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The Influence of Economic Growth, Population, and Fossil Fuel Scarcity on Energy Investments

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Summary

This paper examines the dynamics of energy investments and clean energy Research and Development (R&D) using a scenario-based modeling approach. Starting from the global scenarios proposed in the RoSE model ensemble experiment, we analyze the dynamics of investments under different assumptions regarding economic and population growth as well as availability of fossil fuel resources, in the absence of a climate policy. Our analysis indicates that economic growth and the speed of income convergence across countries matters for improvements in energy efficiency, both via dedicated R&D investments but mostly through capital-energy substitution. In contrast, fossil fuel prices, by changing the relative competitiveness of energy sources, create an economic opportunity for radical innovation in the energy sector. Indeed, our results suggest that fossil fuel availability is the key driver of investments in low carbon energy innovation. However, this innovation, by itself, is not sufficient to induce emission reductions compatible with climate stabilization objectives.

Keywords: Technological change and innovation, Energy investments, R&D Investments, Fossil fuel availability, Fossil fuel prices, Energy Intensity, Carbon Intensity

JEL Classification: O13, Q 43, Q54, Q55

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The influence of economic growth, population, and fossil fuel scarcity on energy investments

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Abstract

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1. Introduction

Technological change and innovation respond to the price signals induced by environmental regulations. Studies have highlighted the importance of policy credibility, the design and architecture of the policy (Baker and Shittu 2006, Blanford 2009, Clarke et al. 2009, Bosetti and Victor 2010, Luderer et al 2010, De Cian and Tavoni, 2011, De Cian et al. 2011), and the portfolio of competing technologies (Clarke et al. 2007, Richels and Blanford, 2008, Bosetti et al 2009b, Edenhofer et al, 2010, Tavoni et al 2011). Socio-economic dynamics and the availability of natural resources can also influence the pathway and direction of technological change, but integrated assessment models have analyzed the implications of these factors to a lower extent.

Outlining possible tendencies for the evolution of technological change throughout the century requires a reasonable modeling of technical change paired with credible socio-economic scenarios. Given the length of the time horizon considered it is hard to anticipate the future evolution of population and economic growth, as well as the direction of technological change. New technologies could make fossil fuels cheaper or lead to major breakthroughs that will completely change the way we use and produce energy. The aim of the RoSE project is to assess energy transformation global scenarios across different reference assumptions for future socio-economic development as well as exhaustible resources availability, and for this purpose a suite of scenarios has been developed.

This paper uses an Integrated Assessment Model with endogenous technical change in clean energy to examine how economic growth, economic convergence, population trends, and fossil fuel scarcity affect clean energy innovation and energy investments in baseline scenarios. Section 2 briefly describes the set-up and the methodology, though the specific details of the scenario design are provided in Kriegler et al. (this issue). Section 3 discusses the role of economic growth, convergence, and population. Section 4 focuses on the role of fossil fuel availability. Section 5 presents some considerations regarding the impact of socioeconomic assumptions versus fossil fuel scarcity. Section 6 concludes.

2. Set-up and Methodology

This paper examines the implications on technological change and energy investments using the WITCH model (Bosetti et al. 2006) for a subset of the global scenarios developed within the context of the RoSE project[1] (see Kriegler et al., this issue). Although policy implications are briefly discussed in Section 5 and 6, we focus on the role of economic growth, population, and exhaustible resources availability independently of climate policy. While the effect of policy has been explored by a number of studies (for applications of

[1] http://www.rose-project.org/

the WITCH model see Bosetti and De Cian 2013, De Cian and Tavoni, 2012, De Cian et al. 2012) to our knowledge the effect of growth and population assumptions and of fossil fuel scarcity has not been assessed in the context of integrated assessment models. Prior studies have mostly focused on the role of economic growth but with no considerations for the role of fossil fuel scarcity (Hübler 2011, Hübler et al. 2012, Hübler and Steckel 2012, Leimbach and Baumstark 2010). This paper aims at filling that gap.

The distinguishing features of the WITCH model have been described in several studies (see Bosetti et al. 2006 for a description of the model structure, while Bosetti et al. 2009 and De Cian et al. 2012 for technological change) and details are available in the electronic supplementary material (ESM) to the overview paper (Kriegler et al, forthcoming). The remainder of this section briefly describes the features important for understanding the results presented in the subsequent sections.

2.1 Brief model description

WITCH is a regional integrated assessment model. The top-down component consists of an intertemporal optimal growth model in which the energy input of the aggregate production function has been expanded to give a bottom-up description of the energy sector. Equation (1) describes the aggregate production assumed in the model. It has a Constant Elasticity of Substitution (CES) structure and it aggregates the Cobb-Douglas nest between capital (K) and labour (L) with energy services (ES), with an elasticity of substitution equal to 0.5:

$$Y_{i,t} = TFP_{i,t}(\alpha_{KL_i}(K_{i,t}{}^{\beta}L_{i,t}{}^{1-\beta})^{\frac{\sigma-1}{\sigma}} + \alpha_{EN_i}ES_{i,t}{}^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}}$$

$$i = 1,\ldots,13 \text{ are the model regions}$$

$$\text{t} = 2005,\ldots,2100 \qquad \text{(Eq.1)}$$

Energy services (ES) is a CES nest between the stock of energy efficiency knowledge (EE_R&D) and the energy inputs, EN:

$$ES_{i,t} = \left[a_1\, EE\_R\&D_{i,t}^{\frac{\sigma_{ES}-1}{\sigma_{ES}}} + a_2 EN^{\frac{\sigma_{ES}-1}{\sigma_{ES}}}{}_{i,t}\right]^{\frac{\sigma_{ES}}{\sigma_{ES}-1}} \qquad \text{(Eq. 2)}$$

Technological dynamics in the energy sectors are partly endogenous. Regions can invest in energy R&D for incremental efficiency improvements in the use of energy inputs. These investments lead to reduction in the energy intensity of the economy. The knowledge stock (EE_R&D) can substitute energy inputs (EN) with an elasticity of substitution equal to 4, $\sigma_{ES} = 4$. Regions can also invest in radical or breakthrough R&D, which lead to new discoveries that, with a time lag of ten years, translate into full commercialization of non-fossil technologies that partially or totally displace established technologies, such as oil in the transport sector or nuclear in the power sector. More precisely, two breakthrough technologies are considered. The breakthrough technology in the power sector is a linear substitute of nuclear power. The breakthrough technology in the final sector is a linear substitute to oil. The process of breakthrough innovation is modeled as a two-factor learning curve for the costs of breakthroughs. Through Learning-By-Researching, the stock of breakthrough knowledge (BT_R&D) reduces the cost of the technology (IC) as shown in Eq. 3. Deployment (CC) contributes to further the cost reduction of the technology (Learning-By-Doing) once this becomes commercialized:

$$\frac{IC_{j,i,t}}{IC_{j,i,0}} = \left(\frac{BT\_R\&D_{j,i,t-2}}{BT\_R\&D_{j,i,0}}\right)^{-c} \left(\frac{CC_{j,t}}{CC_{j,0}}\right)^{-b} \qquad \text{(Eq. 3)}$$

where j is the index for the two breakthrough technologies .

Knowledge production of energy efficiency and breakthrough R&D is described by an innovation possibility frontier that exhibits both intertemporal and international spillovers of knowledge (e.g. blueprints, exchange of ideas between researchers, and imitation). New knowledge cannot be fully protected by patents and therefore there is some unintended diffusion. International knowledge spillovers are described by a relationship that links the stock of energy knowledge in each country to the international pool of knowledge. Foreign knowledge has a positive contribution to domestic knowledge formation only if the recipient country has a sufficiently high absorptive capacity, measured in terms of domestic knowledge stock. The further away countries are from the technology frontier, defined as the gap with the stock of knowledge in high-income countries, the higher the potential for technology diffusion, *ceteris paribus*.

Macroeconomic growth is driven by exogenous total factor productivity (TFP). Economic growth scenarios are simulated by calibrating the dynamic path of TFP. Population scenarios are replicated by adopting the prescribed projections for population, which coincides with the labor production factor in Eq. (1).

2.2 Investments and energy prices in the WITCH model

In the WITCH model energy investments are endogenous. Regions choose the entire sequence of investments in final good, which builds the physical capital stock, K, in the aggregate production function in Eq. 1. Simultaneously they optimally choose investments in energy supply technologies, which include natural gas combined cycle, oil- and pulverized coal-based power plants, integrated gasification combined cycle power plants equipped with carbon capture and storage, hydroelectric power, nuclear power, and wind turbines. These options build the energy nest, EN, in the energy services production function in Eq. 2.

Global Learning-By-Doing also affects wind power investment costs. The cost structure of wind power is described by a one-factor learning curve, as in Eq. 3 with the exponent of Learning-By-Researching set to zero, as this technology is already on the market (e.g. *b=0*). The cost of wind and breakthrough technologies in each given region is thus endogenous and can be influenced by global investments.

Extraction costs are explicitly modelled only in the oil sector. The extraction cost of oil includes three components, a fixed factor, a module that mimics short-term frictions that arise in the market when demand increases too fast, and a module that reflects the exhaustibility of oil. The price of coal and gas is endogenously determined by the marginal cost of extraction, which is linked to current and cumulative extraction by a reduced-form equation. A regional mark-up mimics differences in regional costs. The capital costs of other technology are exogenous.

3. The role of macroeconomic drivers. Economic growth, convergence, and population

This section analyses the effect of macroeconomic drivers - economic growth, economic convergence between developed and developing countries, and population growth - on the energy investment mix and on indicators of environmental performance - energy intensity of GDP and carbon intensity of energy. All scenarios discussed in this section share the common assumption of medium availability of fossil fuels.

Table 1 shows the annual average energy investments, computed throughout the century, the fossil fuel prices in 2100, energy and carbon intensity in 2100 as a percentage change to 2005. In all scenarios the investment mix is dominated by fossil fuels followed by wind and hydro, nuclear, and energy efficiency R&D. Since the scenarios considered do not include climate policies, all energy sources are used, including fossil fuels, to feed the growing demand for energy.

R&D expenditure is increased to the extent this choice allows maximizing welfare. High economic and/or population growth exert a pressure on energy demand, raising the relative prices of energy to capital. The change in relative prices induces an increase in investments in energy saving R&D as a way to partly compensate the growing demand. However, high economic growth does not stimulate new inventions (breakthrough R&D). As long as fossil resources are expected to be abundant (with respect to high fossil scenarios considered in Section 4) and no technology failure of traditional technologies is anticipated, countries would not see the convenience of developing non-fossil alternatives. Economic growth does not induce breakthrough R&D because the medium availability of fossil fuels, together with nuclear power, is expected to meet the growing demand for energy.
In the model the indicator of economic convenience is that of relative technology costs and prices. We do not model issues such as energy security concerns or employment benefits that could introduce a motive for green investments. Is it also important to mention that the initial assumption about breakthrough technology costs affects the threshold of the relative price to oil at which the technology becomes competitive. We here assume that the

initial price of the breakthrough technologies is about ten times larger the 2005 price of commercial equivalents.

Demand–pull forces positively influence energy efficiency R&D. Non-fossil investments also increase with economic growth (BAU FS Gr vs. BAU DEF) or with high population growth (BAU HI Pop vs. BAU SL Gr SL Con), though the ratio of dirty-clean investments (fossil plus oil extraction over nuclear plus wind, hydro and R&D) remains unaffected. The carbon intensity of the energy mix slightly increases with population and economic growth (see the variation in carbon intensity in 2100 compared to 2005 in Table 1).
In contrast, the energy intensity of output is lower in the high growth (BAU FS Gr vs. BAU DEF) and high population (BAU HI Pop vs. BAU SL Gr SL Con) cases. This is driven by the larger energy efficiency R&D investments, but also by the energy –capital substitution at the top-level nest of the production function (see Eq.1).

In order to test the extent to which the reduction in energy intensity is due to innovation, we consider an additional fast growth scenario in which R&D investments are fixed to the slow growth case (BAU FS Gr case with R&D investments as in the case BAU SL Gr SL Conv). In this way we exclude the R&D channel and let only the substitution effect to play. We find that, in the long run, factor substitution between capital and energy explains most of the observed reduction in energy intensity. Although faster economic growth has been implemented in a neutral manner by augmenting total factor productivity (TFP in Eq. 1), and therefore without modifying the relative marginal productivity of the two production factors, the endogenous change in prices induces substitution between capital and energy. In the faster growth scenarios, the economy is relatively more capital intensive. Another effect at play is the change in fuel mix. In the BAU FS Gr all fossil fuel investments increase, but the mix between oil, gas, and coal varies. While oil is reduced, coal and gas go up by a comparable amount. Changes in the fuel mix are reflect in the carbon intensity rather than in the energy intensity of output. In fact, carbon intensity in the BAU FS Gr (BAU HI Pop) case is higher than in the BAU DEF (BAU SL Gr SL Con).

A closer inspection of Table 1 shows that economic convergence also affects the aggregate energy and carbon intensity. The variants with slow convergence (BAU SL Conv versus BAU FS Gr and BAU SL Gr SL Con versus BAU SL Gr) exhibit a lower reduction in energy intensity. Slow convergence (that is lower growth in emerging and developing countries) reduces all investments, including efficiency R&D and wind power. Greater reductions compared to the default case in percentage terms occur in the regions most affected by the convergence hypothesis, namely East Asia, India, Sub-Saharan Africa, and South Asia. The adjustment in developing countries induces an indirect effect in developed countries, which also reduce some of their investments in clean energy (wind) and clean energy R&D. Developing countries demand less energy, dragging down the international price of fossil fuels. As fossil fuels are cheaper, developed regions adjust their energy mix by replacing non-fossil investments with fossil resources.
Higher population growth in developing countries would bring long-term energy intensity back to the levels with fast convergence. In the model

population coincides with the labor force. Since production factors are gross complements, faster population growth compensates for lower growth in total factor productivity.

Figure 1 decomposes the global energy intensity into the structural adjustment induced by the convergence hypothesis and the energy intensity effect taking place within each region. The multiplicative logarithmic mean Divisa index method (LMDI, Ang 2005) is used to decomposes the change in aggregate energy intensity (EI_t) over time in the structural component and the intensity or technology term. The structural effect ($DStr_t$) describes changes in the regional composition of the aggregate energy intensity. The intensity technology effect ($DInt_t$) describes the improvements in energy intensity that occur within each given region. The product of the two effects yields the total variation in energy intensity between 2050 or 2100 and 2005.

The decomposition is illustrated for the slow growth case[2]. The structural effect (*Str*) *reduces* the energy intensity variation over time by lowering the weight of energy intensive developing countries (grey dashed line). On average, developing countries have higher energy intensity compared to the developed ones. As a consequence, when they grow less, aggregate energy intensity is also lower. The intensity effect, which represents the within country improvement due to efficiency R&D and capital-energy substitution, *increases* aggregate energy intensity variation over time. With slow convergence (BAU SL Gr SL Conv), the efficiency improvement is lower (black dashed line). The total effect that results from the combination of these two factors indicates that the intensity effect prevails because aggregate energy intensity is *higher* under slow convergence (red dashed line).

[2] The same analysis can be carried out by comparing the effect of convergence under the assumption of fast growth, namely BAU FS Gr versus BAU SL Con.

Table 1: Annual average energy investments (Billion 2005 US$/yr, computed throughout the century), energy prices in 2100 ($/GJ), energy and carbon intensity in 2100 (as percentage change to 2005) under different growth, convergence, and population scenarios.[3]

Supply-side investments						
Fossil fuel power plants						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
	423.15	345.48	511.70	404.92	448.27	306.67
Nuclear power plants						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
	110.88	89.06	135.20	112.16	128.49	85.21
Wind and hydro power plants						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
	147.65	139.52	157.02	148.42	153.74	136.23
Oil Extraction						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
	1736.01	1585.10	1909.54	1579.88	1751.72	1457.02
R&D| Breakthrough substitute for oil						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
	-	-	-	-	-	-
Demand-side investments						
R&D| Energy efficiency and clean energy						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
	24.44	19.48	31.58	27.35	26.90	17.51
Total						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
	2442.14	2178.64	2745.04	2272.73	2509.12	2002.65
Fossil fuel prices in 2100 ($/GJ)						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
Oil	40.68	26.28	61.84	37.51	49.13	22.08
Gas	9.35	8.61	10.28	9.07	9.54	8.24
Coal	4.35	4.09	4.71	4.26	4.40	3.92
Energy intensity of GDP in 2100						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
	-72%	-62%	-79%	-61%	-75%	-55%
Carbon intensity of energy in 2100						
	BAU DEF	BAU SL Gr	BAU FS Gr	BAU HI Pop	BAU SL Con	BAU SL Gr SL Con
	23%	20%	25%	20%	23%	18%

BAU DEF=Med Pop-Medium Growth - Fast Convergence, med oil, med gas, med coal; BAU SL Gr=Med Pop - Slow Growth - Fast Convergence; BAU FS Gr=Med Pop-Fast Growth - Fast Convergence; BAU SL Con=Med Pop-Fast Growth-Slow Convergence; BAU SL Gr SL Con=Med Pop-Slow Growth-Slow Convergence; BAU HI Pop=High Pop - Slow Growth - Slow Convergence

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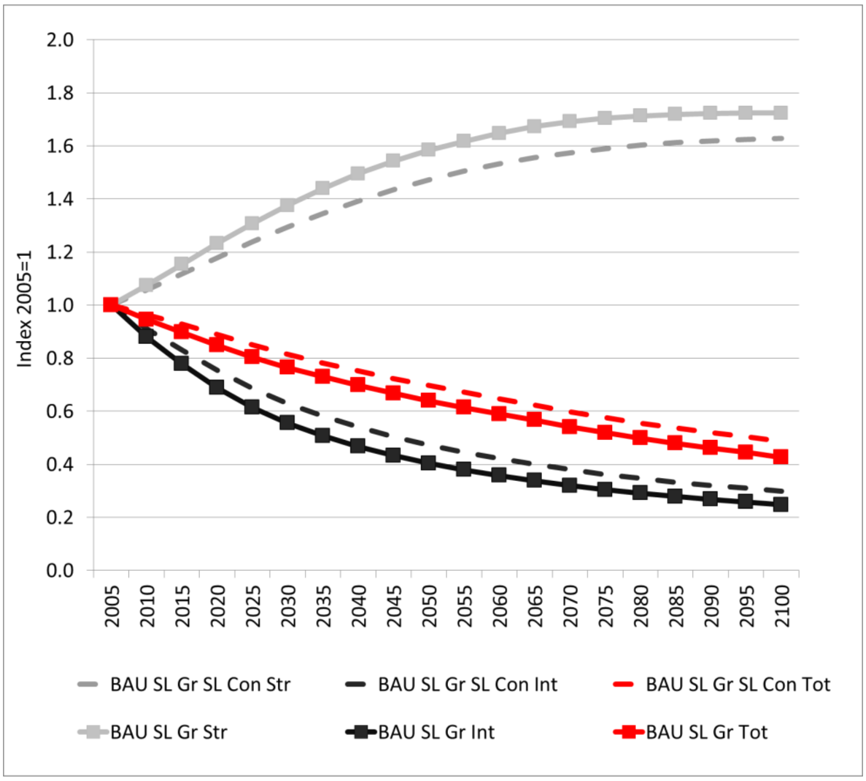
[3] Although Table 1 shows wind and hydropower investments together for the purpose of completeness only wind investments vary across scenarios. Hence the variation reported is attributable only to wind investments. Wind investments represent approximately one third of total (wind plus hydropower) investments.

Figure 1: Decomposition of energy intensity time variation into Structural (Str) and Intensity effects (Int). Slow growth scenarios with fast convergence, medium population growth (BAU SL Gr) and slow convergence, medium population growth (BAU SL Gr SL Con). The total effect is the product of the Structural and Intensity effects.



4. The role of fossil fuel resources availability

This section analyses the effect of fossil fuel scarcity on the energy investment mix and on indicators of environmental performance - energy intensity of GDP and carbon intensity of energy. Alternative futures regarding fossil fuel extraction costs are embedded in the different scenarios proposed in the ROSE project. Two scenarios vary the availability of all resources (BAU LO Fos, BAU HI Fos) compared to the BAU DEF default case. Scenarios BAU HI Coal, BAU LO Oil, and BAU LO OIL HI Gas lead to variations in the relative prices of fossil fuels. The main caveat of our analysis is that only technological change in clean energy is endogenous. Technological change in the extraction sector is exogenous. As a consequence, this section does not aim at fully assessing the trade-off between clean and dirty technical change. It simply aims at showing to what extent fossil fuels availability affects the incentive to invest in clean energy. All the scenarios considered in this section assumes medium economic and population growth and fast convergence.

Table 2 shows the annual average energy investments, computed throughout the century, the fossil fuel prices in 2100, energy and carbon intensity in 2100 as a percentage change to 2005. The availability of fossil fuel resources has significant impacts on investments in clean R&D and energy. Data reported in Table 2 indicates that investments in breakthrough R&D would occur only under the stimulus of high oil prices, triggered by oil scarcity (BAU LO Fos, BAU LO Oil, BAU HI Coal, BAU LO Oil HI Gas vs. BAU DEF). The anticipation that the oil price could almost treble compared to a case with abundant resources (BAU HI Fos), reaching more than 63US$/GJ (390 US$\bb) in 2100, creates a strong price signal that would make it optimal to allocate some of the productive resources to finance breakthrough R&D programs. Differently from the stimulus that comes from economic growth, which boosts incremental R&D programs for the improvement in energy intensity, oil scarcity would require radical technological breakthrough to develop alternatives to oil[4]. The expectation of low oil resources at the global level will redirect ample financial resources from the oil extraction sector to a clean energy R&D sector in order to introduce alternative energy sources. In particular the developed countries – which are the innovation leaders in the WITCH model, calibrated on 2005 data – will provide between half and two third of global financial flows to R&D programs. Following deployment, the Learning-By-Doing effect will further lower the price of breakthrough technologies. It is interesting to note that major changes in investments occur mainly on the supply side. Energy efficiency R&D investments will be also affected but to a minor extent.

The structural change induced by the anticipation of fossil fuels, and in particular or oil scarcity, shows up in lower energy intensity as well as lower carbon intensity (BAU LO Fos vs. BAU DEF in Table 2). In order to test the correlation between fossil fuel scarcity-driven R&D, decarbonization, and energy intensity, we considered a second additional run in which fossil fuels are scarce, but R&D investments are fixed to the level of the high fossil world (case BAU LO Fos with R&D investments fixed to the BAU HI Fos case). This test shows that R&D provides a significant contribution to decarbonization (see discussion in Section 5). Changes in the energy mix also play a role, as coal and gas are reduced relatively more compared to oil. We expect most of the effect being shown in carbon intensity, which is in fact much lower in the BAU LO Fos case.

[4] R&D investments in the breakthrough technology are the same across the various scenarios with low oil because oil scarcity pushes the breakthrough technology to its upper bound. This model version features a deterministic representation of endogenous technical change. We assume that breakthrough innovations occurs if R&D investments are sufficiently high. The probabilistic nature of innovation is analyzed in Bosetti and Tavoni (2008).

Table 2: Annual average energy investments (Billion 2005 US$/yr, computed throughout the century), energy prices in 2100 ($/GJ), energy and carbon intensity in 2100 (percentage change to 2005) under different fossil scenarios.

	BAU DEF	BAU HI Fos	BAU LO Fos	BAU LO Oil	BAU HI Coal	BAU LO Oil HI Gas
Supply-side investments						
Fossil fuel power plants	423.15	426.20	364.81	442.48	414.31	440.17
Nuclear power plants	110.88	106.54	128.15	108.27	115.87	108.80
Wind and hydro power plants	147.65	146.12	153.31	147.45	148.88	147.62
Oil Extraction	1736.01	1653.52	939.53	941.64	939.28	941.12
R&D| Breakthrough substitute for oil	-	-	36.55	36.43	36.54	36.43
Demand-side investments						
R&D| Energy efficiency and clean energy	24.44	18.74	30.35	28.14	29.63	28.19
Total	2442.14	2351.11	1652.70	1704.41	1684.50	1702.34
Fossil fuel prices in 2100 ($/GJ)						
Oil	40.68	22.41	64.11	63.76	63.79	63.75
Gas	9.35	7.87	14.63	7.87	13.98	7.87
Coal	4.35	4.16	6.04	4.21	4.25	4.35
Energy intensity of GDP in 2100	-72%	-67%	-76%	-72%	-75%	-72%
Carbon intensity of energy in 2100	23%	11%	-2%	3%	9%	2%

BAU DEF=Med Pop-Medium Growth - Fast Convergence, med oil, med gas, med coal; BAU LO Fos=BAU DEF low oil – low gas – low coal; BAU HI Coal=BAU DEF low oil – low gas – high coal; BAU LO Oil=BAU DEF low oil – high gas – high coal; BAU LO Oil HI Gas=BAU DEF low oil – high gas – medium coal; BAU HI Fos=BAU DEF high oil – high gas – high coal; BAU LO Oil HI Gas=BAU DEF low oil – high gas – medium coal.

The notion that the direction of technical change relates to factor scarcity dates back to the induced innovation hypothesis formulated by Hicks (1932) and revised by Ahmad (1966). More recent studies have examined the response of innovation indicators, such as R&D expenditure or patenting activity to changing energy prices[5]. These studies suggest that increases in

[5] Popp (2002) estimated a long-run elasticity of energy patenting with respect to energy prices of 0.354. He also concluded that energy prices can stimulate innovation pretty quickly. Newell, Jaffe, and Stavins (1999) examined the extent to

relative prices induced by oil price shocks or policy regulations stimulate green R&D and clean investments.

The fossil fuel sector could also respond to increasing energy prices with more research and development in novel extraction methods in order to make the exploitation of non-conventional resources cheaper. Historical time series of patent counts and public R&D expenditure in the extraction sector reveal a positive correlation with the major oil shocks. This suggests that the oil shocks boosted not just green innovation, but also R&D and patenting in the fossil fuel sector. Considering that overall patenting activity has been increasing over time, the share of international patents in the extraction sector and renewable energy over total patents has been increasing from mid-nineties onward. As a matter of fact, over the past hundred years, technological progress has greatly reduced the marginal costs of using fossil fuels (Rogner et al 1993; Ruttan 2001). More recently, the diffusion of hydraulic fracturing and horizontal drilling[6] have made unconventional gas as cheap as the conventional one.

In a context of scarce oil, the different availability of gas and coal could also affect investment decisions in non-fossil energy and clean R&D, though marginally compared to the prevalent impact of oil price. To tease out the effect of gas, Table 3 compares the two scenarios that differ only in the availability of gas (BAU LO Oil with low oil, high gas, high coal and BAU HI Coal, with low oil, low gas, high coal). Abundant gas would displace wind and nuclear power plants (see Table 2). What if nuclear investments were for some reason constrained? Table 3 also shows the same two cases with low and high gas, but assuming nuclear phase out. Nuclear power would need to be compensated with by renewables, but also with more fossil fuels, as there are no carbon price penalties. However, the change in fossil fuel is small. To meet the growing demand of energy new technologies would need to emerge. Investments in breakthrough power R&D would increase to reach an average amount of 14 billion USD/yr over the century. The larger increase in breakthrough power investments as opposed to fossil fuel investments is also driven by the production structure assumed. While fossil fuels are in CES nest

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which the energy efficiency of the menu of home appliances available for sale changed in response to energy prices between 1958 and 1993. They found that the amount of innovation and energy efficiency improvement respond to changes in energy prices within a time framework of five years. By now a large number of papers also control for the inducement effect of some indicator of environmental policy or pollution expenditure, see Popp, Newell and Jaffe (2009) for a review.

[6] We talk about diffusion rather than invention because these technologies were invented in the 1950s and 1960s. A quick search for patent data using "horizontal drilling" and "hydraulic fracturing" as keywords, reveals that the 29 and 9 patents were granted under these keywords, respectively, between 1950 and 1960. Source: http://gb.espacenet.com/ viewed on December 30 2011.

with nuclear power, the power breakthrough technology is a linear substitute to nuclear. Other R&D and wind investments[7] would be only slightly affected.

Table 3: Annual average (over the century) energy investments (Billion 2005 US$/yr), under different fossil scenarios with and without nuclear power.

Supply-side investments	W nuclear		W/O nuclear	
Fossil fuel power plants	BAU HI Coal	BAU LO Oil	BAU HI Coal	BAU LO Oil
	414	442	415	443
Nuclear power plants	BAU HI Coal	BAU LO Oil	BAU HI Coal	BAU LO Oil
	116	108	-	-
Wind and hydro power plants	BAU HI Coal	BAU LO Oil	BAU HI Coal	BAU LO Oil
	149	147	150	148
R&D| Breakthrough substitute for nuclear	BAU HI Coal	BAU LO Oil	BAU HI Coal	BAU LO Oil
	-	-	14.22	13.63
R&D| Breakthrough substitute for oil	BAU HI Coal	BAU LO Oil	BAU HI Coal	BAU LO Oil
	36.54	36.43	36.50	36.39
Demand-side investments	W nuclear		W/O nuclear	
R&D| Energy efficiency and clean energy	BAU HI Coal	BAU LO Oil	BAU HI Coal	BAU LO Oil
	29.63	28.14	29.55	28.03

BAU HI Coal=BAU DEF low oil – low gas – high coal; BAU LO Oil =BAU DEF low oil – high gas – high coal

Although a glut in natural gas supply (BAU LO Oil case vs. BAU HI Coal) will significantly increase gas power plant investments, the crowding out on energy R&D and non-fossil investments would be negligible. The R&D sector would continue to attract about 10 and 12% of total energy investments, with and without nuclear power, respectively.

5. Growth impacts versus fossil scarcity impacts

When analyzing the effects of socio-economic trends and of fossil scarcity on energy intensity we have highlighted two main mechanisms, the R&D effect and the substitution effect between capital energy as well as between different fuels.

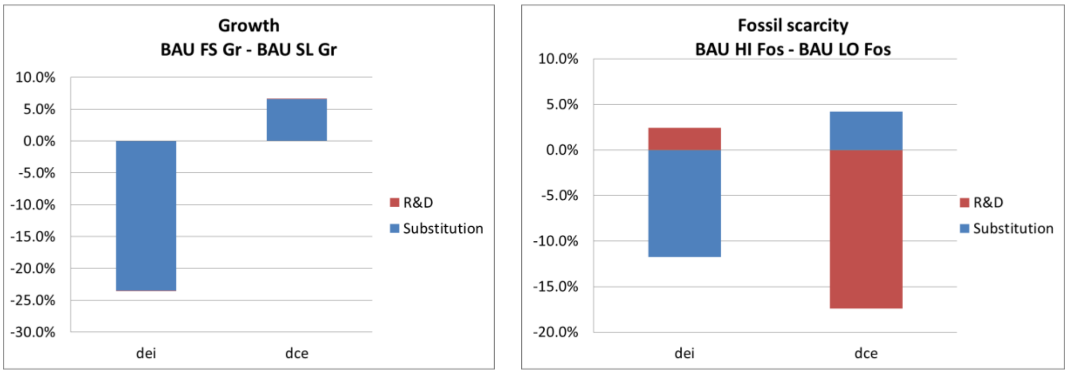
Figure 2 decomposes the variation in energy intensity between 2100 and 2005 (*dei*) and carbon intensity (*dce*) into two effects, the R&D effect (in red) and the substitution effect (in blue). In the left panel the substitution effect is computed as the *percentage point difference* between *dei* and *dce* in the BAU FS Gr scenario with R&D fixed to the BAU SL Gr case and the BAU FS Gr scenario with R&D free to adjust as in the BAU FS Gr case. In the right panel the substitution effect is computed as the *percentage point difference* between *dei* and *dce* in BAU LO Fos scenario with R&D fixed to the BAU HI Fos case and the BAU LO Fos scenario with R&D free to adjust as in the BAU LO Fos.

[7] Investments in hydropower are not discussed because they do no vary across scenarios.

In both panels the R&D effect is the *percentage point difference* between the total variation (*percentage point difference* between BAU FS Gr and BAU SL Gr SL Con and between BAU HI Fos and BAU LO Fos) and the substitution effect just defined.

The R&D effect plays a negligible role in the growth scenario, where the main driver of energy and carbon intensity changes is the substitution effect. In contrast, in the fossil scarcity scenario the R&D effect plays a prominent role in lowering the carbon intensity (*dce*). As fossil fuel scarcity looms, the regions will invest in R&D order to satisfy energy demand with new and cleaner sources of energy. The deployment of new non-fossil technologies reduces the incentive to invest in energy saving technologies, which explains the positive effect on the energy intensity indicator (*dei*).

Figure 2: Decomposition of the 2100-2005 variation in energy intensity of GDP and in the carbon intensity of energy in the substitution (blue) and R&D (red) effect. The substitution effect accounts for variations in both the capital-energy mix as well as in the fossil fuel composition.



Our analysis has illustrated how the portfolio of investments induced by different socio-economic and the fossil scenarios translates into variations of energy efficiency and carbon intensity of the energy mix. What would be the ultimate impact in terms of CO2 emissions?

Figure 3 plots the relationship between per capita CO2 emissions[8] and per capita GDP in the various scenarios. The chart combines the macroeconomic scenarios with solid lines (BAU DEF, BAU SL Gr, BAU FS Gr, BAU HI Pop, BAU SL Con, BAU SL GR SL Con) and the fossil fuel scenarios with dashed lines (BAU HI Fos, BAU LO Fos, BAU LO OIL, BAU HI Coal, BAU LO OIL HI Gas, BAU HI Gas).

The macroeconomic scenarios never show a turning point and per capita emissions increase with GDP per capita. Only in the low growth scenarios (BAU SL Gr and BAU Sl Gr Sl Con), there is long-term growth with constant

[8] CO2 fossil fuel emissions are considered.

emissions. The fossil fuel scenarios display a turning point at about 31k USD in 2080 per capita when scenarios envisage scarce oil resources After that point, GDP per capita grows up to 42k USD in 20 years while emissions per capita decline from the peak value of 6.5 to 6.3 ton CO_2. In the low oil scenarios, long-term per capita GDP can grow to levels close to the medium case (43kUSD in 2100), but with much lower emissions (between 6.3 and 7.8 instead of 9.6 tCO_2 per capita in 2100). The highest emission paths occur when all fossil fuels are abundant (BAU HI FOS), assuming medium population and economic growth, and when there is high economic growth, provided fossil fuels availability is medium (BAU FS Gr). The fossil fuel abundant scenario implies an additional GHG emissions of 1500 $GtCO_2$ (up to 2100) compared to the scenario with low fossil fuels (BAU LO FOS), which has a carbon budget of 5024 $GtCO_2$ (CO_2 emissions excluding land use) considering all century. Cumulative GHG emissions in the fast growing scenario (BAU FS Gr) amounts to 6826 $GtCO_2$, which is similar to the BAU HI FOS case (6524 $GtCO_2$).

Economic growth and faster convergence across countries leads to a more efficient use of energy inputs. Higher fossil fuel prices create an economic opportunity for radical innovation in the energy sector. Yet, the induced R&D and carbon-free investments are not sufficient to induce emission reductions compatible with climate stabilization objectives, shown by the black lines in Figure 3. In the absence of policies, emissions per capita can get at most close to a moderate policy case, which is still inconsistent with the ambitious objectives for slowing down global warming.

R&D investments would lag behind the levels observed in stabilization scenarios, as shown in Figure 4. On average baseline total R&D investments amount to about 67 Billion 2005 US$/yr, while they increase to almost twice as much (113 Billion 2005 US$/yr) in the 450 stabilization scenario (450 DEF).

Figure 3: Fossil CO2 emissions per capita and per capita GDP throughout the century in baseline scenarios and two policy scenarios (450 ppm and moderate policy scenario).[9] Each marker represents a different year from 2005 to 2100.

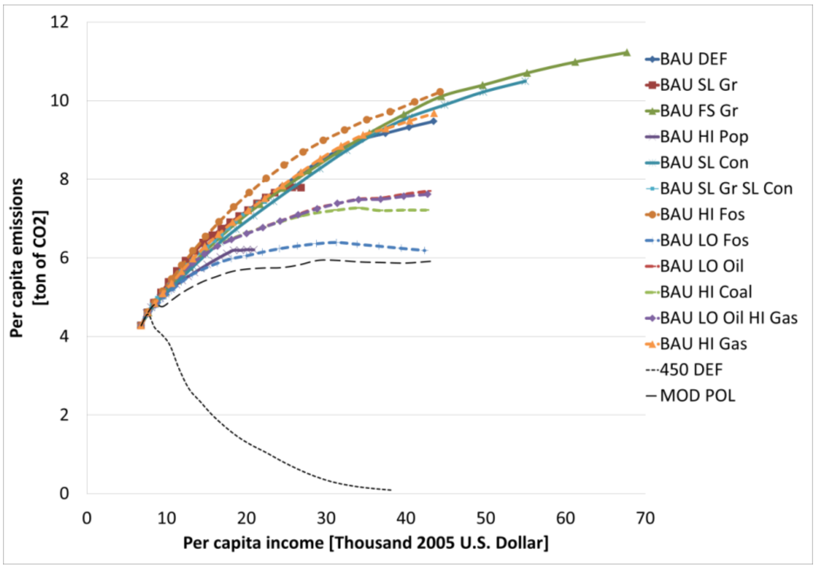
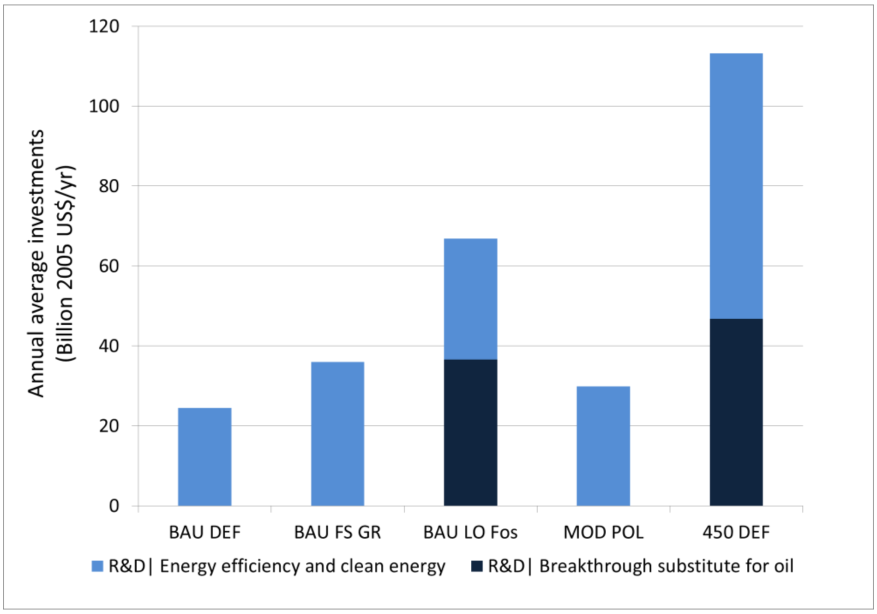


Figure 4: Annual average investments (Billion 2005 US$/yr) throughout the century,



[9] BAU DEF=Med Pop-Medium Growth - Fast Convergence, med oil, med gas, med coal; BAU SL Gr=Med Pop - Slow Growth - Fast Convergence; BAU FS Gr=Med Pop-Fast Growth - Fast Convergence; BAU SL Con=Med Pop-Fast Growth-Slow Convergence; BAU SL Gr SL Con=Med Pop-Slow Growth-Slow Convergence; BAU HI Pop=High Pop - Slow Growth - Slow Convergence; BAU LO Fos=BAU DEF low oil – low gas – low coal; BAU HI Coal=BAU DEF low oil – low gas – high coal; BAU LO Oil=BAU DEF low oil – high gas – high coal; BAU LO Oil HI Gas=BAU DEF low oil – high gas – medium coal; BAU HI Fos=BAU DEF high oil – high gas – high coal; BAU HI Gas=BAU DEF medium oil – high gas – medium coal.

6. Discussion and conclusions

This paper has examined the implications of macroeconomic assumptions and fossil fuel resources availability on the patterns of energy investments and clean energy innovation.

Economic growth and fossil fuel scarcity can both stimulate clean energy innovation and non-fossil-fuel investments. When economies or population grow faster, the increased relative energy-capital price induces a more efficient use of energy resources, but the composition of the energy mix would not be significantly modified. Innovation dynamics would not be significantly affected and fossil fuels remain the prevalent source of energy. These patterns are reflected in lower aggregate energy intensities, but almost unaffected carbon intensity of the energy mix. Faster convergence across countries also leads to a more efficient use of energy inputs.

Faster convergence across countries also leads to a more efficient use of energy inputs globally. On the one hand, faster convergence increases aggregate energy intensity by raising the weight of energy-intensive developing countries. On the other hand, faster convergence improves the use of energy resources via efficiency R&D and capital-energy substitution. This second effect prevails, and overall energy intensity is lower when convergence is faster.

High fossil fuel prices create an economic opportunity for decarbonizing the energy mix even in the absence of a climate policy. When fossil fuel resources are expected to become scarce throughout the century, ample financial resources will be redirected to R&D in order to introduce alternative energy sources. Developed countries will provide between half and two third of the global financial flows to R&D programs.

We also argue that the availability of cheap gas resources would increase gas investments, mostly to substitute coal especially in coal-intensive countries. Yet, it would only marginally displace investments in renewables and clean energy innovation. The R&D sector would continue to attract about 10 and 12% of total energy investments, with and without nuclear power, respectively.

In terms of policy implications our study suggests that, although economic growth and fossil fuel prices can create an economic opportunity for more investments in non-fossil energy technologies and clean energy R&D, those investments do not induce emission reductions compatible with climate stabilization objectives. Only the simultaneous expectation of oil, gas, and coal scarcity could set the per capita emission-GDP relationship on a path that mimics a scenario with moderate and fragmented climate policies.

The main caveat of our analysis is that only technological change in clean energy is modeled as an endogenous process. Future research should look at the dynamics and determinants of clean innovation and technical change versus technical progress in the fossil fuel extraction sector.

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