure a positive level of consumption, it could not provide an alternative base for sustained economic growth. Current global energy consumption is roughly 0.01% of the total incoming solar energy (see Tab. 2), but it is by no means infinite. Historical growth rates of energy use have decreased to 1.6% for the last two decades (Tab. 1). Even if growth of aggregate energy use reduced to one percent, total energy demand would exceed incoming solar energy fluxes within the next millennium. While 1,000 years seem to be large, they are relatively modest compared to major technological breakthroughs of human history like the Neolithic revolution (10,000 years ago), the invention of writing systems (5400 years ago), the paper (2100 years ago), the printing press (550 years ago) or electricity (400 years ago). The historic perspective of current demand growth and its comparison to the past and future extrapolation is illustrated in Fig. 1.

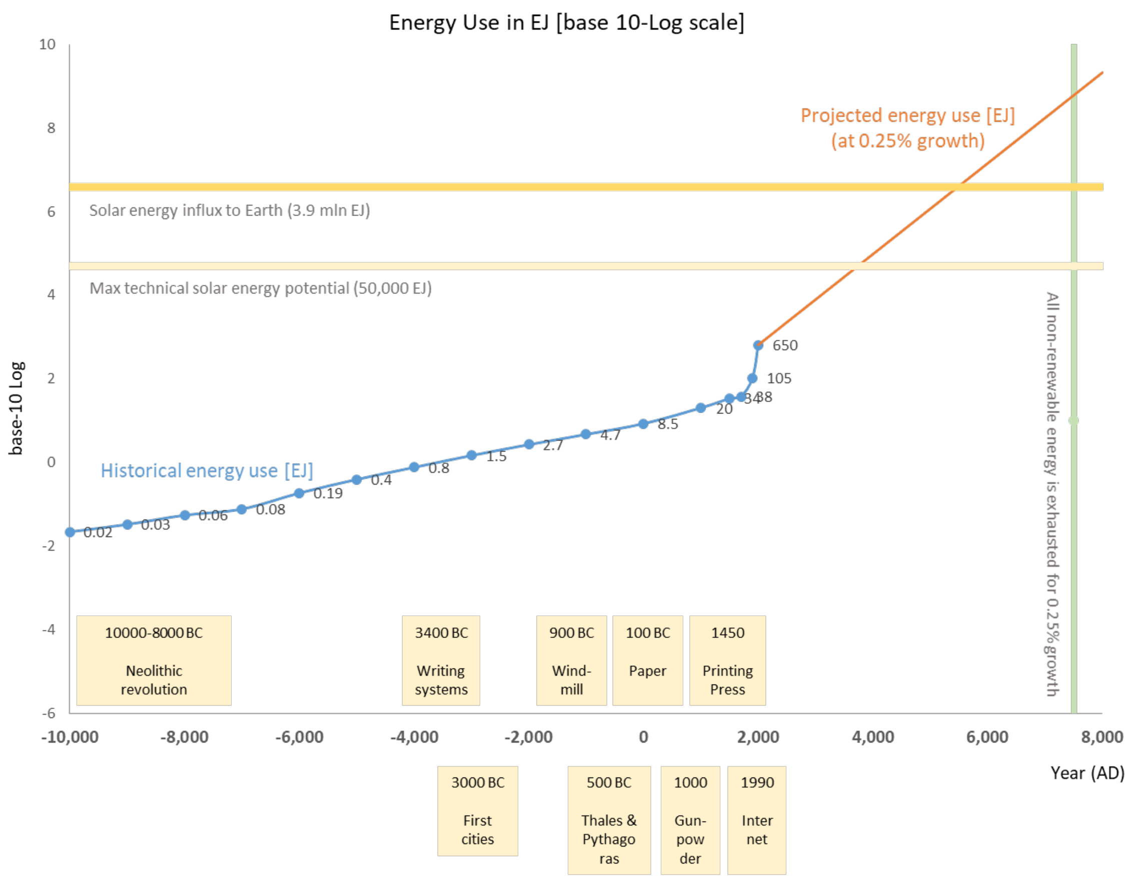
Table 1: Average annual growth rates of energy and GDP.

	Average growth rates in % p.a. (until 2008)		
	Energy	Energy per capita	GDP per capita
Since 1820	1.50	0.58	1.24
Since 1900	2.18	0.83	1.69
Since 1970	1.90	0.35	1.93
Since 1990	1.61	0.30	2.25

Sources: Smil (2010) for energy data and MADDISON-2010 database for GDP.

Without absolute decoupling of energy from economic growth, energy demand grows exponentially and will at some stage hit physical boundaries. This also applies to other types of energy besides solar: fossil energy, geothermal energy or nuclear energy seem to plentiful with respect to current energy consumption – with exponential growth, they are all scarce resources. Tab. 2 estimates the year when energy demand reaches renewable energy supply or when non-renewable resources are completely exhausted for various assumptions on energy demand growth rates. The table depicts physical availabilities of energy which provide an physical upper bound of energy sources. The technical and economic potential is usually several orders of magnitudes lower (Moriarty and Honnery, 2012) but also subject to large uncertainties. Nevertheless, the key message of focusing on the maximum physical energy potential is marked: Without absolute decoupling, long-term wealth will be constrained by the amount of incoming solar energy.

Figure 1: Energy use and key innovations over large time scales.



Source: Own illustration based on historic energy data from Fischer-Kowalski et al. (2014) and Tab. 2 with projections for 0.25% growth rates of energy use.

Table 2: Physical potential and duration of various energy sources.

Energy type	Maximum availability [EJ]	Consumption in 2015 [% max. availability]	Years until max. achieved / exhausted with demand growth rate, p.a. [%]				
			2.00	1.50	1.00	0.50	0.25
Renewable energy							
Max technical solar energy potential	49,837	1.08	226	302	452	905	1,810
Solar energy influx to Earth	3,900,000	0.014	444	592	888	1,777	3,554
Exhaustible energy							
Fossil (reserves and resources)	580,642	0.093	156	189	246	371	522
All Carbon in Earth crust	168,000,000	0.000321	437	564	805	1,472	2,668
All Uranium in Earth crust	6.0E+12	9.0E-09	961	1,262	1,853	3,567	6,856
All Thorium in Earth crust	2.1E+13	2.5E-09	1,024	1,347	1,979	3,820	7,363
Geothermal energy content of Earth	1.0E+13	5.4E-09	987	1,296	1,904	3,669	7,060
All exhaustible combined	3.7E+13	1.4E-09	1,052	1,383	2,035	3,930	7,584

Notes: For renewable energy: Duration until maximum availability of energy is reached assuming constant demand growth rate; for exhaustible energy: Duration until energy resources are depleted assuming constant demand growth rate. *Sources:* Solar energy – Moriarty and Honnery (2012); UNDEP (2000); Fossil energy refers reserves and estimated resources – BGR (2017); Geothermal energy – Rybach (2007). Energy from exhaustible resources Carbon, Uranium and Thorium in Earth crust are estimated from density estimates in Lide (2012) and multiplied with the specific energy densities. Other renewable energy sources (wind, ocean, hydro and biomass) are several orders of magnitude lower than solar energy (Moriarty and Honnery, 2012).

Tab. 2 serves as an illustrative calculation to motivate our paper. Our aim is not to predict the date when physical energy supply becomes a binding constraint to economic value creation. Rather, we aim for two objectives: First, we want to explore the conditions for achieving a decoupling of economic production from energy use which is consistent with thermodynamic laws. Hence, we do not want to assume that energy can be substituted by capital and that energy efficiency for specific machines or products can be increased without bounds. Second, we want to analyze the role of climate policy which implies an early shift from (exhaustible) fossil resources to (partly renewable) fossil-free energy sources.

A key weakness of neoclassical models of economic growth is the assumption of exogenous increases in labor (or energy) productivity. Thus, long-term growth in these models is exogenous. Bretschger (1998) and Bretschger (2005) discuss the role of substitutability growth and resource use in endogneous growth models. A key conclusion from the endogeneous growth models with natural resources is that structural change from resource-intensive sectors to resource-efficient sectors can help decoupling economic growth from resource use (Bretschger and Smulders, 2012).

In this paper, we extend the Romer (1990) model of expanding product variety by energy inputs in the intermediate production. While Van Zon and Yetkiner (2003) develop a similar modification of the Romer model, they consider an elasticity of substitution between capital and energy of unity. Based on our thermodynamic argument made before, we explore the implications for growth when energy cannot be substituted by capital. For illustrative purposes, we model energy as a perfect complement to capital.[1] Moreover, we put a particular emphasize

[1]This assumption disregards any increases in energy efficiency for a specific product or machine. Using a more general function like a constant elasticity of substitution function would allow for a more flexible modeling of substitution possibilities. As the elasticity of substitution has to be below one, there is only a limited increase in energy efficiency possible until an upper bound has been reached. This more general modeling framework increases analyti-

on the growth implications of climate change and climate policy.

In our endogenous growth model, results depend crucially on the energy intensity of new invented products. When energy intensity of new products does not decline, economic growth rates are sensitive to the level of energy prices. Growth rates become negative if energy prices increase at a constant rate, as it would be for an exhaustible resource. As energy supply in the very long run is constrained by inflowing solar radiation energy, economic growth will cease and constant GDP levels will prevail.

When energy intensity of new products declines at a constant rate, energy use can be decoupled from economic growth. On a product (or machine) base, energy is always a perfect complement and no increases in energy efficiency are possible. However, invention of new products with (continuously) lower energy intensity is possible. This type of structural change is similar as in Van Zon and Yetkiner (2003) and Bretschger and Smulders (2012). If new products become less energy and material intensive, e.g. because they depend more and more on ideas, design, art or intellectual works, aggregate energy intensity of the economy decreases. If there exists no lower bound for the energy intensity of new inventions, sustained economic growth is possible with any positive level of energy consumption – aggregate energy depends then on the level of energy prices which have to be constant for convergence to a balanced growth path.

Besides studying long-run growth effects of energy prices and energy availability, we analyze the impacts of climate change and climate policy on GDP levels and long-run growth levels through three channels: (1) mitigating climate change increases the price of energy by switching from cheap fossil to more expensive renewable energy; (2) global warming shifts the energy intensity of the economy through changes in demand for cooling/heating; (3) global warming affects total factor productivity. We show that (1) and (2) can influence the level of GDP of the economy and, in some cases, affect temporarily the growth rate of the economy; only channel (3) can affect growth rates in the long-run. Our work complement the few existing studies that modeled climate change in endogenous growth models (e.g. Dietz and Stern, 2015; Piontek et al., 2018). These works only considered the TFP channel of climate damages in simplified endogenous growth models and neglected impacts of higher energy expenditures or changes in energy intensity on growth rates.

2 The Romer model with energy

We extend the endogenous growth model with expanding product variety (Romer, 1990; Grossman and Helpman, 1991) by explicitly considering energy as an essential input.

cal complexity but has not implications for the growth dynamics of the model because energy efficiency increases are bounded.

2.1 Output sector

Output of the representative firm is given by

$$Y = AL^{1-\alpha}\int_0^N Z_j^\alpha dj \tag{1}$$

with A a parameter on the overall level of productivity, L the (exogenous) labor, Z_j the j-th intermediate composite, N the number of varieties and $\alpha < 1$. Contrary to conventional endogenous growth theory, we consider Z_j to be a composite of the original intermediate X_j and energy that is necessary for the use or employment of Z_j, E_j. We assume for simplicity that all products are used at their thermodynamic efficiency limit and that energy is a perfect complement to X_j. Hence, using X_j requires $\varepsilon_j X_j$ amount of energy; if less energy is used, Z_j decreases linearly in energy input. We can therefore describe Z_j by the Leontief production function

$$Z_j = \min\{E_j/\varepsilon_j, X_j\} \tag{2}$$

Profits of the representative firm are

$$\pi = Y - wL - \int_0^N P_j X_j + QE_j dj \tag{3}$$

$$= Y - wL - QE - \int_0^N P_j X_j dj \tag{4}$$

with w the wage, P_j the price for the j-th intermediate good, Q the price of energy and $E = \int_0^N E_j dj$ aggregate energy use. Optimal labor input is determined by

$$w = \frac{\partial Y}{\partial L} = (1-\alpha)Y/L \tag{5}$$

With the Leontief production function, the optimal use of energy E_j is directly related to X_j, such that $E_j = \varepsilon_j X_j$. Therefore, the first-order condition for energy demand follows from maximizing $\pi = Y - wL - \int_0^N (P_j + \varepsilon_j Q) X_j dj$,

$$X_j = \left(\frac{A\alpha}{P_j + \varepsilon_j Q}\right)^{1/(1-\alpha)} L \tag{6}$$

2.2 Research firms

Researchers are monopolist of each invented blueprint j and set prices $P_j(s)$ at time s to maximize the net-present value of profits:

$$\max_{P_j(t)} V_j(t) = \max_{P_j(t)} \int_t^\infty \pi_j(s) e^{-\int_t^s r(u)du} ds \tag{7}$$

subject to the demand functions (6), with instantaneous profits $\pi_j(s) = (P_j(s) - 1)X_j(s)$, (possible changing) interest rate $r(u)$ and by assuming production costs that are normalized to one. The optimization problem is a static one as there are no intertemporal constraints; we therefore omit the time variable s when explicitly stating it is not necessary. Monopoly profits are maximized if research firms price the intermediate good at

$$P_j = \frac{1 + (1-\alpha)\varepsilon_j Q}{\alpha} \tag{8}$$

with the resulting demand for intermediates according to

$$X_j = L\left(\frac{A\alpha^2}{\varepsilon_j Q + 1}\right)^{\frac{1}{1-\alpha}} \tag{9}$$

Instantaneous profits in the research sector are then

$$\pi_j = (1-\alpha)\alpha A L\left(\frac{A\alpha^2}{\varepsilon_j Q + 1}\right)^{\frac{\alpha}{1-\alpha}} \tag{10}$$

2.3 Households

Households maximize intertemporal utility over per-capita consumption with the iso-elastic utility function $u(c) = \frac{c^{1-\theta}}{1-\theta}$, a pure time preference rate ρ. The budget equation for consumption is $C = wL + rK - dK/dt$ with K denoting assets. Optimal saving dK/dt is determined by the Euler equation $r = \rho + \theta g_c$ with $g_c = \dot{c}/c$.

3 Endogenous growth with homogeneous energy intensity

To better understand the role of energy and energy prices for growth, we first focus on the case of homogeneous and constant energy intensity and energy prices, thus $\varepsilon_j = \varepsilon$ and exogeneously given. In the standard model of expanding product variety, research firms can freely enter the innovation sector by paying the R&D cost η. Basic arbitrage requires therefore that $\eta = V_j(t)$. Taking the time-derivative of (7), we get $r(t) = \pi_j(t)/V_j(t) + \dot{V}_j(t)/V_j(t)$ with $\dot{V}_j(t) = \dot{\eta} = 0$. For a constant energy price Q, $\pi_j(t) = \pi_j$ according to (10), we can solve for r

$$r = \pi_j/\eta = \frac{(1-\alpha)\alpha A L}{\eta}\left(\frac{A\alpha^2}{\varepsilon Q + 1}\right)^{\frac{\alpha}{1-\alpha}} \tag{11}$$

As total assets, K, equal the market value of all research firms, $K(t) = \int_0^{N(t)} V_j(t)dj = \eta N(t)$

and $\dot{K} = \eta \dot{N}$.

3.1 Growth and aggregate variables

The growth rate of consumption g_c is determined by the Euler equation and, thus the interest rate from (11):

$$g_c = \gamma = \frac{1}{\theta}\left[\frac{(1-\alpha)\alpha AL}{\eta}\left(\frac{A\alpha^2}{\varepsilon Q+1}\right)^{\frac{\alpha}{1-\alpha}} - \rho\right] \tag{12}$$

For $\varepsilon Q = 0$, the growth rate takes the usual form as in the standard model of expanding product variety. We can now directly see the impact of energy costs and energy intensity on growth:

Corollary 1. *The higher the energy price Q or the higher the energy intensity ε of the economy, the lower will be the growth rate of the economy.*

The basic intuition behind this result is that profits of innovative firms in (10) are reduced if energy prices are high. This reduces the incentive to innovate by inventing a new product. The expansion of product variety which drives economic growth will therefore be slower.

As the demand for all intermediate goods is equal, aggregate demand for X and aggregate values for output and energy are:

$$X = NX_j = A^{1/(1-\alpha)}\alpha^{2/(1-\alpha)}(1+\varepsilon Q)^{-1/(1-\alpha)}LN \tag{13}$$

$$\begin{aligned} Y &= AL^{1-\alpha}X^{\alpha}N^{1-\alpha} = A^{1/(1-\alpha)}\alpha^{2\alpha/(1-\alpha)}(1+\varepsilon Q)^{-\alpha/(1-\alpha)}LN \\ &= X\alpha^{-2}(1+\varepsilon Q) \end{aligned} \tag{14}$$

$$\begin{aligned} E &= NE_j = N\varepsilon X_j = \varepsilon X = \varepsilon A^{1/(1-\alpha)}\alpha^{\alpha/(1-\alpha)}(1+\varepsilon Q)^{-1/(1-\alpha)}LN \\ &= \frac{\varepsilon\alpha^2}{1+\varepsilon Q}Y \end{aligned} \tag{15}$$

with $\omega := EQ/Y$ the energy expenditure share of the economy. In particular, N, Y, E, c and X grow all at the same rate γ. As energy is proportional to output Y and grows also at the same rate, there is no de-coupling of energy and GDP *growth* possible. Contrary, higher energy prices reduce growth of energy demand due to lower economic growth. A constant or declining energy demand can therefore only be achieved with a 'degrowth' policy that lowers the overall economic growth rate.

Contrary to growth, higher energy prices reduce energy and GDP *levels* through (14) and (15).

Corollary 2. *(i) The elasticity of energy and output to energy prices are*

$$\varepsilon_{E,Q} = -\frac{1}{1-\alpha}\frac{\omega}{\alpha^2} \qquad\qquad \varepsilon_{Y,Q} = -\frac{\alpha}{1-\alpha}\frac{\omega}{\alpha^2} = -\frac{1}{1-\alpha}\frac{\omega}{\alpha} \tag{16}$$

with $\omega := QE/Y$ the energy expenditure share of the economy and $\omega\alpha^{-2} < 1$. (ii) The elasticity with respect to the energy intensity ε equals the elasticity with respect to energy prices. (iii) The elasticity of total output to A is

$$\varepsilon_{Y,A} = \frac{1}{1-\alpha} \tag{17}$$

Proof. (i) Take the log of (15) and (14). The elasticities are $\varepsilon_{E,Q} := \frac{\partial \ln(E)}{\partial Q} Q = -\frac{1}{1-\alpha}\frac{\varepsilon Q}{1+\varepsilon Q}$ and $\varepsilon_{Y,Q} = -\frac{\alpha}{1-\alpha}\frac{\varepsilon Q}{1+\varepsilon Q}$. With $\omega := QE/Y$, we can re-arrange (15) and obtain $\varepsilon = \frac{E}{(\alpha^2-\omega)Y}$ with $\alpha^2 > \omega$, which we can substitute to get the final results. (ii) Follows from (i) as Y and E are functions of εQ. (iii) Follows from (14). □

A direct implication of Corollary 2 is that output responds stronger to relative changes in energy prices Q (and, thus, also ε) than to relative changes in TFP, A, if and only if the energy expenditure share ω exceeds the capital income share α. For $\alpha < 1/2$, follows further that $0 < -\varepsilon_{Y,Q} < 1$, and, thus, output is inelastic in energy prices. Energy demand is inelastic if Q is very small and elastic if Q is very high. While higher energy prices do not affect the energy intensity of intermediate goods because of the Leontief production function, they reduce energy intensity per final output $\Theta := Y/E = \frac{\alpha^2\varepsilon}{1+\varepsilon Q}$.

Proposition 1. *A proportional change in A, Q and ε affects growth rates as follows:*

$$\frac{\partial g_c}{\partial A} A = \Gamma \qquad \qquad \frac{\partial g_c}{\partial Q} Q = \frac{\partial g_c}{\partial \varepsilon}\varepsilon = -\frac{\omega}{\alpha}\Gamma \tag{18}$$

with $\Gamma := \frac{\alpha A L}{\eta\theta}\left(\frac{\alpha^2 A}{Q\varepsilon+1}\right)^{\frac{\alpha}{1-\alpha}} > 0$ (ii) A proportional change in A affects growth rates higher than a proportional change in energy prices Q if and only if $\alpha > \omega$.

Proof. Using (12) we get $\frac{\partial g_c}{\partial A} A = \frac{\alpha A L}{\eta\theta}\left(\frac{\alpha^2 A}{Q\varepsilon+1}\right)^{\frac{\alpha}{1-\alpha}}$ and $\frac{\partial g_c}{\partial Q} Q = -\frac{LQ\varepsilon}{\eta\theta}\left(\frac{\alpha^2 A}{Q\varepsilon+1}\right)^{\frac{1}{1-\alpha}}$. The response to ε is equivalent to the case for Q due to (12). With $\varepsilon = \frac{E}{(\alpha^2-\omega)Y} = \frac{\omega}{Q(\alpha^2-\omega)}$ (the latter equality uses $\omega = EQ/Y$), we get the final result. □

Corollary 2 and Proposition 1 suggest that the relative sensitivity of level and growth effects to changes in energy prices and total factor productivity is similar. Level and growth effects respond stronger to changes in energy prices (than TFP) when the energy expenditure share exceeds the capital income share. This result can explain the economic take-off during the coal-fired industrial revolution: Expenditure shares on energy (including energy contained in food and fodder) were higher than 60% before 1700, declining to approximately 10% in the early 20th century (Fizaine and Court, 2016). Thus, access to cheap energy could have fueled economic growth much stronger during the early days of the industrialization than in recent decades where energy expenditure shares were very low. With low energy expenditure shares, however, changes in TFP through improved institutions or health become more decisive for creating wealth.

3.2 Growing energy prices

Suppose that energy prices increase at constant rate ϕ, $Q = Q_0 e^{\phi t}$ with $\phi > 0$. Over time, energy prices dominate the cost of producing intermediates. We can therefore assume $\varepsilon Q(t) + 1 \approx \varepsilon Q(t)$, which allows us to derive analytical expressions that approximate the economy in the long-run.

Proposition 2. *When energy prices increase at a constant, positive rate and energy intensity is homogeneous, long-run economic growth is not possible. The economy collapses and growth rates become eventually negative for any* $\rho > 0$.

Proof. Net-present value of research firms (7) reads with $\varepsilon Q(t) + 1 \approx \varepsilon Q(t)$:

$$V_j(t) = \int_t^{\infty} (1-\alpha)\alpha AL \left(\frac{A\alpha^2}{\varepsilon Q_0}\right)^{\frac{\alpha}{1-\alpha}} e^{-\left(\frac{\phi\alpha}{1-\alpha} + \tilde{r}(s)\right)s} ds \tag{19}$$

with $\tilde{r}(s) = \frac{1}{s}\int_t^s r(u)du$. Thus, increasing energy prices effectively increase discount rates and reduce NPV of a new innovation. As $V_j(t) = \eta$ and, hence, $\dot{V}_j(t) = 0$. Taking again the time-derivative of (19), we get $r(t) = \pi_j(t)/V_j(t) + \dot{V}_j(t)/V_j(t)$ with $\dot{V}_j(t) = \dot{\eta} = 0$. Contrary to the former case of constant energy prices, however, $\pi_j(t) = (1-\alpha)\alpha AL \left(\frac{A\alpha^2}{\varepsilon Q_0}\right)^{\frac{\alpha}{1-\alpha}} e^{-\frac{\phi\alpha}{1-\alpha}s}$, which is not constant but declines at the rate $\frac{\phi\alpha}{1-\alpha}$. Interest rates decline to zero as profitability of new innovations decreases to zero. With the Euler equation, this implies negative consumption growth rates when $r(t) > \rho$. □

One direct implication of this corollary is that any Hotelling price path – which would occur if only exhaustible resources existed – will also lead to a collapse of the economy.

3.3 Endogenous energy prices and transition to the zero-growth economy

In the previous analyses, we assumed that any amount of energy can be used at an exogenously given price $Q(t)$. This assumption is appropriate if energy is abundant and only costs need to be paid to make energy usable for humans (e.g. by extracting fossil fuels or building power plants). On competitive energy markets, energy prices in this case equal production costs. While there exist uncertainties in the total amount of energy available, exhaustible as well as renewable energy supply is finite. With constant energy prices, however, energy demand grows unbounded due to (15). Hence, when all exhaustible resources are exhausted and all renewable energy is used at its maximum physical potential, E^*, economic growth must cease and output needs to be constant as well. When energy consumption is binding at E^* and economic growth ceased, there exist a unique energy price Q^* that clears markets according to (15) such that

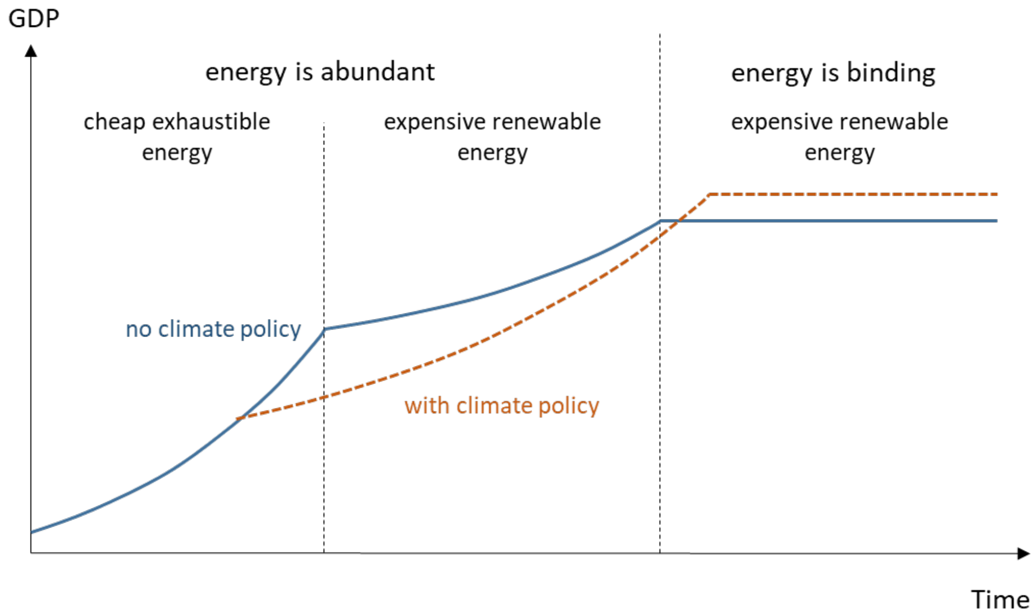


Figure 2: Stages of economic growth when energy intensity is homogeneous.

$E = E^*$. We can therefore endogenize energy prices if demand equals physically determined supply.

The transition from the growth stage to the zero-growth stage is illustrated by the blue solid line in Fig. 2. We assume that the exhaustible energy is cheap (relative to renewable energy) and supplied at extraction costs. We disregard any Hotelling price dynamics nor expectations that exhaustible energy ceases at some date and needs to be substituted by renewable energy. Considering these aspects would smooth growth rates between the different stages but is analytically intractable because of the changes in the NPV of the profits of innovators. Rather, the switch from one energy regime to another comes as a shock. Because exhaustible energy is cheap, it is used first and growth rates are highest; when the non-renewable energy is exhausted, the renewable energy era begins with lower growth rates due to higher costs in energy production. As the economy still grows at a constant rate, the maximum supply of renewable energy is reached eventually – the zero growth era begins.

3.4 Implications of climate change and climate policy

We consider three main channels of climate change and climate policy in our growth economy: First, mitigating climate change means to switch from cheap exhaustible fossil resources, that contribute to global warming, to more expensive renewable energy sources. While levelized cost of electricity generation (LCOEs) differ widely among technologies and regions, costs for renewable energy tends to be up to 0-50% more expensive than for fossil energy (IEA, 2015; IPCC, 2014; IRENA, 2018; Lazard, 2018), although renewable energy is in some places

Channel	Relative change of variables (1=100% increase) low estimate	central estimate	high estimate
Energy price Q	0.25	0.5	1.0
Energy intensity ε	-0.1	-0.2	-0.3
TFP A	0.04	0.09	0.20
Net effect (in TFP-equiv.)	-0.01	-0.01	-0.03

Table 3: Impact of climate policy (mitigation) on key variables (relative changes) in the medium to short term (assuming abundance of fossil energy resources). See main text for sources on estimated changes. The net effect is expressed in terms of TFP changes and calculated as weighted sum with $-\omega/\alpha = -1/3$ as weight for the Q and ε channel according to Corollary 2 and Proposition 1.

already cheaper than fossil energy and in some places more than twice expensive as fossil energy. Decarbonization of heating and transport sectors tends to be more expensive. Hence, we can expect an increase in Q by a factor between $0.0-0.5$ with a lower value around 0.25 as a likely average estimate as suggested by the previous studies. Such a number is also consistent with 2–5% consumption losses for achieving the 1.5°C temperature target (Rogelj et al., 2015). If these losses are all assigned to higher energy prices and energy expenditures are 10% of GDP, energy price increases between 20–50% can explain these losses as a first-order effect of climate policy.

Second, higher global temperature levels affect the aggregate energy intensity ε of the economy as, e.g. demand for cooling and heating changes. Hsiang et al. (2017) estimates that unmitigated warming (around 4°C until 2100) implies 10–30% higher energy demand for the US. De Cian and Wing (2017) provide a comprehensive assessment of energy demand for various sectors and estimate 17% increase in energy for the RCP 8.5 scenario by 2050, i.e. where around 2°C warming of average global surface temperature has occurred.

Third, higher global temperature reduce agricultural productivity (Schlenker and Roberts, 2009) and labor productivity (Graff Zivin and Neidell, 2014). Estimates on TFP impacts for 4°C warming range from 3.8% in DICE-2016R (Nordhaus, 2017) and approx. 4% (Hsiang et al., 2017, US only) over 9.2% in Kalkuhl and Wenz (2018) up to approx. 20% in Burke et al. (2015). These damages can be considered as reductions in A.

Combining all three channels and disregarding any delays between costs of climate policy and climate damages, we obtain:

Corollary 3. *The instantaneous level and growth effects of TFP increases are $-\omega/\alpha$ times relative increases in energy prices or energy intensity.*

Proof. Follows directly from Corollary 2 and Proposition 1. □

Hence, for typical values of $\alpha = 1/3$ and $\omega = 1/9$, the relative strength of the energy channel is about $1/3$ of the TFP channel. Tab. 3 summarizes the key impacts of a policy that would mitigate strong global warming of, say, 4°C compared to a no-temperature increase scenario where cheap fossil energy is completely substituted by more expensive non-fossil energy.

For the three illustrative scenarios, this would always result in a (very small but) negative net effect, implying that mitigation leads to lower current TFP and lower growth rates (as long as fossil energy is available). Combinations of low energy price impacts and high TFP damages would turn the sign around: Neglecting energy intensity effects, mitigation becomes output and growth enhancing as soon as TFP losses due to climate damages are at least one third of the increases in energy prices.

Considering the temporal dynamics in this assessment gives a more nuances picture. From Corollary 1 follows that mitigating climate change reduces growth *rates* as the economy switches earlier from cheap fossil energy to more expensive renewable energy (red dashed line in Fig. 2). Note that these growth effects are temporary as fossil energy is eventually exhausted and the switch to renewable energy will occur anyway. Without climate policy, the renewable energy era (blue solid line in the middle stage in Fig. 2) has lower growth because of the climate damages that reduce growth rates through higher ε and higher A. In the long-run growth ceases anyway as soon as energy demand reaches physical energy supply. In the long-run, however, per capita GDP is determined by A and and ε – both would be reduced due to climate damages. Thus, besides temporary countervailing growth effects (lower growth in the near term, higher growth in the mid-term), climate policy leads ultimately to higher consumption levels in the zero-growth stage. The normative choice of mitigating climate change depends in this case on the discount rate, among others.

4 Innovation with decreasing energy intensity

We now move to the case where energy intensity ε_j is heterogeneous but decreases exogenously with new product inventions. We again assume that energy prices are constant and exogenous – thus, energy is available in abundance and can be used at extraction or production costs. Let us assume that new products arrive at a declining energy intensity rate, according to $\varepsilon_j = \varepsilon_0 e^{-\beta j}$ with ε_0 the energy intensity of the first product. Thus, energy intensity of every new product decreases, in relative terms, by β. While energy prices matter for demand of energy in sector j, they become increasingly irrelevant as $\varepsilon_j Q$ converges to zero for new products. Hence, for large enough t, profits of research firms (10) are

$$\pi_j \approx (1-\alpha)\alpha AL \left(A\alpha^2\right)^{\frac{\alpha}{1-\alpha}} \tag{20}$$

Importantly, energy prices and energy intensity do not influence the innovation process in the long-term and the growth rate of the standard Romer model holds:

$$g_c = \gamma = \frac{1}{\theta}\left[\frac{(1-\alpha)\alpha AL}{\eta}\left(A\alpha^2\right)^{\frac{\alpha}{1-\alpha}} - \rho\right] \tag{21}$$

Growth is independent from the level of the energy price and the energy intensity of the economy. Aggregate energy is

$$E(t) = \int_0^{N(t)} E_j(t)dj = \int_0^{N(t)} \varepsilon_j X_j(t)dj \tag{22}$$

Substituting $X_j(t)$ from (9) and $\varepsilon_j = \varepsilon_0 e^{-\beta j}$ gives

$$E_j(t) = L\varepsilon_0 e^{-\beta j}\left(\frac{\alpha^2 A}{Q\varepsilon_0 e^{-\beta j}+1}\right)^{\frac{1}{1-\alpha}} \tag{23}$$

With $N(t) = N_0 e^{\gamma t}$, the integral (22) can be solved

$$E(t) = \frac{(\alpha-1)\alpha^{\frac{\alpha+1}{1-\alpha}} AL\left(\left(\frac{A}{Q\varepsilon_0+1}\right)^{\frac{\alpha}{1-\alpha}} - \left(\frac{A}{Q\varepsilon_0 e^{-\beta N_0 e^{\gamma t}}+1}\right)^{\frac{\alpha}{1-\alpha}}\right)}{\beta Q} \tag{24}$$

Proposition 3. *If energy intensity of new products decreases by the rate $\beta > 0$, (i) total energy demand is continuously growing and (ii) converges to a finite number $0 < E^{**} < \infty$ while per-capita production increases at a constant rate.*

Proof. For (i), take $\frac{DE(t)}{dt}$ which is strictly positive for any $t \geq 0$ but converges to zero for $t \to \infty$. (ii) $\lim_{t\to\infty} E(t) = \frac{(\alpha-1)\alpha^{\frac{\alpha+1}{1-\alpha}} LA^{\frac{1}{1-\alpha}}\left((Q\varepsilon_0+1)^{\frac{\alpha}{\alpha-1}}-1\right)}{\beta Q} = E^{**}$. Clearly, $0 < E^{**} < \infty$ if $Q\varepsilon_0 > 0$. □

The key insight from this corollary is that sustained economic growth with finite energy supply is possible. While energy efficiency of existing products cannot be increased due to the assumed thermodynamic constraints, decoupling is possible if the economy invents new products that require less and less energy input. Interestingly, decoupling is possible for any $\beta > 0$ – even if the decrease in energy intensity for new products is extremely small.

The equation for aggregate energy demand (22) further allows to identify necessary and sufficient conditions that make a decoupling of economic growth and absolute energy use impossible:

Corollary 4. *If there exists an arbitrarily small but strictly positive lower bound $\underline{\varepsilon} > 0$ for the energy intensity of new goods, such that $\varepsilon_j \geq \underline{\varepsilon}$ for all j and $\varepsilon_i > \varepsilon_j$ for $i < j$, energy use will not be bounded by above and de-coupling of energy and economic growth is not possible.*

Proof. With (22) follows $E(t) \geq \int_0^{N(t)} \underline{\varepsilon} X_0 dj = \underline{\varepsilon} X_0 N(t)$ with X_0 the demand for the first intermediate (i.e. the intermediate with the highest energy intensity ε_0 which is given from (9)).

For sustained economic growth, $N(t)$ grows to infinity, implying that energy demand with also grow without bound. $\square$

A simple example for a function with a positive minimum energy intensity is $\varepsilon_j = \underline{\varepsilon} + \varepsilon_0 e^{-\beta j}$. In this case, even strongly declining energy intensity due to a high β will still imply unbounded energy use if $\underline{\varepsilon} > 0$.

4.1 Energy prices and aggregate energy

When innovation creates new products that are less energy intensive, long-run growth rates are independent from the price of energy but the price of energy affects the energy used per each variety j through (23).

Corollary 5. *(i) If energy prices Q converge to infinity, long-run energy demand E^{**} becomes zero. (ii) If energy prices Q are zero, long-run energy demand is $E^{**}_{|Q=0} = \frac{\alpha^{-\frac{2}{\alpha-1}} L\varepsilon_0 A^{\frac{1}{1-\alpha}}}{\beta} < \infty$ and bounded. (iii) Long-run energy demand falls monotonically in energy prices.*

Proof. (i) Take $\lim_{Q\to\infty} E^{**}$ with E^{**} from the proof of Proposition 3 which gives zero. (ii) Substituting $Q = 0$ into E^{**} gives the result. (iii) As $\frac{dE_j(t)}{dQ} = \frac{L\varepsilon_0^2 e^{\beta(-j)} \left(\frac{\alpha^2 A}{Q\varepsilon_0 e^{\beta(-j)}+1}\right)^{\frac{1}{1-\alpha}}}{(\alpha-1)\left(e^{\beta j}+Q\varepsilon_0\right)} < 0$, total derivative of total energy $dE(t)/dQ$ as the integral over all varieties is negative and $dE^{**}/dQ < 0$ as well. $\square$

A remarkable outcome is that any arbitrarily low energy consumption can be achieved by increasing the level of energy prices sufficiently – without affecting long-run growth of the economy. Moreover, the growing economy has finite energy demand even if energy prices are zero. In particular, any level of energy consumption $0 < E(Q) < E^{**}_{|Q=0}$ can be achieved by a specific choice of Q. If energy supply is bounded physically by E^* and if this limit is binding in the sense that the demand of the economy with zero energy prices would exceed this limit, there exist a unique energy price Q^* which equalizes demand with physical supply.

4.2 Global warming

Global warming impacts occur through the same channels as in Section 3.4. Mitigation leads to lower energy prices and – as warming will be limited – to higher TFP. Additionally, energy intensity might be affected via mean global energy. While climate damages through TFP reductions imply permanent growth reductions, increased energy prices as well as changes in energy intensity are irrelevant for long-run growth. They have, however, level effects.

Figure 3 illustrates the dynamics of climate policy if fossil energy is cheap and global warming affects productivity levels A negatively. Continuing with fossil energy use mean higher consumption levels until climate damages become prevalent. These damages are permanent as temperature levels are altered permanently. While consumption levels drop due to

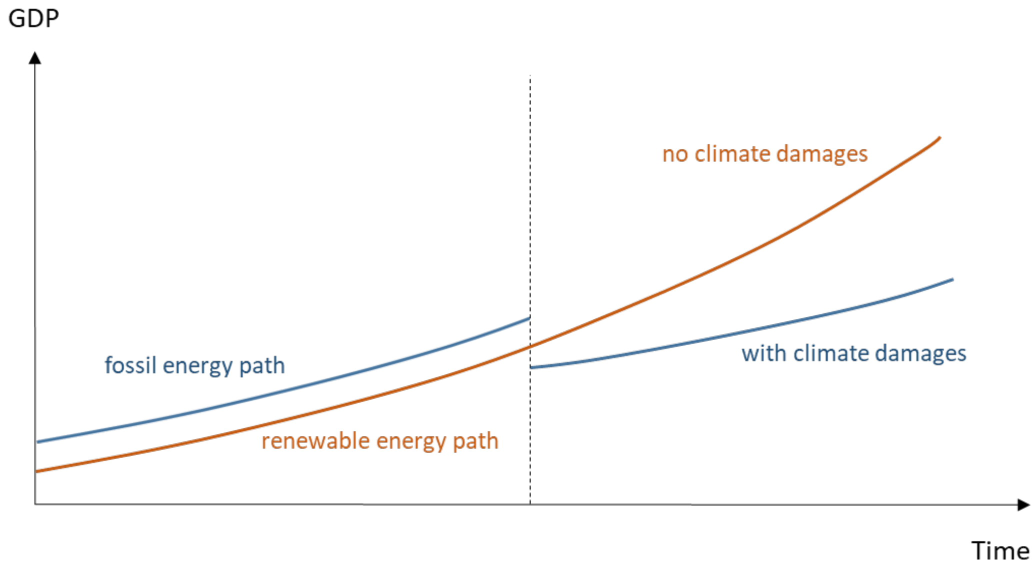


Figure 3: Economic growth under a renewable and fossil energy path when energy intensity is heterogeneous.

lower A (and, potentially, higher ε_0), also growth rates decrease. Hence, the economy will experience permanently lower growth rates than under mitigated global warming.

4.3 Normative analysis of climate policy: level vs. growth effects

In terms of welfare, temporary gains in consumption might justify permanent reductions in growth rates. To see this, consider two consumption series, $c^P = e^{\gamma t}$, the policy case with no climate damages and renewable energy, and $c^R = \Lambda e^{\lambda \gamma t}$, the reference case with fossil energy, implying initially higher levels of consumption as $\Lambda > 1$ but lower growth rates as $0 < \lambda < 1$. With iso-elastic utility $u(c) = \frac{c^{1-\theta}-1}{1-\theta}$ and disregarding temporal heterogeneity of mitigation costs and climate impacts, we can derive

Proposition 4. *Climate policy is welfare superior when*

$$\frac{\rho}{\gamma} < \frac{(\theta-1)\left(\Lambda - \lambda\Lambda^{\theta}\right)}{\Lambda^{\theta}-\Lambda} \qquad \theta > 1 \tag{25}$$

$$\frac{\rho}{\gamma} < \frac{1-\lambda}{\ln(\Lambda)} \approx \frac{1-\lambda}{\Lambda-1} \qquad \textit{log utility} \tag{26}$$

Proof. Discounted welfare is

$$W^P = \frac{\frac{1}{\rho} - \frac{\Lambda^{1-\theta}}{\gamma(\theta-1)\lambda+\rho}}{\theta-1} \tag{27}$$

$$W^R = \frac{\frac{1}{\gamma(\theta-1)+\rho} - \frac{\Lambda^{1-\theta}}{\gamma(\theta-1)\lambda+\rho}}{\theta-1} \tag{28}$$

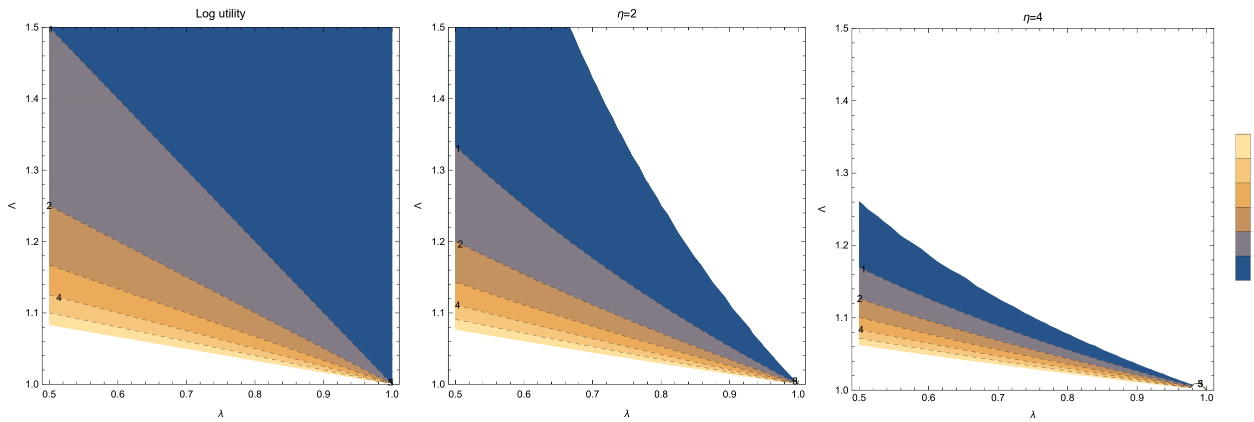


Figure 4: The RHS in (25) for different values of (λ, Λ).

and for log-utility:

$$W^P = \frac{\gamma}{\rho^2} \tag{29}$$

$$W^R = \frac{\gamma\lambda + \rho\log(\Lambda)}{\rho^2} \tag{30}$$

Climate policy is welfare superior when $\Delta W := W^P - W^R > 0$ with

$$\Delta W = \frac{\frac{\Lambda^{1-\theta}}{\gamma(\theta-1)\lambda+\rho} + \frac{1}{\gamma(-\theta)+\gamma-\rho}}{\theta - 1} \qquad \theta > 1 \tag{31}$$

$$\Delta W = \frac{\gamma(-\lambda)+\gamma-\rho\log(\Lambda)}{\rho^2} \qquad \text{log utility} \tag{32}$$

Re-arranging gives the proposition. □

Thus, for the log-utility case, climate policy is always welfare superior if the discount rate ρ is sufficiently small. Growth effects become in this case always dominant even if near-term consumption losses due to climate policy are large. For the more general isoelastic case, this condition narrows down as the RHS in (25) decreases in θ.

Fig. 4 illustrates for what combinations of level impacts λ and growth impacts Λ the RHS exceeds specific critical values. Consider the case of $\rho/\gamma \approx 1$, positive growth effects of climate policy dominate negative level effects for all combinations of (λ, Λ) below the blue area. The set of values for (λ, Λ) that meet this criterion gets smaller if η increases (see middle and right panel in Fig. 4). For the log-utility case, the social planner would be indifferent between choosing climate policy if positive growth effects equal negative level effects in relative terms (i.e. 10% increase in growth rates due to climate policy but 10% reduction in consumption levels). For $\theta > 1$, higher growth impacts would be needed to be indifferent between climate policy and no policy. The explanation for this is that higher η puts more weight on current generations as they are the worst-off in a growing economy. While higher growth rates increase welfare for future generations, they also increase inequality between generations.

5 Quantitative analysis: growth and level effects of climate policy

In order to obtain a rough figure of the quantitative effects of climate damages and climate policy in an endogenous growth framework, we simulate level and growth effects.

5.1 Model calibration

We calibrate our model on GDP and energy use for the global economy, see Tab. 4. The price of energy is based on typical estimates of energy costs (e.g. IEA, 2015) and results in an energy expenditure share of 8.3% which corresponds well to global expenditure estimates of 8.1% in 2008 by King et al. (2015). Population is normalized to one and assumed to be constant to exclude additional scale effects in growth rates. Preference parameters are depicted from standard ranges; the TFP growth rate of 2% also reflects long-run growth rates of industrialized economies. Technology parameters A and ε as well as R&D costs are calibrated with the other parameters and using base-year parameters for total output, energy use and varieties (the latter is again normalized to one).

Table 4: Parameterization of the base model

Variable / parameter	Symbol	Value	Unit
Price of energy	Q	0.01	trln $/EJ (= 1000$/GJ)
Labor	L	1	
Capital income share	α	1/3	
Pure time preference rate	ρ	0.02	
Inverse of the elasticity of substitution	θ	1	
Growth rate	γ	0.02	
Calibrated parameters			
Energy intensity	ε	296.3	
Level of technology	A	53.2	
R&D cost	η	361.1	
Base year values used for calibration			
GDP	Y	65	trln USD
Primary energy use	E	540	EJ
Varieties (Sectors)	N	1	

We do not attempt to estimate the rate of decreasing energy intensity, β for two reasons: (i) The highly non-linear relationship between β and total energy use E in (24) does not allow for standard techniques to estimate β in a time series model of energy use data. (ii) While it matters whether β is strictly larger than zero or not, short and long-term response of GDP and growth rates do not depend on the level of β. We therefore report results for the two cases $\beta = 0$ (homogeneous energy intensity) and $\beta > 0$ (declining energy intensity) without providing empirical evidence for what case actually holds.

5.2 Numerical results

Based on the discussion in Section 3.4, we consider the following quantitative impacts: (i) climate policy increases costs of energy prices by 25%; (2) climate policy reduces energy intensity by 10% because unmitigated global warming would increase energy demand; climate policy increases the level of technology by 4% because unmitigated global warming reduces productivity. The chosen values are more on the lower end of the possible ranges reviews in Section 3.4 but tend to be conservative choices.

Tab. 5 shows the results for the three impact channels separately – and for the combined effect where all channels are considered simultaneously. Consider the case for homogeneous energy intensity, $\beta = 0$, first: Based on Corollary 2, increases in energy costs reduce GDP levels by 8.2%. We expect this impact to occur in the short-term and simultaneously with the implementation of mitigation policy. Consumption gains related to avoided climate damages of climate policy through lower energy intensity and higher TFP levels amount to 4.0 and 6.1%. We expect these to occur several decades after climate policy has been implemented. While benefits outweigh costs in the medium- to long-run, the intertemporal welfare analysis depends on the delays between near-term costs and medium-term benefits and normative parameters related to the discount rate.

With homogeneous energy intensity, growth effects apply only in the medium-term, i.e. as long as the total amount of energy is not binding (and growth is possible). Using Proposition 1, higher energy prices imply reductions of the overall growth rate by 0.33 percentage points – while avoided climate damages imply 0.4 percentage points increases in growth rates.

If energy intensity declines, short-run level effects are the same as for homogeneous energy intensity (just using a weighted average energy intensity over different varieties that matches to the calibrated energy intensity). Because energy intensities converge to zero, higher energy prices and energy savings due to climate policy become irrelevant in the long-run. The only growth effect arises due to avoided TFP damages. As energy intensities converge to zero, the growth rate of the economy increases in general. Climate policy increases growth rates by 0.48 percentage points in the long-run, which corresponds to a 12% increase in growth rates (Tab. 5).

With these values, we can further assess whether climate policy is welfare-enhancing using Proposition 4. Assuming that climate policy has short-term level-effects of -8.2% and long-term growth impacts of 12.2% (Tab. 5), we can set $\Lambda - 1 = 0.082$ and $1 - \lambda = 0.122$. The ratio (RHS in (25)) is 1.48 and clearly exceeds $\rho/\gamma = 0.45$.[2] Hence, long-term growth effects dominate level effects of climate policy. Higher climate damages would further improve the welfare of mitigation policy over laisser-faire. For TFP damages of unmitigated warming of

[2]Note that the long-run growth rate of the economy is 4.5% because of declining energy intensity. This growth rate can be observed in the very long-term. However, even for near-term growth rates of 2% due to currently high energy intensities, the RHS in (25) exceeded $\rho/\gamma = 0.1$.

4%, energy price increases of 40% or higher would turn this assessment, and make the laisser-faire policy welfare-superior.

Table 5: Numerical simulation: Impacts of climate policy

		Homogeneous energy intensity ($\beta = 0$)		Declining energy intensity ($\beta > 0$)	
Impact channel	Impact in %	Level effect in %	Growth rate effect in pct. points	Growth rate effect in pct. points	in % change
Energy price	25	-8.2	-0.33		
Energy intensity	-10	4.0	0.16		
TFP	4	6.1	0.24	0.48	12.2
Combined		1.4	0.06	0.48	12.2

For magnitude of impact channels, see Section 3.4. Level effect is calculated according to Corollary 2; growth effects are calculates using Proposition 1. Growth effects for the case of declining energy intensity are calculated in the same way but using $\varepsilon = 0$ as energy intensity converges to zero in the long run.

6 Conclusions

This paper combined insights from thermodynamics on energy conversion rates and available energy flows with an expanding product-variety endogenous growth modeling approach to assess the role of energy and climate policy for economic growth. In particular, we set-up an endogenous growth model that respects crucial thermodynamic laws. Our insights provide various contributions to ongoing debates (i) on possibilities to de-couple economic growth from energy use, (ii) on the thermodynamic feasibility of sustained economic growth, (iii) on potential growth impacts of mitigation policies and (iv) on potential growth impacts of climate damages.

Thermodynamic laws suggest that the substitutability between energy and and capital is limited for a *specific* machine or product. Hence, sustained increases in energy efficiency is only possible through the development of new product or varieties that are less energy intensive as previous ones. Whether there exist a thermodynamically-constrained minimum amount of energy for a new product is an open question: while products have some material or energy-related base, it is not clear whether there exists a lower bound. Immaterial products, ideas, art, knowledge are examples where energy requirements relative to the value of the output could possibly be arbitrarily small. The implication of the existence of a lower bound of energy content are tremendous: if energy intensity can converge to zero, decoupling of economic growth and energy use is possible. In that case, energy use can be maintained at any constant level without affecting asymptotic growth rates. If energy intensity of new products faces a non-zero lower bound, decoupling is not possible: The wealth of humanity converges to a constant level and will be determined by the influx of solar energy.

Our results emphasize why the price of energy affects growth rates and innovation in the short-run. High energy prices reduce monopoly profits from newly invented products and are therefore an incentive to innovate less. This growth effect, however, is only temporary and diminishes over time: Either energy intensities converge to zero (and the price of energy becomes irrelevant), or if energy intensities do not converge to zero, the economy will eventually stagnate when energy demand hits physical supply.

These findings show that cheap energy can be important for spurring economic growth and innovation. Fossil energy use, though cheap in many cases, contributes to global warming which increases energy intensity in the long run and reduced total factor productivity. The latter effect constitutes a permanent growth rate reduction effect. It is a priori unclear whether negative growth rate reductions dominate short term increases in GDP levels from a welfare perspective. For our base parameter setting, higher energy prices due to switching from fossil to renewable energy reduce GDP levels by 8.2% and growth rates by 0.33 percentage points; long-run growth rates, however, increase by 0.24 to 0.48 percentage points. Our back-of-the-envelope calculation suggests that climate policy is welfare-superior to laisser-faire. This assessment changes, however, if normative parameters and costs over benefit ratios change only slightly.

Further promising research avenues arise from this work: (i) Empirical research could investigate vertical vs. horizontal improvements in energy efficiency, i.e. to what extent energy intensity of new products behaves differently than energy improvements of existing products. This could ultimately help to better estimate the β coefficient of our model and to test whether $\beta > 0$ or $\beta = 0$. (ii) Our theory can be extended by endogenizing the choice of β. This could be done by assuming that energy improvement of a new product depends on research effort – or that energy intensities are outcome of a probability distribution where only products with sufficiently low energy intensity survive. (iii) An augmented Romer model with vertical and horizontal product innovation could constitute a new class of Integrated Assessment Models (IAMs) to assess optimal climate policy. These models could be calibrated to empirical data and are more flexible with respect to functional forms than our theoretical approach. Moreover, this class of IAMs would be best equipped to address the trade-off between short-term level reductions and long-term growth-rate increases of mitigation and derive optimal emission and temperature paths as well as more comprehensive social cost of carbon estimates.

Finally, more empirical research could shed light on potential limits to energy use and how they differ between sectors. Demand for lighting, heating or cooling could be saturated once optimal per-capita levels are obtained for human well-being. In particular, unbounded income growth would not lead to unbounded demand growth for these energy-intensive services. Also, the transportation sector – at least for human travel – faces an upper bound which is given by the total amount of time a person could allocate to traveling and the most energy intensive way of traveling per unit of time. Whether there exists a reasonable upper bound for transporting goods, however, is less clear. Globalization, specialization and differentiation of value chains could link energy demand to economic growth. A major driver for energy could also be triggered by ongoing digitization and automatization of the economy: energy demand of communication networks, personal computers, and data centers grows substantially stronger than the energy demand of the aggregate economy (Van Heddeghem et al., 2014). Carbon emissions – and thus energy demand – for information and communication technologies (ICT) are estimated to increase by 6% per year until 2020 (Webb et al., 2008). If economic value creation consists more and more on computation-intensive digital services, energy demand could increase without bound. Similarly, if economic production is performed by robots that require energy, energy demand could as well increase without bound. Thus, while human needs with respect to lighting, heating, cooling and travel could be met with a bounded energy per capita supply, digitization and automatization could turn out to be a major driving force for coupling economic growth to energy use.

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