"It's the energy, stupid!"
Energy supply, physical constraints and the end of Economic Growth

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Firms' Dynamics and Economic Growth

Abstract

What are the effects of energy constraints on production growth? Energies – fossil-fuels, like oil, as well as electricity – are key to the production process and complementary to other inputs. However, due to finite reserves, declining production of fossil-fuels, or political decisions to shrink greenhouse gas emissions, energy use will be restricted in the near future. This might results in a decline in firms production and in aggregate output growth. The aim of this project is to quantify this decrease. First, using production function estimation, we will quantify the transmission at the firm level, and second, using a network approach, we will explore the reallocation and amplification channel across sectors. These two sets of evidence, along the facts supporting the implausibility of "green growth" scenarios, should allow to quantify the forthcoming decline in economic growth.

To produce any given motion, to spin a certain weight of cotton, or weave any quantity of linen, there is required steam; to produce the steam, fuel; and thus the price of fuel regulates effectively the cost of mechanical power. Abundance and cheapness of fuel are hence main ingredients in industrial success. It is for this reason that in England the active manufacturing districts mark, almost with geological accuracy, the limits of the coal fields.

Robert John Kane –*The Industrial Resources of Ireland (1844)*

1 Introduction and motivation

As observed by the chemist and politician Robert Kane during the Industrial revolution in Ireland and Great Britain, access to energy resources has always been a crucial factor in economic development and growth. All the sectors of our economies – transportation, manufacturing, but also services – rely on energy and electricity supply, which may have effects on business cycles. Indeed, the recessions of 1973, 1990 and 2008 were all preceded by decline in energy supply or oil price shocks. In this article, I wish to provide a clearer view on the effects of energy on growth.

What are the effects of a reduction in energy supply on GDP growth? What are the transmission channels at the firm micro-level and the reallocation channels at the aggregate level? Can we associate a single number to the elasticity of production to energy costs or do we observe heterogeneity across firms and sectors ? The aim in this project is to provide quantitative answers to these questions.

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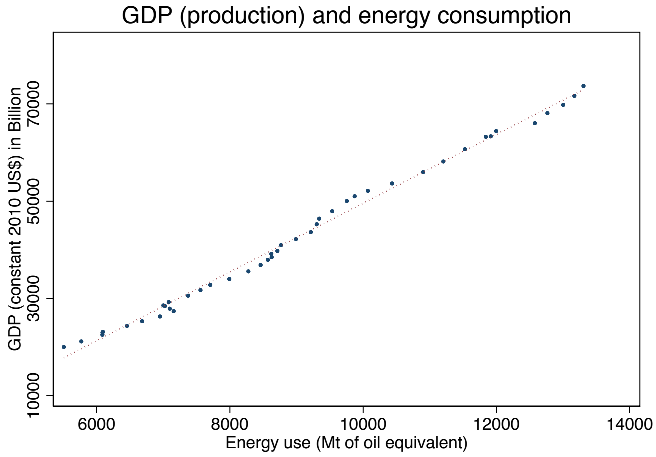


Figure 1: Linear relation at the world level

Historically, GDP and production in goods and services has always been linearly associated with energy use and production. As displayed in the next fig. 1, world GDP is linearly associated with energy production – all energies put together, measured in Tons of Oil Equivalent (the energy produced by burning one ton of crude oil). As displayed in fig. 2 for a panel of 60 countries – including G20, European and OPEC and other developing economies – we see that such relation carries through at the country level. Moreover, even if not displayed, this linear relation is still valid with a high degree of significance with various indicators for energy and electricity, controlling for population and country fixed effects.

In the medium-run, the energy used in production is determined by two underlying trends: a decline in energy production due physical constraints and the necessary decline in energy demand intrinsic to policies addressing global warming.

First, what are the causes and implications of a declining ***energy supply***? Most fossil resources like oil, gas and coal, but also metals or minerals like lithium or phosphorus[1] have finite reserves. Despite a innovation in extraction efficiency, the production of these resources follows a bell shaped curve – as shown in the "Hubbert peak" theory[2]. Nowadays, many geologists claim that the peaks of conventional crude oil and natural gas happened in the first decades of the 21st century. Hence, we expect to see a decline in these two major sources of energy. Similarly, due to a lack in profitability and increasing costs, the shale-oil industry have shown some difficulties in maintaining high production growth in the latest years. These three trends are confirmed in the forecasts by the International Energy Agency, IEA (2018) underlining the "risk of of a supply crunch". More generally, we observe a long-term slowdown in the growth of energy production at the world level, as displayed in fig. 3 – where we plot the growth rate in energy supply (all sources together) and the five-years average growth. More details about this first fact are provided in section 4.

This secular decline in energy supply could also be an underlying explanation to the so-called "***secular stagnation***", c.f. Summers (2014). As argued by L. Summers in 2013, updating A. Hansen's Keynesian theory of 1938, a shortage of demand have brought the U.S. and world economic growth to a halt. Long-term interest rates – and "natural interest rate" – have declined

[1]Lithium is massively used in battery. Phosphorus is used as a fertilizer in agriculture

[2]Hubbert peak theory is summarized in section 4: At a given (oil-)field level or mine-level, production follows a bell-shaped curve, reaching a peak around half the stock of resources before decreasing slowly until full depletion

to record low levels in the decade after the Great Recession. Capacity utilization, inflation and potential growth have been slowing down and are expected to remain low on the long-run. Many causal channels have been explored to rationalize this hypothesis: on the one hand, demand-side stories, like hysteresis, long-lasting effects of the recession AND rising inequality may have caused low consumer spending and declining demand. On the other hand, other authors have advocated in favor of structural factors related to demographics – with an aging population or related to an Asian "saving-glut" – and a long run decline in TFP with a slowdown in innovation and business dynamism. The hypothesis of a long-term decline in energy supply can offer an alternative explanation to this secular stagnation hypothesis.

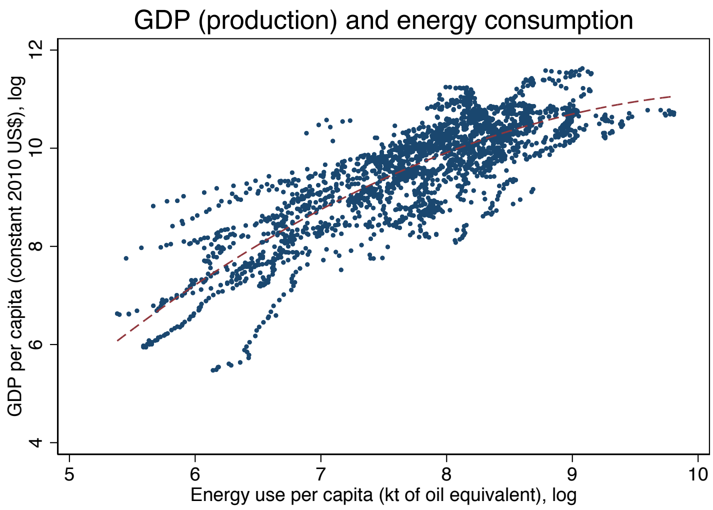


Figure 2: Cross country evidence, 60 countries 1960-2017

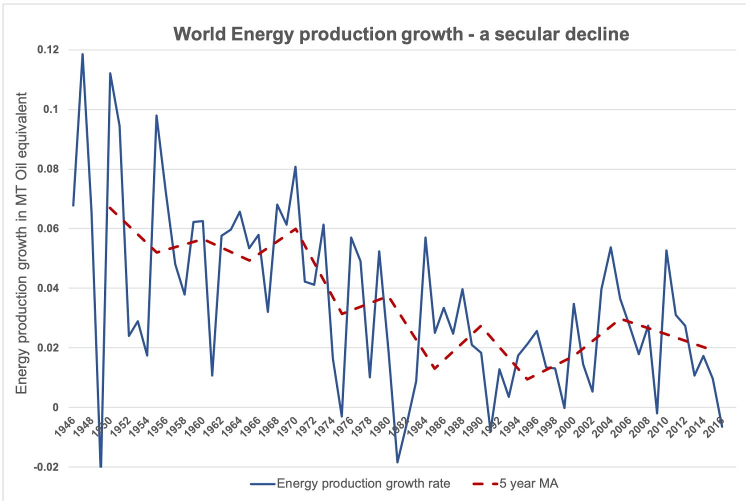


Figure 3: Decline in world energy production

A second reason backing a reduction in energy used in production relates to a necessary dampening of demand, in a context of ***climate change and global warming***. The fossil energy consumption – which represents over 80% of energy sources – is the main, if not the only, source of greenhouse gas emissions. Consistent with the 2016 Paris agreement, many countries, cities or companies have announced in the recent year their objective to be "carbon-neutral" in the next two or three decades. Keeping world temperature below 1.5° or 2°C indeed requires to decrease world greenhouse gas emissions to zero by 2050 – as suggested by the scenarios of the IPCC – Intergovernmental Panel on Climate Change. As currently around 80% of our energy are based on fossil fuels, the most optimistic scenario implies to divide by three – from 45 to 15 $GTCO_2$/year (corresponding to the level in 1975) – our emissions and energy consumption in the next two decades. As this energy consumption can not be fully produced by renewable energy in this short horizon, reducing these carbons emissions involve to decrease goods production and ultimately GDP growth. Our last section section 5 provides a more comprehensive focus on this question.

Given these two factors leading to a sharp reduction in energy consumption in the next three decades, our aim in this article is to quantify the effects of this capacity constraints in terms of manufacturing production and overall production growth. Our strategy is twofold:

In a first part, our aim is to quantify the effects on production, investment and factor reallocation of energy use at the firm-level. Can we measure an elasticity of these variables to energy costs? Our guess is that this elasticity vary greatly across firms or across sectors. Indeed, services have lower need in electricity than manufacturing or transport. However, we also expect that most production functions are strongly non-linear in energy, as this factor is greatly complementary to other factors – materials, capital and labor. We explore our methodology in the section section 2.

In a second section, our aim is to understand the aggregation effects of change in energy supply, through a network approach. A reduction in energy production will have heterogeneous effects across sectors, with a non-trivial effects on the aggregate growth rate of value-added and GDP. Our aim is to rely on input-output data and a production functions with parameters for elasticity of substitutions between factors as estimated in the previous section. We can measure the effects of a reduction in energy across sectors and at the aggregate level, on production, investment and final consumption. Moreover, as hinted above, if we expect the energy use to have a non-linear effect at the micro-level, its macroeconomic impact likely to be non-linear as well. To analyze this question, we use a methodology inspired by Baqaee and Farhi (2019), where we investigate the non-linearity of this capacity constraint. We develop this framework in section 3.

Moreover, in section 4 we provide more details about the physical constraints suggesting a forthcoming decline in fossil-fuels, as rationalized in Hubbert's peak theory. In particular, finite resources and declining energy return on investment suggest an unavoidable deterioration of production growth in the coming decades.

Lastly, most economists and policy-makers consider different scenarios in their policy against climate change and rely on strong assumptions on growth of production efficiency and productivity in renewable energy. In our last section 5, we explore how these scenarios are inconsistent with historical evidence. Our conclusion is that either the fossil-fuel energy demand is reduced at a large cost in terms of production growth or the fight against climate is doomed to fail.

2 The transmission channel – production function estimation

Our goal in this section is to take an Industrial-Organization approach to understand the transmission of energy shocks: typically supply shocks that raises the costs of energy services. Would these supply shocks induce reduction in activity and production, reallocation across input factors – like investment in capital, labor decisions and reallocation toward materials.

A naive model that people have been assuming is the simple Cobb-Douglas production, with capital k, labor ℓ, material m – like intermediary goods – and energy inputs e – like oil/gas and electricity. Cobb-Douglas is known to be the first-order log-linear approximation of any production function, which may be enough for a preliminary analysis – as implement

$$y = Ak^{\alpha_k}\ell^{\alpha_\ell}m^{\alpha_m}e^{\alpha_e} \tag{1}$$

where the sum $\alpha_k + \alpha_\ell + \alpha_m + \alpha_e$ may or may not sum to one (due to slightly decreasing return to scale). Moreover, the smaller α_e, the more non-substitutable the energy-input is in the production process. Allcott et al. (2016), using such Cobb-Douglas specification, with e as electricity used in manufacturing firms, they estimate a parameter α_e for electricity to be around 0.019 with a range across industry of $0.016 - 0.022$ (much less varying than the ranges of parameters for labor or capital).

In the following, we explore the two production functions used in Atkeson and Kehoe (1999) sometimes denoted Putty-Putty and Putty Clay models in the case of energy.

In the first model, also denoted Putty-Putty model, Pindyck-Rotemberg model, or simply Nested-CES model, we separate the substitution between capital k and energy e on one side and capital-energy service F and labor ℓ on the other.

$$\begin{aligned} y &= G(F(k,e),\ell) \\ F(k,e) &= \left[\omega_F k^{\frac{\alpha-1}{\alpha}} + (1-\omega_F)e^{\frac{\alpha-1}{\alpha}}\right]^{\frac{\alpha}{\alpha-1}} \\ G(F,\ell) &= \left[\omega_G F^{\frac{\beta-1}{\beta}} + (1-\omega_G)\ell^{\frac{\beta-1}{\beta}}\right]^{\frac{\beta}{\beta-1}} \end{aligned} \tag{2}$$

Notice that if $\alpha \to 0$ the elasticity of substitution between energy and capital goes to zero, the production becomes Leontieff. Similarly, when $\alpha = 1$, it is Cobb-Douglas and when $\alpha = \infty$, it is linear, with perfect substitution. A version of this is used in Hassler, Krusell, and Olovsson (2010) and Hassler, Krusell, and Olovsson (2012) for macro-theoretical exercises[3]. In the second example, using macroeconomic time series – and energy as fossil fuels, oil, coal and natural gas – they measure $\alpha \approx 0.0044$ with standard error of 0.0127. Hence, we cannot statistically reject a Leontieff production. In Atkeson and Kehoe (1999) to reproduce elasticity of energy use on macroeconomic time series, they calibrate the model using $\alpha = 0.3$. They derive elasticity of substitution for energy as follow: on the RHS the short run elasticity, by keep capital stock constant, and the RHS the long run elasticity, by letting the capital adjust until the interest becomes constant:

$$\varepsilon_{sr} = \frac{d\log e}{d\log p}\Big|_{\substack{dG=0\\dw=0\\dk=0}} = -\frac{1}{(1-s_e)\frac{1}{\alpha} + s_e\frac{1}{\beta s_\ell}} \qquad \varepsilon_{lr} = \frac{d\log e}{d\log p}\Big|_{\substack{dG=0\\dw=0\\dr=0}} = -\alpha(1-s_e) - s_e s_\ell \beta$$

Using the factor share, with s_e share of revenue paid to energy and s_ℓ the labor share. These two variables could be estimated from the firm-level data to evaluate the complementary of energy with the rest of production.

Moreover, in a second model, also denoted Putty-Clay in Atkeson and Kehoe (1999), another production function is assumed. Taking as given a Leontieff production for each intermediary,

[3]More precisely, the nested CES used in Hassler et al. (2010) has $\omega_G = 1$ and the one used in Hassler et al. (2012) reverse the order of the nests:

$$G(F,\ell) = \left[\omega_G k^{\frac{\beta-1}{\beta}} + (1-\omega_G)\ell^{\frac{\beta-1}{\beta}}\right]^{\frac{\beta}{\beta-1}} \underset{\beta=1}{=} k^{\omega}\ell^{1-\omega} \qquad F(G,e) = \left[\omega_F G^{\frac{\alpha-1}{\alpha}} + (1-\omega_F)e^{\frac{\alpha-1}{\alpha}}\right]^{\frac{\alpha}{\alpha-1}}$$

using a range of capital indexed v with different energy intensities – measured by $k(v)/v$ – with distribution $f(v)$ a firm can produce :

$$
\begin{aligned}
y &= G(z,\ell) - pm \\
z &= \int_V \min\{k(v)/v \; ; e(v)\}\, f(v)dv \\
\text{s.t.} \quad m &= \int_V e(v)\, f(v)dv
\end{aligned}
\tag{3}
$$

This second model allow for a smoother substitution between energy and other inputs (i.e. capital) the range of varieties $v \in V$. One of the properties of this production is the existence of a cutoff rule $v^\star$, where if $v > v^\star$, the capital $k(v)$ is fully utilized, or otherwise not utilized at all. This cutoff depends on the price of energy p and total energy services used. Hence the cost of energy services will have not only an impact at the intensive margin but also at the extensive margin on the range of inputs used in production. We can use Cobb-Douglas form for $F(\cdot)$ and $G(\cdot)$ pinned down by s_e and s_ℓ the factors shares and energy prices to find the cutoff $v^\star$ and $v = k/e$ due to the Leontieff production assumption.

The use of these three models have very different implications for prediction and rationalizing the empirical observations. Cobb-Douglas model implies that there are gains in substituting input factors for energy in case its costs increases. In the contrary, Putty-Putty model suggest that firms and sectors facing higher energy prices – due to geographical differences – have a dramatically lower capital. This effect is somehow consistent with empirical evidence. However, the Putty-Clay also predict such consequence of factor complementarity but align in a more consistent way with empirical evidence.

Endogeneity concerns

One of the main issue emphasized in the Industrial Organization literature is the endogeneity concern in this estimation, c.f. Syverson (2011). Indeed, if the firms productivity is high, it might require and use more energy/electricity, which in turn affects the production and sales of the company. To interpret the parameters in input factors as causal – i.e. as elasticities – one should provide exogenous variation, i.e. with instruments variable, to this input.

An example of this strategy can be found in Allcott, Collard-Wexler, and O'Connell (2016) for Indian firms. To estimate the short-run impact of electricity shortage on production – when a grid power outage implies an "infinite electricity input tax" – they instrument these shortages with shifts in electricity supply from hydroelectric power availability – not associated to demand factors. Using a structural model, they estimate a 5 percent decrease in revenue for a one percentage point increase in electricity shortage, and they show that it impact firm entry and industry composition. Similarly, Fisher-Vanden, Mansur, and Wang (2015) estimate the effects of electricity shortage for China's industrial firms and point out evidence of reallocation and substitution for energy by materials (i.e. other intermediary inputs) to avoid productivity losses.

Moreover, there are large fluctuation in energy prices in a highly non-competitive market – as mentioned and developed in Asker, Collard-Wexler, and De Loecker (2019) and Kellogg (2014). The market for energy and prices being determined at the world level (for oil, gas and coal) or national levels (for renewable energies), the prices fluctuations are largely exogenous. In the case of oil, market power by the OPEC, and the geopolitics of Middle East, Russia and the U.S. have influence on its price, and we expect that these concerns are exogenous to firm-level performance. More generally, we can assume than most firms – on the demand side of the energy markets – are price-takers in the energy market and hence take price and cost fluctuations as given. We could hence use these price variation as an appropriate instrument of energy expenditure.

More specifically, the macroeconometrics literature has disentangled the different sources of oil price movement, see for example Kilian (2009), Kilian and Murphy (2014). For example, Kehrig and Ziebarth (2017) used Kilian (2009) methodology to investigate the influence of oil supply shocks on wage dispersion and labor demand and general equilibrium prices. Our goal would be to use these exogenous variations to instrument firm-level energy use and hence estimate production elasticity to energy costs.

3 The reallocation channel – Networks

What is the transmission of shock to the energy sector – for example a drop in fossil-fuel energy supply – on the rest of the economy? If the energy and electricity sectors were manufacturing sectors like any other, the standard diversification argument would hold and the shock would average out with disaggregation. However, the energy sector is likely to be linked to all the other sectors of the economy – since as we argued above, oil or electricity are hardly substitutable in goods and services production. As a result, the energy sector is likely to be the typical example of "star network" where all the sectors are interconnected to this input producer. Hence, the microeconomics shock to energy sector can not be averaged out, as argued in the now large literature on networks, for example in Acemoglu, Akcigit, and Kerr (2016), Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012) or Baqaee and Farhi (2019) and other related articles by the same coauthors.

Our aim in this part of the project is to quantify the impact of shocks to the energy sector on the aggregate economy with 3 deviations:

(i) a non-trivial input-output network – inducing cascade effects since energy and electricity sectors supply most other industries and services –

(ii) a non-Cobb Douglas production – involving potentially non-linearity since energy is used in production is an Leontieff/non-substitutable fashion.

(iii) a deterministic decline in the productivity of a sector – since the efficiency of the energy sector has been declining c.f. evidence in section 4 and section 5.

We wish to quantify the impact in terms of output and welfare gains of these deviations from the standard macro framework.

First, it is appropriate to follow the approach of the network literature, the main variable in this context lie in the Input-Output matrices $\Omega = \{\omega_{ij}\}_{ij}$, with $i \in \mathcal{I}$ the number of our economy. The input share $\omega_{ij} = \frac{p_j x_{ij}}{p_i y_i}$ is the share of good j (where x_{ij} is the quantity j supplied to i) – it represents the direct exposure, as expenditure share of input on revenue. The total – indirect – exposure of the input j is given by the column of the Leontieff-inverse matrix:

$$\Psi = (I - \Omega)^{-1} = \sum_{n=0}^{\infty} \Omega^n$$

The influence of a particular sector on total output is measured by the vector of Domar Weights $\lambda = b'\Psi = \{\lambda_i\}_i$, where $\lambda_i = \frac{p_i y_i}{\sum_{j=1}^{n} p_j x_j}$ is the share of sale of a producer on aggregate revenue.

The effects of a supply shocks to sector/producer i is hence given by Hulten's theorem on the LHS – a first order approximation, exact for Cobb Douglas production function – or the second order extension by Baqaee and Farhi (2019).

$$d\log Y = \lambda' d\log A + \Lambda' d\log \Lambda$$

Supply shock, or analogously to productivity shocks to A_i – have a (first order) direct given by λ – the Domar-Weight – on . The second effect given by reallocation across sectors of given by the vector Λ and the change in the Domar-Weight following the shock.

Moreover, decomposing the variance of output, Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012) find a relation between the variance of aggregate output Y and the distribution of degree of the network, the degree is defined as the sum of each column of the input-output matrix Ω, i.e. $d_i^n = \sum_{j=1}^{n} \omega_{ij}$ – with n the number of sectors. As given by their Theorem 2, given the Cobb-Douglas assumption, we have:

$$\mathbb{V}\mathrm{ar}(\log Y^n) = \mathcal{O}\big(\tfrac{1}{n} ||d_i^n||_2\big)$$

This implies if some sectors has a high outdegree d_i^n, despite the growing disaggregation $n \to \infty$, the variance of output doesn't shrink with diversification.

This framework, extended to second order, could allow to analyze more general productions functions – analogous to the one we developed in section 2. Consider a network structured as in fig. 4, where the production are Nested-CES: Two factors, electricity E and labor L are used in the production of intermediary goods:

$$x_m = \left(\alpha e^{\frac{\varepsilon-1}{\varepsilon}} + (1-\alpha)\, \ell^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}$$

The final consumption good is

$$c = y = \Big[\sum_{m=1}^{N} \omega_m x_m^{\frac{\sigma-1}{\sigma}}\Big]^{\frac{\sigma}{\sigma-1}}$$

Moreover, we assume that the substitutability at the final consumption stage is greater than for the intermediary good process: i.e. $\sigma \gg \varepsilon$. This is consistent with empirical gathered in section 2.

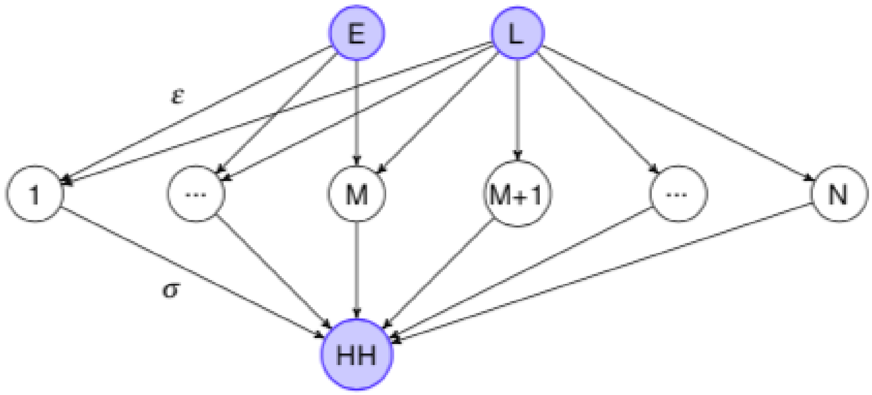


Figure 4: Energy-based economy, Network example in Baqaee and Farhi (2019)

As mentioned by the Hulten theorem, the first order effect of shock to the productivity of the energy sector is simply the Domar Weight $\frac{\partial \log Y}{\partial A_E} = \lambda_E = \frac{p_e e}{\sum_m p_m x_m} \in (0, 1)$. The methodology and example given in Baqaee and Farhi (2019) yields a second order term as follow:

$$\begin{aligned}
\frac{d^2 \log Y}{d \log A_E^2} &= \frac{d\Lambda_E}{d \log E^2} \\
&= \lambda_E \frac{(\varepsilon-1)(1-\frac{N}{M}\lambda_E) + (\sigma-1)\lambda_E(\frac{N}{M}-1)}{1+(\sigma-1)\lambda_E\frac{\frac{N}{M}-1}{1-\lambda_E} + (\varepsilon-1)\frac{1-\frac{N}{M}\lambda_E}{1-\lambda_E}} \\
&\underset{M=N}{=} \lambda_E \frac{(\varepsilon-1)(1-\lambda_E)}{\varepsilon} = \underbrace{\frac{(\varepsilon-1)}{\varepsilon}}_{\substack{\to+\infty \\ \varepsilon\to 0}} \underbrace{\lambda_E(1-\lambda_E)}_{>0}
\end{aligned}$$

$$\Rightarrow \qquad \lim_{\substack{\varepsilon\to 0 \\ d\log A_E<0}} \frac{d^2 \log Y}{d \log A_E^2} = -\infty$$

Hence, for elasticity of substitution of energy ε close to zero – i.e. the Leontieff case – the second order effects can be particularly large, showing the impact of non-substitutability on the aggregate production growth. This effect could rationalize the long-term decline in potential output, as shown in the secular stagnation hypothesis.

Lastly, the network structure also has important policy implications. We emphasized in introduction the two sources in reduction in energy use: one comes from a decline in supply of fossil-fuels, and the second comes from a shrinkage of demand due to policies fighting climate change. As developed in Acemoglu, Akcigit, and Kerr (2016), in first-order, the supply-side shocks would propagate downstream while demand-side shocks propagate upstream. Hence, the physical constraints causing a drop in energy – analogous to a TFP shock – would propagate downstream, with a potentially amplification effect as explained above.

However, the costs of a policy-driven reduction in energy consumption can be implemented in different ways: one could impose a carbon-tax, inducing a wedge in the fossil-fuel energy sector, whose impact will be distributed downstream. Alternatively, government could also implement quotas, which would act on the resource constraint and would propagate mainly upstream. Hence, the shock would affect much more strongly the fossil-fuel industry – which has relatively less upstream supplier – but would have a milder effect on the rest of the economy. Depending on the political views and the vested-interests underlying energy policy, the welfare gains and costs of different scenario could be analyzed in this framework.

4 Hubbert's peak theory and the decline in energy supply

Hubbert's peak has been one of the most striking empirical regularity in geosciences. First observed for U.S. Conventional Oil Production, it has been observed in most non-renewable resources – for a review of the concept, see Bardi (2019). The main idea is the following: At a given field-level or mine-level, the production usually rises slowly, due to high fixed costs and time required for mining. The extraction rises until it reaches a peak around half of the stock of resources. Afterward, due to increasing marginal costs, the exploitation decreases until the field or mine is fully depleted. At the world level, many geologists claim that the peaks of conventional crude oil and natural gas happened in the first decades of the 21st century. Hence, we expect to see a decline in these two major sources of energy, emphasized by the forecasts of the International Energy Agency IEA (2018), which underlines the "risk of of a supply crunch" in the coming years – due to reduction in activity in U.S. shale oil producers. More generally, we observe a long-term slowdown in the growth of energy production at the world level, as schemed in fig. 5 and fig. 6 for a basic model calibration of the Hubbert's peak model.

The General Depletion Picture

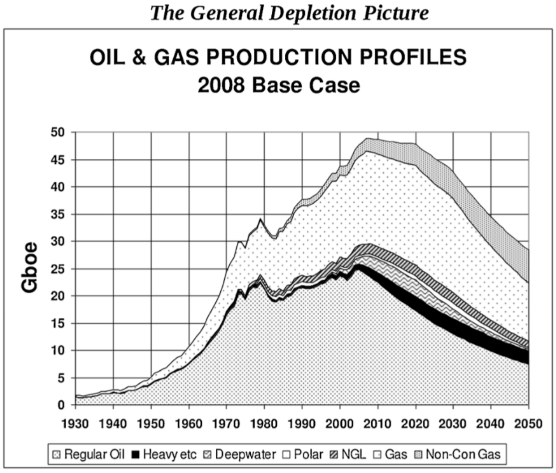


Fig. 1. The projection of oil production appearing in the 100th (and last) issue of the ASPO newsletter in 2009. It shows the peak for "regular oil" to appear around 2008, while the peak for "all liquids" (the sum of conventional and non-conventional oil) appears around 2010 [5].

Figure 5: Peak Oil predicted in 2009, from Bardi (2019)

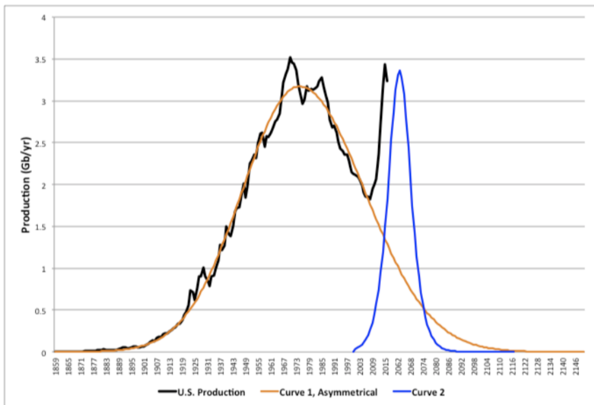


Fig. 15 U.S. production data fit with an asymmetric curve (Curve 1) approximating the production cycle of conventional resources, with Curve 2 fit to the production of tight oil.

Figure 6: Hubbert's peak model, calibrated on U.S. Oil production in 2017 – from Peebles (2017)

Even if one doesn't believe in Hubbert's peak theory – after all the shale oil production has been overlooked even if this source was available several decades ago – there exists a consensus on the decline in energy capacity out of these fossil fuel as summarized by the concept of EROI. The Energy Return on investment is a notion of cost of energy production, defined as the ratio between the energy delivered to consumers and the energy invested by producers in its exploitation and distribution.

$$EROI = \frac{E \text{ produced}}{E \text{ Invested}}$$

The continued increasing supply in oil and natural gas has be made possible thanks to the hydraulic fracking revolution in 2009-2012. However, one of the under-looked feature of this source of energy has been the decline in its EROI.

According to the meta-analysis in Hall, Lambert, and Balogh (2014), the EROI in the fossil fuel extraction industry have been declining substantially in the last decades. Traditionally, the EROI or conventional oil and natural gas averaged 25:1. However, non conventional extraction – like Tar sands and Shale Oil that requires energy-intensive fracking – have shown to have an EROI lower than 10. Overall, the EROI of the Oil and Gas have declined from around 30:1 in 1990 to 15:1 in 2010. Coal represent an exception as its EROI is still high – despite declining – around 40:1, which explain its continued use for energy production in most emerging and several developed economies. Overall, more recent studies, e.g. Brockway, Owen, Brand Correa, and Hardt (2019) confirm this downward trend for fossil fuels.

This increasing cost in energy and the declining EROI should divert a higher share of funds toward the energy sectors. Moreover, this reduce production, investment and future growth in the short-run. As argued in Tverberg (2012), this would generate a decrease in energy demand. Indeed, historically and as suggested in section 2, peak in energy prices are associated with a reduction in investment, production and energy demand – potentially leading to recessionary episodes. Indeed, recessions like the ones in the 1930s (c.f. Tverberg (2017)), late 1970s and 2008-2010 were all associated with ex-ante peak in price of energy (coal and oil respectively) and a stagnating production. The drop in aggregate demand resulting from the crisis depresses energy demand would in turn would decrease energy prices in the medium-run. Hence, energy demand and supply follow some kind of cycle production, preventing the price to rise too high and dampening investment and innovation in more costly sources of energy. If this hypothesis needs to be explored theoretically for future research, this can be an explanation for these long-run cyclical and volatile pattern of oil prices.

Given first these for medium to long-run trends in energy supply reduction, and second the concern about climate change mentioned in introduction, we would like to question the alternative scenarios. Can we replace this declining energy supply by oil and gas by alternative renewable energies and can generate growth in the medium-run – i.e. are the scenarios of green growth credible? We will see that it is unfortunately not the case.

5 Is green and clean growth possible in the medium-run? (the answer is no!)

Following the same strategy as above for fossil fuel, one could compute the EROI of renewable energy. Despite an average low level, solar panel and photovoltaic electricity production have shown a return on energy increasing, from less than 2:1 in 1980 to around 6:1 in 2010, c.f. Hall, Lambert, and Balogh (2014). Even with reestimation of the photovoltaic to around $\sim 6-12$:1 for electricity generation, as shown in Raugei et al. (2012), the level stay significantly smaller than fossil fuels[4], c.f. Bhandari, Collier, Ellingson, and Apul (2015) and King and Van Den Bergh (2018).

Two additional factors make the use of renewable energies – i.e. solar panel, wind turbines and hydroelectric plants – unlikely for providing energy to the entire economy. First, renewable energies have highly volatile production – called intermittency – throughout the year. In the US, the daily solar production varies from a factor ~ 2 between the winter and the summer (i.e. the production in July is twice larger than in January). Similarly, the hydroelectric and wind production are respectively $\sim 50\%$ and $\sim 30\%$ larger in spring than in fall c.f. Tverberg (2019) for U.S. Data and Jancovici (2019) for German data. Moreover, volatility is even larger – by a factor $\sim$ 5-7 – at higher frequency (day, week) due to meteorological factors. This renders the use of renewable energies for mass production – i.e. 100 % of the energy mix – unlikely and highly costly in terms of energy losses.

Even with massive policy intervention, the cost of reconverting non-renewable sources – fossil fuels sources accounts for more than 80% of energy produced – greatly outweighs the costs related this reallocation. Different scenarios forecast that – to provide actual consumption – renewable power sources should grow by factor 90 to 200 by 2050, which represent a growth between 13% and 15% per years. No source of energy in history has never achieved growth of this level – as even affordable coal and oil has always displayed a growth smaller than 10%.

This *Green Growth* scenario – achieving 100 % renewable electric system globally by 2060, as unlikely as it might be – would also reduce the efficiency of the energy sector. Indeed, according to the study by Capellan-Perez et al. (2019), this transition would decrease the EROI of the system from current 12:1 to 5:1. This level is below the threshold identified as viable for complex societies. Indeed, for an energy system to be sustainable, the net energy – the energy supply after deducting the energy used in production, preparation, storage, distribution and production of the involved infrastructures – should be strictly positive. A low EROI system make this scenario highly unlikely.

This idea underline the concept of ***"net energy cliff"***: the net energy available to the society is expressed as $Net\ Energy = Energy\ Produced \times (1 - \frac{1}{EROI})$. This function is highly non-linear when $EROI$ decrease below 5:1, causing an abrupt reduction in energy available for other sectors.

[4] When considering final-stage energy generation, we should take the ratio of energy readily available to consumer – after extraction (the standard EROI), preparation (such as refining, for the point of use EROI), and distribution to the point of use (the extended EROI). More broadly, for renewable energies, we should also account for energy used to manage storage/intermittency of the system and to build the infrastructures/machines that produce all the elements of the production sector (from the solar panel/wind turbines to the distribution).

An example of this notion is displayed in the fig. 7, and more rigorous analysis can be found in Hall, Balogh, and Murphy (2009) and Brockway, Owen, Brand Correa, and Hardt (2019).

To study the potential different scenarios in case of reduction in EROI, one can find comprehensive study in King and Van Den Bergh (2018) and Capellan-Perez, de Castro, and Gonzalez (2019). The main implication is a sharp reduction in net final energy per capita – as mentioned throughout this proposal. King and Van Den Bergh (2018) forecasts a decline of 0.7% per year in the next three decades – with a drop of 30% by 2050 – as opposed to a rise of 0.5% historically, as displayed in fig. 8.

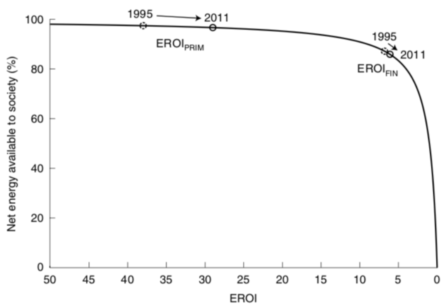


Figure 7: Net energy cliff: with EROI (Energy Return on Investment) on the x-axis and the Net Energy $= 1 - \frac{1}{EROI}$ on the y-axis, from Brockway et al. (2019)

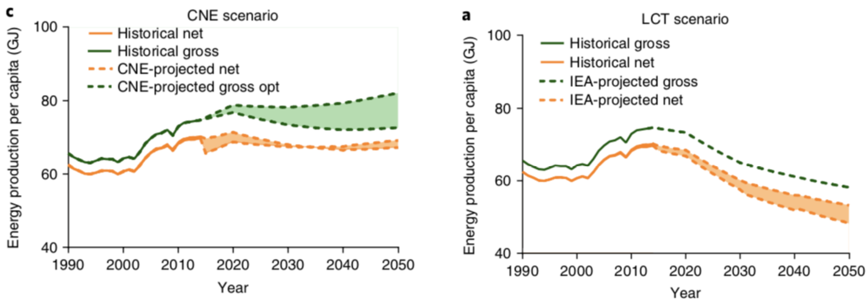


Figure 8: Stagnation or Decline in world energy per capita, depending on the Scenario: either a Low-Carbon transition (LCT, aimed at satisfying the $2°C$ limit), or a Constant Net Energy (CNE, aimed at maintaining the energy consumption per capita), from King and Van Den Bergh (2018)

To understand more broadly this conclusion of King and Van Den Bergh (2018) and to see how the concept of "green growth" may be misplaced, one should analyze the greenhouse gas emissions using the framework[5] of KAYA identity (or $I = PAT$ identity, with impact I, population P, affluence A & technology T)

$$CO_2 = P \times \frac{Y}{P} \times \frac{E}{Y} \times \frac{CO_2}{E}$$

If one would like to control or reduce CO_2 emissions, policies should try leveraging other factors by reducing:

(i) Reduction in population P – the demographic transition may decrease population, but only after a peak above 10 billions at the end of the 21st century[6]

(ii) Reduced emission due to cleaner energy CO_2/E – hard to implement in the short-run due to the reasons invoked above, e.g. low EROI and high costs for renewable energies

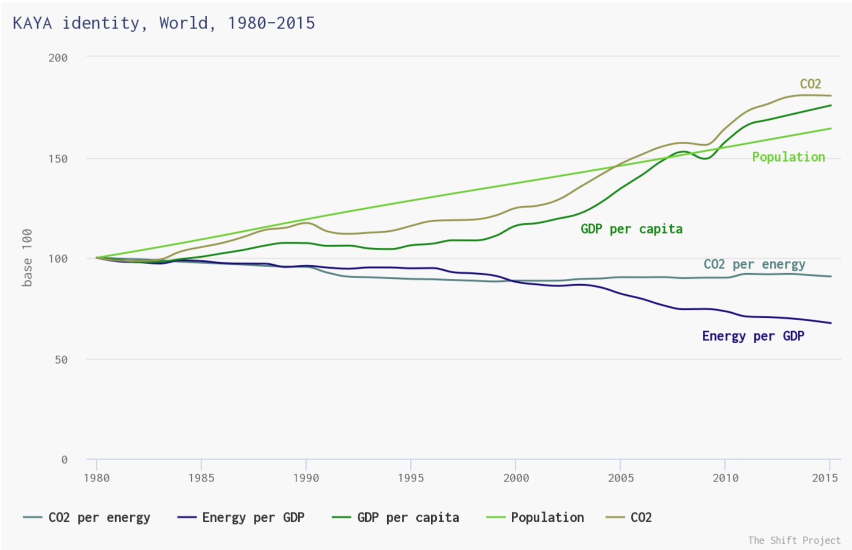
(iii) Improvement in efficiency (i.e. reduction in E/Y) – also potentially hard to implement at a high scale for the same reasons – low EROI of renewable energies

(iv) Reduction in ... growth i.e. production per capita Y/P

[5] One could find emissions simulators in `http://climatemodels.uchicago.edu/` built by David Archer from UChicago

[6] Forecast by the United Nations c.f. `https://www.un.org/development/desa/en/` and `https://www.worldometers.info/`

The share of these different channels of reductions in greenhouse gas emissions can be summarized in the following graph. One can see that the first item to have increased the overall greenhouse gas emission is precisely the production per capita. Our argument in our entire project above is to show that reducing the source of emission – the use of energy – and production may actually be linked and shall be understood as one leverage to reduce emission.

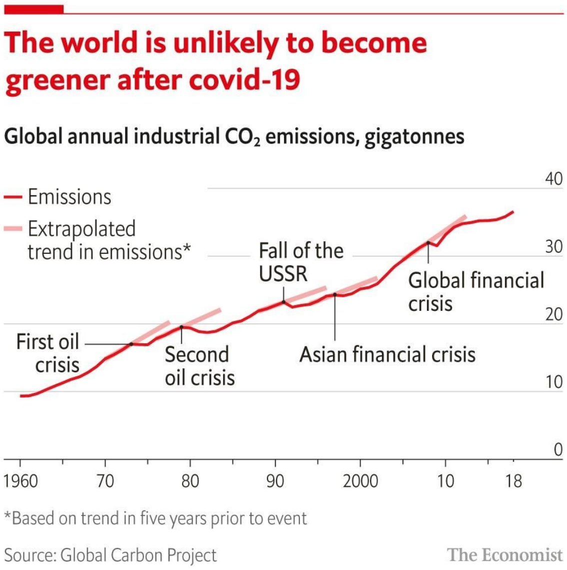


6 Conclusion

To conclude, in the two previous sections we tried to gather facts that are often underlooked in the economics literature: (i) energy resources like fossil-fuels have decreasing supply in the medium-run (in the coming 30-40 years) due to finite reserves and other physical constraints, and (ii) renewable energy are less efficient to produce a large share of the energy mix – even less so in the short-run (in the next 10-20 years). This makes impossible to both sustain economic growth and meet the requirement of the fight against climate change.

We start from these two facts as a rational for the main shock we consider – a reduction in production of energy and electricity – and we wish to quantify the effects of this shock at different levels of disaggregation. First, we wish to investigate the effects at the firm-level to analyze the microeconomic transmissions effects. This could provide estimates for the elasticity of substitution of this input with – potentially exogenous – variation in cost/price. Moreover, we can assess the non-linear effects of reducing supply and the heterogeneity in energy use across sectors and throughout the firm distribution.

Second, we wish to analyze the macroeconomic impact of such shock using a network approach. The energy and electricity sectors are central in our economy in the sense that they supply all sectors and this input is used in a non-substitutable way. This makes the Cobb-Douglas assumption difficult to accept and we show that the second-order effects can have large costs in terms of growth and welfare gains.



These different facts show that there is indeed a trade-off between economic growth and the environment, since the fight against climate change can not be implemented without decline in aggregate production.

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