Energy efficiency policies and climate change mitigation costs: a general equilibrium assessment

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Abstract

This paper revisits the relationship between technical change and economic growth in a hybrid general equilibrium model, where energy prices induce energy efficiency. The sensitivity of climate mitigation costs to energy efficiency and the timing of action is assessed. Energy efficiency in productive sectors lowers energy prices, increasing demand through lower prices of non-energy goods and higher household revenues driven by higher employment and wages. Energy efficiency lowers the carbon price, shifting the emission constraint away from household energy consumption. Energy efficiency policies drive economic growth and reduce policy costs, but only if energy efficiency policies in industrialised regions are combined with measures to accelerate technology transfers towards other regions. The timing of efforts reveals a trade-off between short and long term costs. Early action triggers energy efficiency but shows high short term costs and should be considered in combination with policies to accelerate technology diffusion, while late action shows high long term costs, even when combined with policies to enhance innovation and accelerate diffusion. Early action could reduce the uncertainty surrounding the appropriate discount rate for policy assessment, while late action would require measures to reduce long term costs, including policies to alter household energy demand.

Keywords: Energy Efficiency; Climate policy; General Equilibrium; Technical change

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1 Introduction

The nature of the interaction between energy and economic growth is still an unresolved issue in the economic literature. Following (38), some econometric studies have identified energy use as a determinant and possible limiting factor of economic growth, while other studies have questionned the causal relationship between energy use and economic output, see (48) for a review. The relationship between energy prices and economic growth is less controversial. Econometric analyses have indeed demonstrated the correlation between oil price shocks and short-term economic growth downturns (29). At the same time, high energy prices may bias innovation towards energy efficient technologies (see (50) for a review), which would allow energy saving technical change to reduce energy use and CO_2 emissions while sustaining long-term economic growth.

This paper revisits the issue of the relationship between technical change, energy and economic growth in a hybrid general equilibrium model where macroeconomic feedbacks link energy supply and demand to the structure of the economy. In particular, the paper assesses the impact of energy efficiency policies on the macroeconomic costs of abating CO_2 emissions and illustrates the interplay between such measures and carbon pricing in productive and end-use sectors, with a particular focus on industry. A series of numerical experiments are performed in order to assess the sensitivity of climate mitigation costs on energy efficiency improvements and on the timing of climate action. The paper is structured as follows. Section 2 presents a brief review of the empirical literature on energy-saving technical change and of traditional approaches to model the relationship between technical change and economic growth. Section 3 presents the hybrid general equilibrium model Imaclim-R which aims at bridging the gap between existing modelling approaches. Section 4 presents the impact of energy efficiency improvements on climate mitigation costs. Section 5 examines the impact of the speed of diffusion of energy efficient technologies and of the timing of climate action on mitigation costs. Section 6 concludes.

2 Literature review: technical change and economic growth in energy-economy models

2.1 Technical change, energy and economic growth

Technical change is defined as the evolution of technologies and processes. Induced technical change is the alteration of the rate and direction of technical change in response to policy (9). Technical change can be induced by investments in R&D, learning-by-doing, or relative price changes, see (50) for a review. While R&D investments may influence the rate and direction of technological change, learning-by-doing may reduce the unit cost of a particular good as a function of experience. Technical change may also occur as a change in the relative prices of factors spurs innovation directed at reducing the use of a factor which has become relatively expensive (30). Energy efficiency improvements, particularly in industrializing countries, may be driven by technology transfers as well. The diffusion of energy efficient technologies across regions is seen as critical to mitigate climate change. In particular, the Clean Development Mechanism of the Kyoto Protocol has been used as a tool to facilitate the transfer of low carbon technologies towards industrializing countries (40).

Empirical studies show that higher energy prices have been associated with energy efficiency improvements. For instance, (51) shows that energy prices and energy intensity of industrial production have been negatively correlated in eight energy intensive U.S. industries over the 1970-1990 period, with two thirds of the change in energy consumption due to price-induced factor substitution and the remaining third resulting from induced innovation. (20) also identify rising energy prices as one of the key factors of energy intensity reduction in Chinese industry between 1997 and 1999. Higher fossil energy prices driven by carbon pricing may induce firms to invest in new knowledge to develop less carbon intensive processes and products (46). A rise in energy prices may also drive households to purchase more energy-efficient equipment, products and services. However, the general equilibrium effect of energy efficiency improvements may well lead to higher overall emissions, as energy-saving technical change may result in greater energy consumption by households driven by lower energy prices[1]. The overall effect of climate mitigation on economic growth is thus ambiguous. Nonetheless (41), estimating elasticities on past data, found that energy efficiency accounts for most of the growth attributed to technological progress. However, international technology transfers do not necessarily translate into an increase of the productivity of all factors. Again in the case of the Chinese industrial sector, imported technology may be labour and energy saving but capital using, (20) .

2.2 Modelling the relationship between technical change and economic growth

Long-run studies of the interaction between technical change, the economy and climate policies have been traditionally performed either by using bottom-up approaches (often in partial equilibrium) or top-down general equilibrium energy-economy models, see (35) for a review. On the one hand, stylised top-down models explore the link between technical change and macroeconomy at a very aggregate level. Top-down models usually rely on the use of production functions (58), which mimic the set of available techniques and the technical constraints on an economy (3; 36) and often use constant

[1] This is the case for China, as shown by (19) and (21)

elasticity of substitution. However, the aggregate representation of a continuous space of technologies via production functions is only theoretically justified near the equilibrium, and the use of constant elasticities of substitution may lead to incorrectly exceed feasible technical limits in the case of large departures from the reference equilibrium (44; 23), as may well be the case for ambitious climate policy. At this level of aggregation, technical change encompasses both the choice of techniques and structural change, and explicit energy technologies are usually not modelled since production function often fail to capture specific technology or resources constraints (4). On the other hand, bottom-up models embark detailed representation of energy production technologies, with special attention to the representation of inertia in building production capacity. Technical change is usually modelled using one or two factor learning curves for energy technologies, and can be induced by specific policies, such as a carbon price, which may favour learning in low-carbon technologies. Bottom-up studies are needed to explicitly track the time paths of the sets of available and operated techniques and allocate the changes in emissions and system costs between substitution effects and technological change (59). However, this bottom-up approach does not account for the impact of the evolution of the energy sector on economic growth through its impact on the structure of the economy, trade and the regional distribution of economic activity. In particular, (51) points out that assessing the long term effects of induced innovation require a general equilibrium analysis to account for the impact of demand on energy prices.

Either model structure cannot be justified when assessing policies aiming at changing development styles and the structure of economic activity to stabilize the climate (25; 34). Some attempts have been made to coupling bottom up models to conventional macroeconomic growth models (14; 56). The Computable General Equilibrium (CGE) model Imaclim-R aims at bridging the gap between these branches of the literature. This hybrid CGE model replaces the conventional aggregate production function by a recursive structure that encompasses bottom-up modules to capture the macroeconomic feedbacks between energy use and supply and the structure of the economy by transposing micro-economic mechanisms at the aggregate level.

3 Methods: technical change in a hybrid modelling framework

3.1 Imaclim-R: beyond the aggregate production function

Imaclim-R is a recursive, dynamic, multi-region and multi-sector hybrid CGE model[2] of the world economy (62). It is calibrated for the year 2001 by modifying the set of balanced input-output tables provided by the GTAP-6 dataset (15) to make them fully compatible with 2001 IEA energy balances (in Mtoe) and data on passengers' mobility (in passenger-km) from (57). The model includes market imperfections and partial uses of production factors and reveals the economic and technical transitory adjustments induced by the interplay between choices under imperfect foresight and the inertia of technical systems. Hybrid matrices ((23)) ensure a description of the economy in consistent money values and physical quantities (54). This hybrid accounting framework represents the material and technical content of production processes and allows for abandoning standard aggregate production functions. The absence of a formal production function is compensated for by a recursive structure that allows a systematic exchange of information between an annual macroeconomic equilibrium framework and technology-rich dynamic modules.

The static equilibrium models short-term macroeconomic interactions at each date under technology, capacity and investment constraints (figure Aa). The equilibrium is calculated assuming Leontief production functions with fixed intermediate consumption and labour inputs, decreasing static returns due to increasing labour costs at high utilization rate of production capacities (12) and fixed mark-up in non-energy sectors. Households maximize their utility through a trade-off between consumption goods, mobility services and residential energy use with fixed end-use equipment. Market clearing conditions can lead to a partial utilization of production capacities given fixed mark-up pricing and the flexibility of labour markets. Solving this equilibrium provides a yearly snapshot of the economy, i.e. a set of information about relative prices, output, physical and financial flows and profitability rates for each sector and the allocation of investments among sectors.

Each year, dynamic modules[3] use the snapshot of the economy stemming from the previous static equilibrium to assess the response of technical systems to this information and send back new input-output coefficients to the static module to determine the next equilibrium (figure Ab). Each year, technical choices are flexible but only modify at the margin the input-output coefficients and labour productivities embodied in existing equipment, which result from past technical choices. This putty-clay

[2] The twelve regions are USA, Canada, Europe, OECD Pacific, Former Soviet Union, China, India, Brazil, Middle-East, Africa, rest of Asia, Rest of Latin America. The twelve sectors are three primary energy sectors (Coal, Oil, Gas), two transformed energy sectors (Liquid fuels, Electricity), three transport sectors (Air, Water, Terrestrial Transport) and four productive sectors (Construction, Agriculture, Industry, Services).

[3] Including demography, capital dynamics, and reduced forms of energy production sectors and other economic sectors.

assumption allows representing the inertia of technical systems.

3.2 Technical change in energy and productive sectors

Induced technical change in productive sectors is modelled through two main channels in Imaclim-R, including varying details among sectors. First, energy efficiency improvements in productive sectors are induced by energy prices. Second, energy substitution may occur in all sectors, driven by learning-by-doing processes. At the aggregate level, energy efficiency improvements and energy substitution may result in the structural change of economic activity.

3.2.1 Energy efficiency improvements in productive sectors

For each productive sector (industry, services, agriculture), the region with the lowest final energy use per unit of production at base year is identified as the most energy efficient region, thus dividing the world into one leader region and eleven followers for each sector. The energy efficiency of the leader evolves as a function of the energy price index, given an exogenous trend for energy efficiency improvements at constant energy prices. The energy price index is determined endogenously, and the energy efficiency growth rate of the leader will increase (resp. decrease) in response to increases (resp. decreases) of energy prices. For each sector, the energy intensity of the followers is assumed to converge towards the performance of the leader, and the speed of convergence also depends on the level of energy prices. Some emerging economies may appear to be more energy efficient in some sectors at calibration year[4]. In these regions, the energy intensity of the concerned sectors is allowed to reach higher levels than the energy intensity of the leader at first, before converging towards the leader. Energy efficiency improvements are assumed to be in part free, and in part to coincide with an increase in the mark-up rate of firms, linking energy efficiency improvement to the cost of capital. Energy efficiency improvements in productive sectors are not biased towards low carbon energy as the use of fossil and non-fossil energy decreases uniformly but may result in lower emissions from productive sectors if fossil energy dominates the energy mix. A shift from carbon intensive to low carbon energy use in these sectors may be induced by the increase in fossil energy prices due to the introduction of a carbon price. In general, substitutions between energy carriers (coal, oil, gas, electricity, refined fuel) and transportation modes (road, rail, air, water) are driven by relative prices given explicit constraints on energy production and end-use equipment.

[4] From hybridizing IEA energy matrices and GTAP input-output tables, agriculture in Africa appears to be 12% more efficient than the leader (Japan), which can be due to missing reporting, difference in nature, difference in development and justify the precaution. (11) also reports some African countries to display an energy output to input ratio very high (Uganda is 380 times more "efficient" than Japan.

Energy efficiency improvements induce lower energy consumption per unit of output (ICu_{ener}) in each productive sector. This may result in higher or lower aggregated energy consumption (IC_{ener}), depending on the relative effects of lower unitary energy consumption and higher sectoral production (Q) induced by lower prices. Lower overall energy consumption affects energy prices through two channels: a decrease in tax-exclusive prices because of lower energy use (IC_{ener}) and a relaxation of the carbon tax required to reach a set climate objective because of lower emissions. Overall, lower energy consumption thus results in lower tax-inclusive energy prices. As energy efficiency improvements are driven by the energy price index, lower energy prices may in turn counterbalance energy efficiency improvements. On the production side, lower unitary energy requirements (ICu_{ener}) decrease production costs and prices (p), driving up demand and production (Q).

3.2.2 Substitution and structural change

Substitution between energy goods (i.e. coal, oil, natural gas, electricity, refined liquid fuels) and substitution between transportation modes (i.e. by road, rail, air or water) are driven by relative prices, given the explicitly modelled constraints on energy production and end-use infrastructure, including energy production and conversion capacities and available end-use equipment. These substitutions occur at the level of all end-use sectors.

At the micro level, learning-by-doing may induce substitution between technologies, which in turn induce energy substitution, for instance from coal to gas for electricity production. Technology substitution is also explicitly modelled at the end-use level for transport, for instance between conventional and electric cars. Energy efficiency improvements are not biased towards low or high carbon energy, as the consumption of all types of energy decreases uniformly. However, for those sectors using fossil fuels, carbon pricing will increase the energy price index. The substitution between energy sources however depends on relative prices and relies on a logit decision function for new vintages (the sectoral energy mix being the sum of energy demands of all vintages). Technical change may occur at the level of specific technologies through learning-by-doing processes. The cost of building energy production capacities is assumed to decrease with cumulative investment and production through learning-by-doing, using learning curves for all explicit technologies. The pace of cost reductions down the learning curve depends on initial built capacity, the learning rate and the floor cost. This approach has been used to characterise energy technologies, see for instance ((43; 45)). It is used in Imaclim-R to model electricity and oil production technologies, or for demand technologies (such as cars). In energy production sectors, learning-by-doing in low-carbon electricity production technologies (triggered by carbon prices) may improve the carbon efficiency of energy transformation through the substitution from fossil energy towards low carbon-alternatives. At the macro level, carbon pricing policies may induce a change in the structure of demand both at the household and firm levels by altering energy prices, which may in turn change the nature of the goods produced, therefore the structure of each sector and in the relative weight of each sector in total economic output.

3.3 Modelling economic growth

The natural growth rate is the growth rate that an aggregated one-sector economy would follow under full employment of production factors (49). In Imaclim-R, the natural growth rate is given by exogenous assumptions on active population[5] and labour productivity. The growth rate of labour productivity is prescribed over time for each region and sector[6]. In this multi-sectoral framework with partial use of production factors, the effective economic growth rate may depart from its exogenous trend. Indeed, the structure and rate of effective growth are endogenously determined by: (i) the allocation of the labour force across sectors which is governed by the final demand addressed to these sectors, and (ii) the shortage or excess of productive capacities which result from past investment decisions under imperfect expectations. First, the twelve production sectors have different productivities, captured by unitary labour requirement for production. The effective labour productivity of the economy therefore depends on the allocation of the labour force among production sectors. For instance, the overall productivity of labour increases through structural change that favours the reallocation of labour towards highly productive sectors, which may accelerate realised economic growth with respect to its natural rate. Second, yearly Leontieff production functions represent short term constraints imposed on production by the availability of capital. This specification captures the effect of technical inertias which affect the realised productivity of a sector, as exogenous labour productivity gains may not be transformed into actual growth in the case of investment shortages.

[5] Derived from UN medium scenarios.

[6] Exogenous labour productivities satisfy a convergence hypothesis (2) and are informed by historical data (42) and best guess assumptions (47). All sectors within one region exhibit the same growth in labour productivity, while its initial level is sector and region specific. Investments in education are calibrated, but the relationship between investments in education and the trend in labour productivity is not explicitly modelled.

4 Results: energy efficiency as a key determinant of economic growth and climate mitigation costs

4.1 Displacing the constraint from energy supply towards energy demand

The relationship between energy efficiency assumptions and economic growth under climate constraint is explored in climate policy scenarios corresponding to RCP 3.7 (550ppm target). In the modelled scenarios, for each year, the carbon price is determined endogenously to satisfy the CO_2 emission constraint. The CO_2 price (figure 1a) and consequently climate policy costs thus directly relate to the shape of the emissions constraint (figure B). The CO_2 price slowly increases between 2010 and 2040, followed by a steep increase between 2040 and 2070 as the bulk of the efforts is imposed. The carbon price stabilizes in the long term as the emission constraint levels off (2070-2100). The marked dip between 2070 and 2090 results from the expansion of bioenergy with carbon capture and storage in the electricity mix, allowing for net negative emissions combined with the slowing of emissions abatements imposed by the abatement trajectory.

The Kaya decomposition of emissions factors (figure 1b) presents energy and macroeconomic determinants of CO_2 emissions. Population and modelled lifestyles are identical between scenarios. Emissions changes can be explained by the evolution of three variables: GDP growth, final energy intensity of GDP and carbon intensity of final energy. This decomposition shows a larger contribution of energy efficiency improvements in emission reductions in the high energy efficiency scenario, with a smaller contribution of carbon intensity of energy. Besides, high energy efficiency reduces the stringency of the carbon constraint, allowing for higher GDP growth.

Under a given emission constraint, high energy efficiency lifts part of the decarbonisation effort because of lower energy needs in productive sectors. The emissions constraint is therefore less stringent for other sectors, and high energy efficiency results in lower carbon prices. In parallel, lower carbon prices explain the slower decarbonisation of energy production in the high energy efficiency scenario. Energy efficiency improvements in productive sectors thus induce a shift of the emissions constraint from energy supply towards energy demand.

4.2 Energy demand: shifting emissions from productive sectors towards household consumption

Displacing the constraint from energy supply to energy demand is not neutral with regards to sectoral demand and emissions. The emissions target imposes a constraint on the economy through the carbon price. The response of economic sectors to this constraint is heterogeneous, as some sectors may be easier to decarbonise than others[7]. The contribution of carbon and energy intensity improvements to emissions reduction relates to the distribution of abatement efforts among sectors, which depends on the relative responsiveness of each sector to the carbon price. The heterogeneity of sectoral responsiveness to carbon prices is illustrated by looking at the effect of energy efficiency on emissions from productive sectors and household energy use, as shown in figure 2.

The industry and composite sectors decarbonise faster in the high energy efficiency scenario, despite higher demand for industrial and composite goods in most regions (figure C), as emissions per unit of production in both sectors decrease faster in all regions in the high energy efficiency case. Emissions do not stabilize at the same level at the end of the period. This is due to different assumptions on the final level of the energy efficiency of the leader region[8] and different evolutions of the energy price index. The slight increase of industrial and composite emissions after 2080 is explained by the decrease in carbon prices in both scenarios following the complete decarbonisation of electricity production (figure D). In the low energy efficiency case, the peak in carbon prices after 2080 even commands negative emissions in this sector with increasing production of electricity from biomass combined with carbon capture and storage.

Contrary to the case of productive sectors, the transportation and residential sectors do not directly benefit from higher energy efficiency standards in this scenario setting. Lower carbon prices in the high energy efficiency case delay the decarbonisation of the residential sector, with higher final energy use and slightly slower improvements of the carbon intensity of final energy in that sector in the high energy efficiency scenario[9]. Higher final energy use in the residential sector is driven by higher household revenues and lower energy prices. Similarly, higher emissions from transport in the high energy efficiency case are induced by higher mobility (figure E) and higher CO_2 intensity of transport, mainly driven by larger automobile use due to lower petrol prices and higher income[10]. Low carbon prices also delay

[7] For instance, demand for transportation and fuel consumption of vehicles are relatively inelastic to energy prices in the short term (24).

[8] the high energy efficiency scenario, the energy efficiency of the leader is assumed to increase by 1.0% per year, contrasting with an increase of only 0.3% per year in the low energy efficiency case.

[9] Carbon intensity of final energy use in the residential sector decreases at the average rate of 0.9% per year in the high energy efficiency scenario, compared to 1.0% in the low energy efficiency case.

[10] Household income (in real terms) increases at an average growth rate of 2.5% per year over the period in the high energy efficiency case, compared to 2.3% in the low energy efficiency case.

the decarbonisation of electricity production, both in terms of overall emissions and CO_2 intensity of electricity production[11]. Higher emissions from electricity production are due to higher coal use without CCS, despite lower electricity production (figure D).

Energy efficiency improvements thus induce lower final energy consumption and emissions in all productive sectors and displace the emissions constraint away from energy production, transport and residential use. The following section illustrates the mechanisms at play in the industry, which accounts for over 70% of emissions from productive sectors in the base year, in order to understand the drivers of growth in productive sectors, and in the economy as a whole.

4.3 Industrial output: A decomposition

This section examines the interactions of energy efficiency with the determinants of industrial output and illustrates (figure 3) the economic channels by which energy efficiency decreases unitary energy consumption and impacts economic growth. Industrial output (measured in US$) can be divided into five types of expenditures: energy intermediate consumption, intermediate consumption of non-energy goods, labour costs, profits[12] and production taxes. Equation 1 presents this decomposition[13]. Each component is examined in turn to explain the drivers of industrial production growth. The impact of energy efficiency assumptions on each component[14] is summarised in tables A, B and C for industry.

$$\begin{aligned} p \cdot Q &= \sum_{energy} pIC \cdot ICu \cdot Q + \sum_{others} pIC \cdot ICu \cdot Q + w \cdot l \cdot Q + \pi \cdot p \cdot Q + tax \cdot p \cdot Q \\ output &= energy\ IC + other\ IC + labour\ costs + profits + prod.\ taxes \end{aligned} \tag{1}$$

p	price of the industrial good	US$/US$
Q	industrial production	US$
pIC	price of one unit of intermediate consumption	US$/toe or US$/US$
ICu	unitary intermediate consumption	toe or US$
w	wages	US$/worker-hour
l	inverse of the productivity of labour	worker-hour/US$
π	mark-up rate	%, i.e. US$/US$
tax	rate of production taxes	%, i.e. US$/US$

[11] Carbon intensity of electricity production decreases at the average rate of 3% per year over the 2010-2050 period in the high energy efficiency scenario, compared to 6% in the low energy efficiency case.

[12] Here profits refer to all earnings minus all operating expenses, CAPEX (investments, amortization and depreciation). As such, $profit = output - operating\ expenditures\ (incl.\ intermediary\ consumptions\ and\ wages) - taxes$.

[13] The subscript corresponding to the sector is omitted for clarity, and the decomposition is valid for all sectors.

[14] With the exception of production taxes which will not be examined further, as the tax rate is defined exogenously and overall production taxes follow industrial output.

4.3.1 Energy costs

The direct effect of energy efficiency improvements in industry is to decrease the required energy input for the production of industrial goods, e.g. one ton of steel (ICuener in toe/ton of Steel). From a sectoral viewpoint (free of any general equilibrium or intertemporal effects), this translates into lower unitary energy costs (ICener in $/ ton of Steel). Lower unitary energy costs in turn reduce overall production costs.

Energy efficiency improvements have two indirect effects on economic output. First, higher energy efficiency lowers global energy consumption[15], which relaxes tensions on energy markets and results in lower tax exclusive energy prices in the first half of the period (figure Ga). Second, lower energy needs command lower carbon prices to reach the same climate objective, particularly in the second half of the period (figure 1a). Both effects act to lower tax-inclusive energy prices (figure Gb). Energy efficiency improvements therefore results in lower energy prices in all regions. Finally, higher energy efficiency in productive sectors result in lower overall production costs of industrial goods, leading to an increase in industrial production quantities (+29%) and output (+3%).

4.3.2 Non-energy costs

Energy efficiency improvements affect the economy through the transmission of lower energy prices – as compared to low energy efficiency scenario – to all sectors, through the input-output matrix in the general equilibrium framework. Higher industrial output (measured in US$, figure C) requires higher input of non-energy goods (+18% in 2050). Higher total input of non-energy goods in value terms (+5% in 2050) occurs despite lower unitary costs of non-energy goods (-17% in 2050) in the high energy efficiency scenario. Lower unitary costs may be attributed to two separate effects relating to energy requirements and prices. First, lower energy requirements in all productive sectors (i.e. industry, services, agriculture and construction) decrease the costs of producing non-energy goods, which lowers their price. Second, lower (tax-inclusive) prices of non-energy goods (such as industry) also decrease the production cost and price of other non-energy goods.

4.3.3 Labour costs

Higher industrial output also entails higher labour requirements in physical terms (the production of more goods requires the increase of the number of hours worked or the increase of the number of workers). As each sector's labour requirements are determined by an exogenous trend of unitary labour

[15] Cumulative final energy consumption is 13% lower in the high energy efficiency scenario.

productivity over time, they directly follow sectoral output. Following (7), our modelling framework accounts for imperfections in labour markets by using regional wage curves which relate real wages to the unemployment rate, cf. (27). Higher labour requirements in productive sectors (and in the economy overall) result in lower unemployment and higher wages. However, unitary labour costs decrease (-9% in 2050), as wages are indexed on a consumer price index which decreases following energy efficiency improvements.

4.3.4 Profits

Investments in energy efficiency improvements are paid for by an increase of the mark-up rate, which induces higher profits[16], hence higher economic output following equation 1. Overall global investments are higher in the high energy efficiency scenario (2.0% average growth rate, compared to 1.9% in the low energy efficiency case). Higher investments from households are explained by higher household revenues (Figure 4), driven by higher employment and wages[17], while higher investments from firms are driven by higher economic output and higher mark-up rates in most regions and over most of the period[18]. The increase in investments from firms is relatively small, as higher profits from production increase are compensated by lower prices.

4.3.5 Summary schematics of interactions between energy efficiency and economic output

The results presented in tables A, B and C account for general equilibrium effects, and therefore include demand changes and intersectoral adjustments. In 2050, high energy efficiency standards result in lower energy expenditures (-46%), higher non-energy expenditures (+5%), labour costs (+17%), profits (+10%) and taxes (+14%) in the high energy efficiency scenario, for a higher total output (+3%). This hides a large increase of production (+29%). Unitary expenditures decrease for all items: energy (-58%), non-energy (-18%), labour (-9%), profits (-15%), taxes (-11%), leading to a price decrease of -20%. In summary, lower energy consumption results in lower production costs and lower prices of industrial goods which drives up industrial output, hence household revenues through increased labour requirements and wages. These results illustrate the virtuous circle created by energy efficiency improvements in this energy-intensive sector.

[16] The profits include all capital expenditures (investments, amortization and depreciation).
[17] Saving rates are exogenous and identical in both scenarios.
[18] Auto-investment rates are exogenous and identical in both scenarios.

4.4 Economy-wide impacts of energy efficiency

The case of industry has shown that energy efficiency improvements reduce energy requirements in this sector while increasing industrial output. The mechanisms described above occur in all productive sectors (figure C). Lower energy use reduces production costs through lower (tax-exclusive) energy prices and lower carbon prices, hence driving demand for all non-energy goods and consumption[19], while allowing for higher energy use in transportation and residential sectors. Energy efficiency improvements thus act as a shield to protect household consumption of energy, non-energy goods and mobility from higher prices induced by stringent emissions constraints.

Figure 4 shows that energy efficiency improvements in productive sectors reduce total final energy consumption, and decrease primary energy production, electricity production. Energy efficiency also reduces labour requirements in energy sectors but higher demand for non-energy goods drives overall employment, which, together with higher wages in all productive sectors[20], seems to trigger a virtuous circle of higher demand driven by higher revenues. In the Imaclim-R modelling framework, economic growth is driven by endogenous mechanisms associated with the functioning of energy and labour markets, and may thus depart from its natural rate[21]. Natural growth is not the only driver of realised economic growth. Rather, the evolution of labour and energy costs, which is determined endogenously in the model, has a significant impact on growth. This effect contributes to mitigate the overall costs of abating carbon emissions. Indeed, in the climate scenarios considered, high energy efficiency result in higher GDP and consumption overall. Also in terms of policy costs compared to the baselines, high energy efficiency always induces lower costs over the whole period. The impact of energy efficiency on growth and costs is further examined in section 5.

5 Discussion: the interplay between energy efficiency policies and the timing of climate action

The results have shown the ways in which energy efficiency improvements in productive sectors mitigate climate policy costs by shifting the efforts away from household use of energy services through lower carbon and energy prices. While energy efficiency improvements are clearly beneficial over the

[19] The energy intensity of consumption decreases at the average rate of 2.3% per year in the high energy efficiency case, against 1.9% per year in the low energy efficiency scenario.

[20] For instance, wages in industry (normalised to the consumer price index) are higher in all regions in the high energy efficiency scenario.

[21] The natural growth rate is defined as the growth rate that an aggregated one-sector economy would follow under full employment of production factors. In Imaclim-R, the natural growth rate is given by exogenous assumptions on active population and labour productivity.

period, the results have shown their sometimes ambiguous effect in terms of the timing of sectoral emissions. The discussion investigates the role of the timing of specific policies to induce energy efficiency improvements.

5.1 The impact of the speed of convergence on final energy and growth

5.1.1 On baselines

As described in section 3, the energy efficiency of all productive sectors evolves as a function of the energy price index, given an exogenous trend for energy efficiency improvements at constant energy prices for the leader region, and assumptions on the responsiveness to energy prices of the speed of convergence of follower regions towards the leader. The relationship between energy efficiency and economic growth is further examined by looking at the influence of energy efficiency in the leader and follower regions on economic growth in baseline scenarios. Two types of parameters are thus considered: the rate of energy efficiency improvements of the leader region at fixed energy prices and the speed of convergence in other regions towards the level of energy efficiency of productive sectors in the leader region. Four scenarios are examined combining alternatives on the exogenous trend at fixed energy prices for the leader (low or high) and on the speed of followers' convergence (slow or fast).

The economy benefits from energy efficiency improvements in productive sectors in baseline scenarios, with a gain of 0.1% average economic growth over 2010-2100 between lowest and highest energy efficiency scenarios. Over the whole period, a high level of GDP seems to coincide with a low level of final energy consumption and therefore a low final energy intensity of GDP. This average economic growth rate is determined by the rate of energy efficiency improvements of the leader and seems to be independent from the speed of convergence. This is explained by the fact that regardless of the speed of convergence, all followers aim at the level of the leader. In fact, the speed of convergence determines the level of the final energy intensity of GDP in the medium term while the level of the leader determines the final energy intensity of GDP in the long term (cf. figure 5).

5.1.2 On climate policy scenarios

Figure 6 presents instantaneous and discounted GDP losses for two convergence speeds. In the case of slow convergence, a higher level of energy efficiency in the leader region does not reduce climate policy costs (red vs. green). In the case of fast convergence however (blue vs. pink), higher energy efficiency of the leader greatly reduces costs for all discount rates. This result suggests that innovation in energy efficiency in industrialized regions would reduce the global costs of climate policy only if combined with specific measures targeted at technology transfers in industrializing regions.

While faster convergence always reduces policy costs in the case of an energy efficient leader, the speed of convergence has a non-trivial effect on the timing of climate mitigation costs in the case of a relatively inefficient leader. Indeed, slow convergence translates into a higher carbon price until 2040 and induces short term losses compared to the fast convergence case, while after that date costs are lower in the slow convergence scenario (figure 7, full lines). This behaviour is explained by the fact that with slower convergence, a larger contribution of the transportation and residential sectors to emissions reduction is required to meet the emission constraint, thus commanding higher CO_2 prices which affect economic output, as described in section 4. When looking at discounted costs[22], the benefits of fast convergence remain ambiguous for the case of an inefficient leader: slower convergence (red) induces higher discounted costs when focusing on the short term and lower discounted costs when focusing on the long term, which directly relates to the evolution of the CO_2 price mentioned above. This result points out to the impact of the timing of climate policy and the timing of energy efficiency improvements on policy costs.

5.2 Early action as a trigger of energy efficiency

The interplay and between the speed of convergence among regions and the timing of policies is explored by examining the impact of the timing of the constraint on the cost of climate policy. For that purpose, two emission profiles are tested (figure H), both corresponding to RCP 3.7. The late action trajectory is identical to the emissions constraint used in the first part of the study. It imposes relatively weak efforts until 2030 but stringent efforts in the longer term. By contrast, the early action trajectory imposes stronger efforts in the short term, allowing for less stringent efforts in the longer term to reach the same carbon budget. Figure 7 presents the results of this study. In all scenarios, the early action profile (dashed lines) commands higher CO_2 price in the short term compared to the late action case (full lines) to meet the stringent emissions constraint, but significantly lower taxes in the longer term. Indeed, the high short term CO_2 tax has triggered the early decarbonisation of the economy which is better prepared to abate emissions and faces a slower decarbonisation constraint in the medium term.

The results show that even in the case of early climate action, a high energy efficiency of the leader does not reduce climate costs if other regions converge only slowly towards that level (red vs. green, dashed). However, early action removes the ambiguity between fast and slow convergence in the case of a relatively inefficient leader, as faster convergence is then superior to slow convergence for discount rate

[22] Discounted costs are plotted as a function of discount rates. High discount rates translate short-term perspective with higher weight given to short term costs while low discount rates refer to a long-term perspective with equal weight given to short and long term costs.

above 2% (red vs. pink, dashed). Early action thus acts as a trigger of energy efficiency improvements in the case of a relatively inefficient leader (as confirmed in figure I, red and pink, dashed vs. full). This result is confirmed by comparing the relative contributions to emission reductions of energy efficiency improvements and carbon intensity reductions in early and late action scenarios: the Kaya decomposition shows a larger contribution of energy efficiency improvements in early action compared to late action in all cases. Early action erases the differences in terms of the relative contribution of carbon intensity reduction and energy efficiency reduction due to the speed of convergence of the followers. The speed of convergence thus plays a less significant role for climate change mitigation in the case of early action. When comparing energy efficiency assumptions, the only robust result across all discount rates is the superiority of the scenario combining a very energy efficient leader and fast convergence of other regions towards the leader. More precisely when looking at the long term costs of late action, policies targeted at enhancing energy efficiency improvements in leader regions and allowing the fast transfer of technologies among regions would compensate for high long-term costs induced by late action combined with lower energy efficiency (blue vs. red, pink and green, full lines).

In all cases, early action expectedly reduces discounted losses at low discount rates (long-term focus – up to 4%) and increases discounted losses at high discount rates (short-term focus – from 5%). Early action thus shows relatively high short term costs and should be considered in combination with ambitious policies to accelerate technology diffusion. Early climate action reduces the spread of discounted costs of all scenarios across discount rates (3.2-7.9%) compared to late action scenarios (2.3-10.8%), with a lower average losses over the considered discount rates for early action scenarios. This result shows that early action should be preferred given the uncertainty and controversy surrounding the appropriate discount rate for assessing climate policies.

5.3 Policy recommendations

The timing of the action nevertheless reveals a trade-off between short-term and long-term costs, translated into the choice of discount rate. If early action always appears more favourable in the long term whereas late action always appears to favour the short term, a relevant question is therefore what preference for the present makes them equivalent. In terms of policy design, this value is very important to be able to discriminate strategies. Policy-makers using social discount rates of 4 to 5% will consider early and late climate action as equivalent options based on their respective economic costs. In that case, one option cannot be favoured over the other on a mere option value basis, based on our scenarios.

The trade-off between early and late action should be considered in view of other policy levers.

Late climate action results in relatively high long term policy costs, even when combined with policy measures to enhance the energy efficiency of leader regions and to accelerate the convergence of other regions towards the leader. The results presented in section 4 illustrated the impact of decarbonising productive sectors through improved energy efficiency on the carbon intensity of the transportation and residential sectors. Additional measures to mitigate long term costs of late action could include policies aimed at altering the structure of households demand for energy services, particularly infrastructure policies in the transport sector.

6 Conclusion

This study has explored the links between energy efficiency improvements and economic growth using a hybrid general equilibrium model. Energy efficiency is endogenously modelled (i) via substitution and learning by doing in energy supply technologies; (ii) price-induced energy demand in productive sectors; and (iii) price-induced investment decisions in technologies for mobility and residential energy demand. We investigated the channels through which economic growth is driven by energy use and prices in a carbon-constrained world, by looking at the interplay between energy efficiency policies and the timing of climate action.

Energy efficiency improvements in productive sectors reduce energy requirements in these sectors while increasing output, as was illustrated in the case of industry. Lower energy costs reduce the price of non-energy goods and drive demand, which coincides with higher employment, wages and revenues. The obvious result that enhancing energy efficiency in productive sectors results in lower energy consumption and lifts the emissions constraint in industry conceals the less obvious result that the constraint is shifted away from household energy use. Indeed, higher final energy use in the residential sector is driven by higher household revenues and lower energy prices, while higher emissions from transport are induced by higher mobility and higher CO_2 intensity of transport, driven by larger automobile use due to lower petrol prices and higher income. By lowering the carbon price signal, energy efficiency improvements act as a shield to protect household consumption of energy, non-energy goods and mobility from stringent emissions constraints.

Energy-saving technical change combined with technology diffusion drive economic growth in baseline scenarios, where a high level of GDP seems to coincide with a low level of final energy consumption and therefore a low final energy intensity of GDP over the whole period. Innovation in energy efficiency determines final energy intensity in the long term while the pace of technology diffusion sets its level in the medium term. Energy efficiency improvements in productive sectors can greatly reduce the costs of climate mitigation, but only when energy efficiency policies in industrialised regions are combined with specific measures to accelerate technology transfers towards industrialising countries. In fact, the slow diffusion of energy efficient technologies may greatly increase these costs. Energy efficiency policies aimed at innovation and knowledge diffusion thus drive economic growth and reduce climate change mitigation costs.

Early climate action acts as a trigger of energy efficiency improvements and partly compensates for slow technology transfers. However, the timing of climate action reveals the trade-off between short and long term costs. Early action shows relatively high short term costs and should be considered in combination with ambitious policies to accelerate technology diffusion. By contrast, late climate action results in relatively high long term policy costs, even when combined with policy measures to enhance the energy efficiency of leader regions and to accelerate technology transfers. Policy-makers using social discount rates of 4 to 5% will consider early and late climate action as equivalent options based on their respective economic costs. However, the exploratory scenarios presented here show that early action reduces the spread of discounted policy costs across discount rates from 0% to 10%. This result, which should be confirmed by a full uncertainty analysis, hints at favouring early action as a way to reduce the uncertainty surrounding the appropriate discount rate for assessing climate policies. The opposite course of action would require additional measures to mitigate long term costs. These measures may include policies aimed at altering the structure of households demand for energy services, such as investment in infrastructures for low-carbon mobility.

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Bibliography

[1] A. Atkeson and P. J. Kehoe, *Models of energy use: Putty-putty versus putty-clay*, The American Economic Review, (1999).

[2] R. J. Barro and X. Sala-i Martin, *Convergence*, Journal of political Economy, (1992), p. 223–251.

[3] E. R. Berndt and D. O. Wood, *Technology, prices, and the derived demand for energy*, The review of Economics and Statistics, 57 (1975), p. 259–268.

[4] C. Böhringer, *The synthesis of bottom-up and top-down in energy policy modeling*, Energy economics, 20 (1998), pp. 233–248.

[5] C. Böhringer and T. F. Rutherford, *Combining bottom-up and top-down*, Energy Economics, 30 (2008), pp. 574–596.

[6] R. Bibas and A. Méjean, *Potential and limitations of bioenergy options for low carbon transitions*, Working Paper CIRED, (2012), p. Submitted to Climatic Change.

[7] D. G. Blanchflower and A. J. Oswald, *An introduction to the wage curve*, The Journal of Economic Perspectives, 9 (1995), pp. 153–167.

[8] L. Clarke, J. Weyant, and A. Birky, *On the sources of technological change: Assessing the evidence*, Energy Economics, 28 (2006), pp. 579–595.

[9] L. Clarke, J. Weyant, and J. Edmonds, *On the sources of technological change: What do the models assume?*, Energy Economics, 30 (2008), pp. 409–424.

[10] R. J. Coers and M. Sanders, *The energy-GDP nexus; addressing an old question with new methods*, Utrecht School of Economics Working Papers, (2012).

[11] P. Conforti and M. Giampietro, *Fossil energy use in agriculture: an international comparison*, Agriculture, ecosystems & environment, 65 (1997), pp. 231–243.

[12] C. Corrado and J. Mattey, *Capacity utilization*, The Journal of Economic Perspectives, 11 (1997), p. 151–167.

[13] R. Crassous, *Modéliser le long terme dans un monde de second rang : application aux politiques climatiques*, PhD thesis, AgroParisTech, 2008.

[14] R. Crassous, J. C. Hourcade, and O. Sassi, *Endogenous structural change and climate targets modeling experiments with imaclim-r*, Energy Journal, 27 (2006), p. 161–178.

[15] B. V. Dimaranan, *The GTAP 6 data base*, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, (2006).

[16] T. Downing, D. Anthoff, R. Butterfield, M. Ceronsky, M. Grubb, J. Guo, C. Hepburn, C. Hope, A. Hunt, and A. Li, *Social Cost of Carbon: A Closer Look at Uncertainty. Final Report. Stockholm Environment Institute*, Oxford, UK, 2005.

[17] M. G. Finn, *Perfect competition and the effects of energy price increases on economic activity*, Journal of Money, Credit and Banking, (2000), p. 400–416.

[18] B. S. Fisher, N. Nakicenovic, K. Alfsen, J. C. Morlot, F. De la Chesnaye, J. C. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, and A. Matysek, *Issues related to mitigation in the long term context*, Climate change, in B. Metz et al. (Eds.), Climate Change 2007: Mitigation of Climate Change. (2007), pp. 169–250.

[19] K. Fisher-Vanden and M. S. Ho, *Technology, development, and the environment*, Journal of Environmental Economics and Management, 59 (2010), pp. 94–108.

[20] K. Fisher-Vanden, G. H. Jefferson, M. Jingkui, and X. Jianyi, *Technology development and energy productivity in china*, Energy Economics, 28 (2006), pp. 690–705.

[21] K. Fisher-Vanden and I. Sue Wing, *Accounting for quality: Issues with modeling the impact of R&D on economic growth and carbon emissions in developing economies*, Energy Economics, 30 (2008), pp. 2771–2784.

[22] M. Frondel and C. M. Schmidt, *The capital-energy controversy: an artifact of cost shares?*, The Energy Journal, 23 (2002), p. 53–80.

[23] F. Ghersi and J. C. Hourcade, *Macroeconomic consistency issues in e3 modeling: The continued fable of the elephant and the rabbit*, The Energy Journal, (2006), p. 39–62.

[24] P. Goodwin, J. Dargay, and M. Hanly, *Elasticities of road traffic and fuel consumption with respect to price and income: a review*, Transport Reviews, 24 (2004), pp. 275–292.

[25] M. Grubb, *Policy modelling for climate change: the missing models*, Energy Policy, 21 (1993), pp. 203–208.

[26] M. Grubb, J. Köhler, and D. Anderson, *Induced technical change in energy and environmental modeling: Analytic approaches and policy implications*, Annual Review of Energy and the Environment, 27 (2002), pp. 271–308.

[27] C. Guivarch, R. Crassous, O. Sassi, and S. Hallegatte, *The costs of climate policies in a second-best world with labour market imperfections*, Climate Policy, 11 (2011), pp. 768–788.

[28] C. Guivarch, S. Hallegatte, and R. Crassous, *The resilience of the indian economy to rising oil prices as a validation test for a global energy–environment–economy CGE model*, Energy Policy, 37 (2009), p. 4259–4266.

[29] J. D. Hamilton, *Oil and the macroeconomy*, 2008.

[30] J. R. Hicks, *The theory of wages*, Macmillan, London, 1963.

[31] W. W. Hogan and A. S. Manne, *Energy economy interactions: the fable of the elephant and the rabbit?*, 1977.

[32] J.-C. Hourcade, *Calcul économique et construction sociale des irréversibilités: leçons de l'histoire énergétique récente*, in Les figures de l'irréversibilité en économie, R. Boyer, B. Chavance, and O. Godard, eds., Editions de l'EHESS, Paris, editions de l'EHESS ed., 1991, pp. 279–310.

[33] J. C. Hourcade, *Modelling long-run scenarios: Methodology lessons from a prospective study on a low CO2 intensive country*, Energy Policy, 21 (1993), p. 309–326.

[34] J. C. Hourcade, M. Jaccard, C. Bataille, and F. Ghersi, *Hybrid modeling: New answers to old challenges*, (2006).

[35] J.-C. Hourcade, R. Richels, and J. Robinson, *Chapter 8: Estimating the costs of mitigating greenhouse gases*, in Climate Change 1995: Economic and Social Dimensions of Climate Change, J. P. Bruce, L. Hoesung, and E. F. Haites, eds., Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, 1996.

[36] D. W. Jorgenson and B. M. Fraumeni, *Relative prices and technical change*, Modeling and Measuring Natural Resources Substitution, MIT Press, Cambridge, (1981).

[37] M. Khanna and D. Zilberman, *Adoption of energy efficient technologies and carbon abatement: the electricity generating sector in india*, Energy Economics, 23 (2001), pp. 637–658.

[38] J. Kraft and A. Kraft, *Relationship between energy and GNP*, J. Energy Dev.;(United States), 3 (1978).

[39] R. Kummel and D. Lindenberger, *Energy, technical progress and industrial growth*, Advances in Energy Studies: Energy Flows in Ecology and Economy, (1998), pp. 207–222.

[40] F. Lecocq and P. Ambrosi, *Policy MonitorEdited by maureen CropperThe clean development mechanism: History, status, and prospects*, Review of Environmental Economics and Policy, 1 (2007), pp. 134–151.

[41] D. Lindenberger and R. Kümmel, *Energy and the state of nations*, Energy, 36 (2011), pp. 6010–6018.

[42] A. Maddison, *Monitoring the world economy, 1820-1992*, OECD Development Center, 1995.

[43] A. McDonald and L. Schrattenholzer, *Learning rates for energy technologies*, Energy policy, 29 (2001), pp. 255–261.

[44] J. R. McFarland, J. M. Reilly, and H. J. Herzog, *Representing energy technologies in top-down economic models using bottom-up information*, Energy Economics, 26 (2004), p. 685–707.

[45] L. Neij, *Cost development of future technologies for power generation—A study based on experience curves and complementary bottom-up assessments*, Energy policy, 36 (2008), pp. 2200–2211.

[46] W. D. Nordhaus, *Modeling induced innovation in climate-change policy*, Technological change and the environment, (2002), p. 182–209.

[47] J. Oliveira-Martins, F. Gonand, P. Antolin, C. de la Maisonneuve, and K. Y. Yoo, *The impact of ageing on demand, factor markets and growth*, OECD Economics Department Working Papers, 420 (2005).

[48] I. Ozturk, *A literature survey on energy–growth nexus*, Energy Policy, 38 (2010), pp. 340–349.

[49] E. Phelps, *The golden rule of accumulation: a fable for growthmen*, The American Economic Review, 51 (1961), p. 638–643.

[50] D. Popp, R. G. Newell, and A. B. Jaffe, *Chapter 21 - energy, the environment, and technological change*, in Handbook of the Economics of Innovation, B. H. Hall and N. Rosenberg, eds., vol. Volume 2, North-Holland, 2010, pp. 873–937.

[51] D. C. Popp, *The effect of new technology on energy consumption*, Resource and Energy Economics, 23 (2001), pp. 215–239.

[52] J. J. Rotemberg and M. Woodford, *Imperfect competition and the effects of energy price increases on economic activity*, Journal of Money, Credit and Banking, 28 (1996), p. 549–577.

[53] J. Rozenberg, S. Hallegatte, A. Vogt-Schilb, O. Sassi, C. Guivarch, H. Waisman, and J. C. Hourcade, *Climate policies as a hedge against the uncertainty on future oil supply*, Climatic change, 101 (2010), p. 663–668.

[54] R. D. Sands, S. Miller, and M. K. Kim, *The second generation model: Comparison of SGM and GTAP approaches to data development*, PNNL report, 15467 (2005).

[55] O. Sassi, *L'impact du changement technique endogène sur les politiques climatiques*, PhD thesis, 2008.

[56] O. Sassi, R. Crassous, J.-C. Hourcade, V. Gitz, H. Waisman, and C. Guivarch, *Imaclim-r: a modelling framework to simulate sustainable development pathways*, International Journal of Global Environmental Issues, 10 (2010), p. 5–24.

[57] A. Schafer and D. G. Victor, *The future mobility of the world population*, Transportation Research Part A: Policy and Practice, 34 (2000), p. 171–205.

[58] R. M. Solow, *A contribution to the theory of economic growth*, The Quarterly Journal of Economics, 70 (1956), p. 65–94.

[59] I. Sue Wing, *Representing induced technological change in models for climate policy analysis*, Energy Economics 28, 28 (2006), pp. 539–562.

[60] ——, *The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technologies and the cost of limiting US CO2 emissions*, Energy Policy, 34 (2006), pp. 3847–3869.

[61] B. van der Zwaan, R. Gerlagh, G, Klaassen, and L. Schrattenholzer, *Endogenous technological change in climate change modelling*, Energy Economics, 24 (2002), pp. 1–19.

[62] H. Waisman, C. Guivarch, F. Grazi, and J. C. Hourcade, *The imaclim-r model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight*, Climatic Change, (2012), p. 1–20.

Vitae

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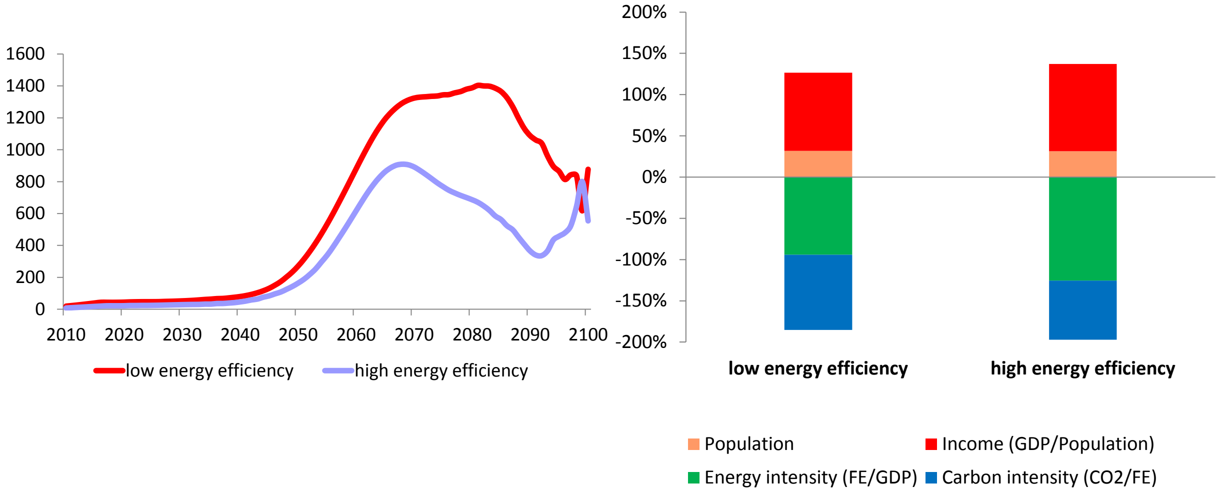
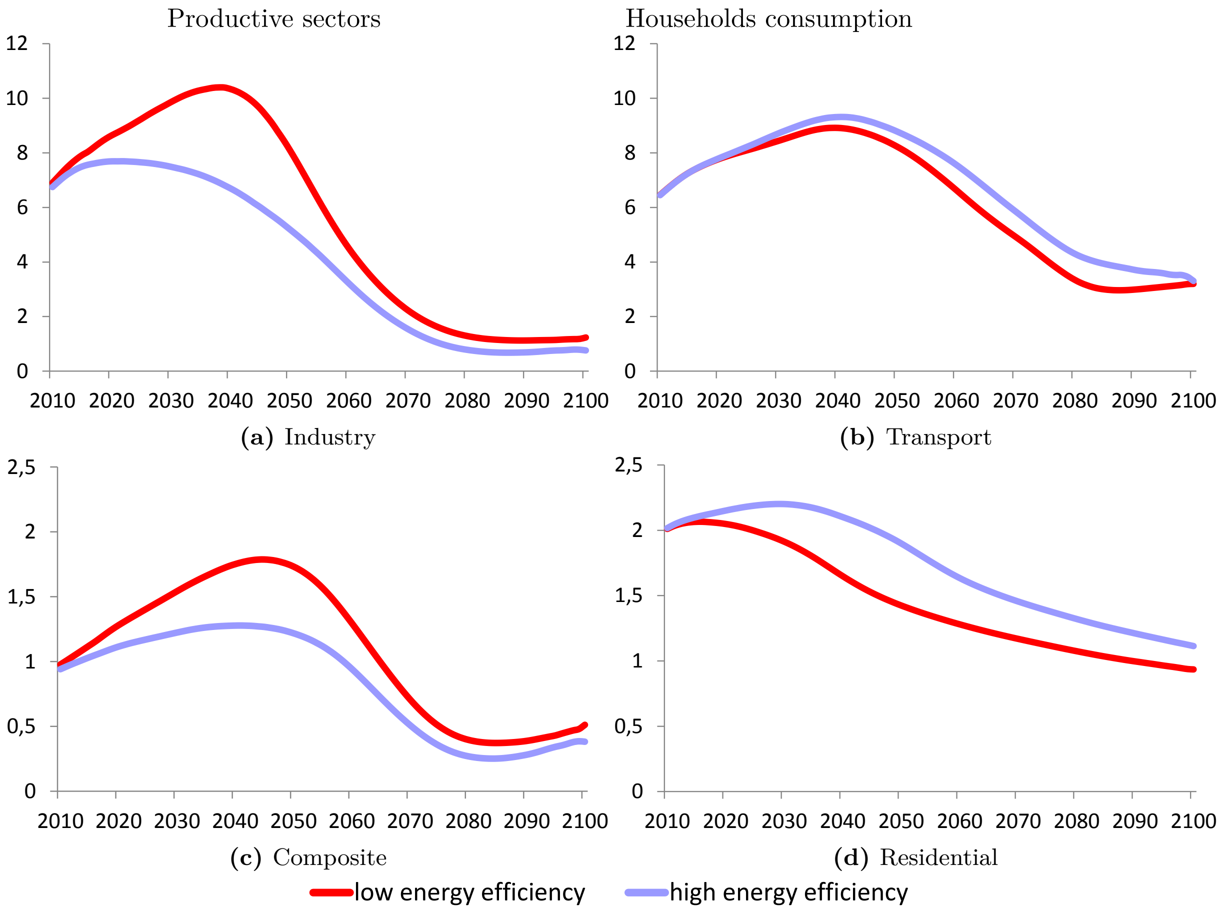
Figures



(a) CO_2 price ($US\$/tCO_2$) **(b)** Kaya decomposition of the scenarios

Figure 1: CO_2 price and Kaya decomposition - high and low energy efficiency



(a) Industry **(b)** Transport **(c)** Composite **(d)** Residential

Figure 2: CO_2 emissions in largest emitting sectors - high and low energy efficiency scenarios

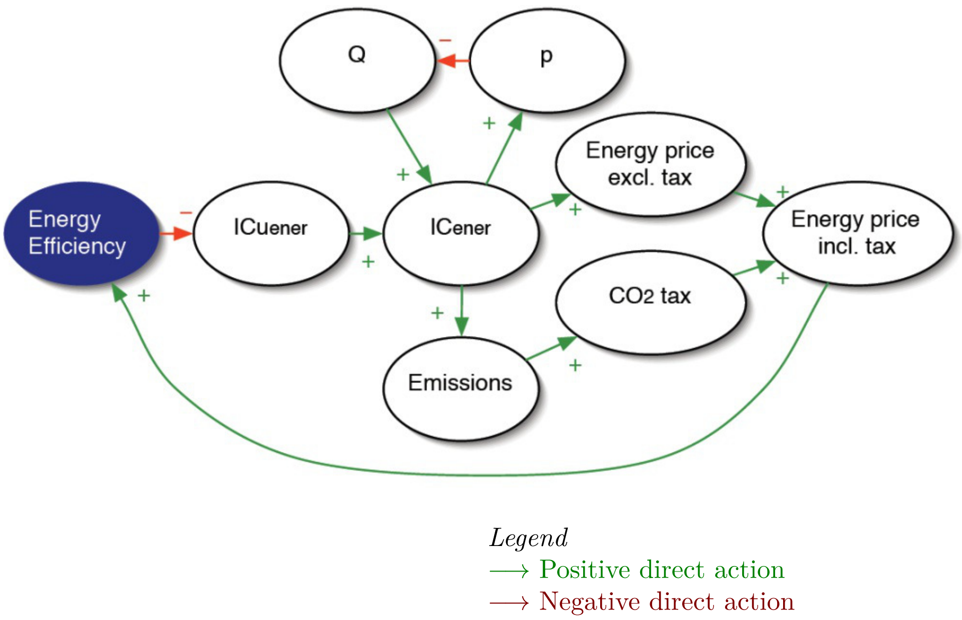
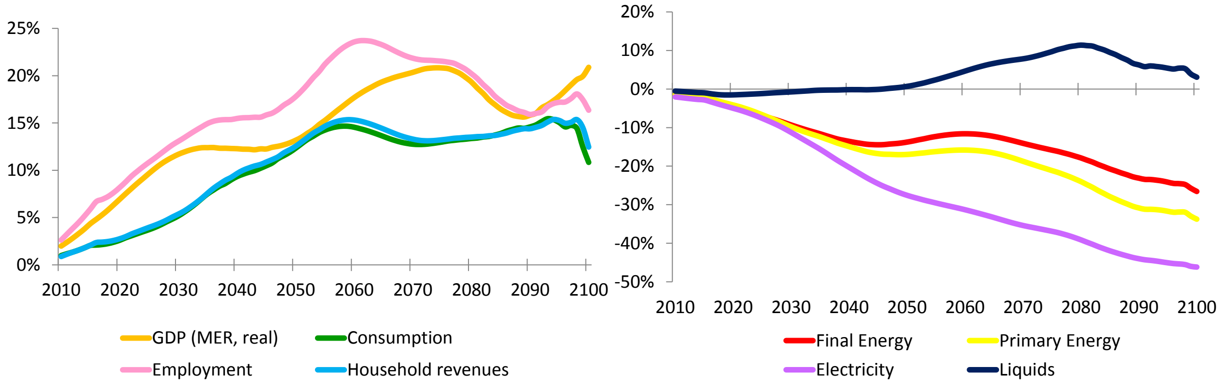
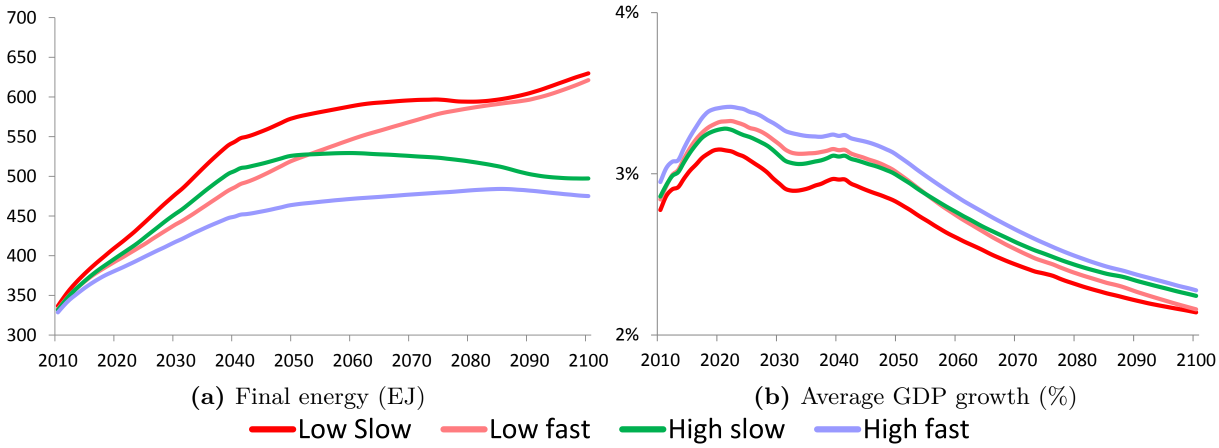


Figure 3: Influence diagram



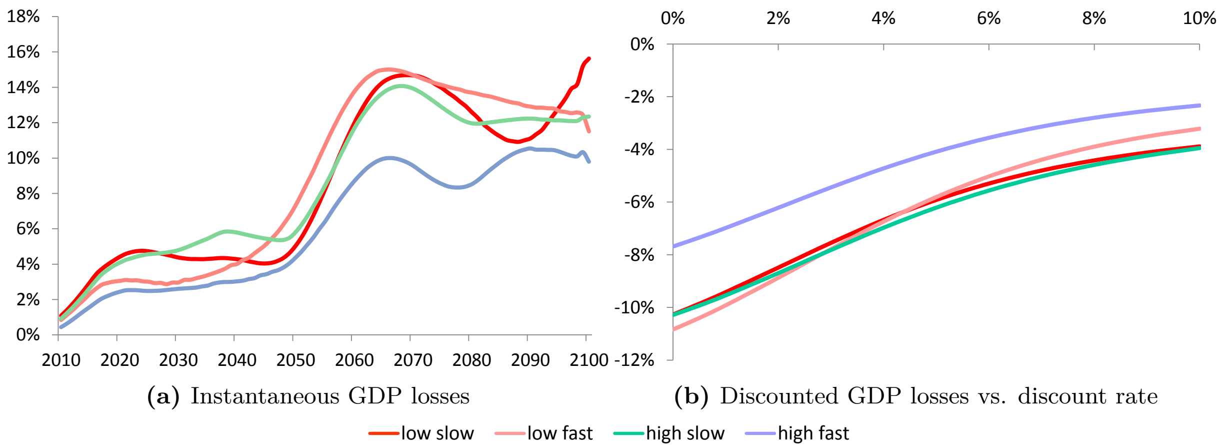
(a) Economic indicators **(b)** Energy indicators

Figure 4: Aggregate indicators change in high energy efficiency scenario vs. low energy efficiency (%)



(a) Final energy (EJ) **(b)** Average GDP growth (%)

Figure 5: Final energy use and GDP growth in baseline scenarios



(a) Instantaneous GDP losses **(b)** Discounted GDP losses vs. discount rate

Figure 6: Policy costs over 2010-2100 (real MER GDP losses)

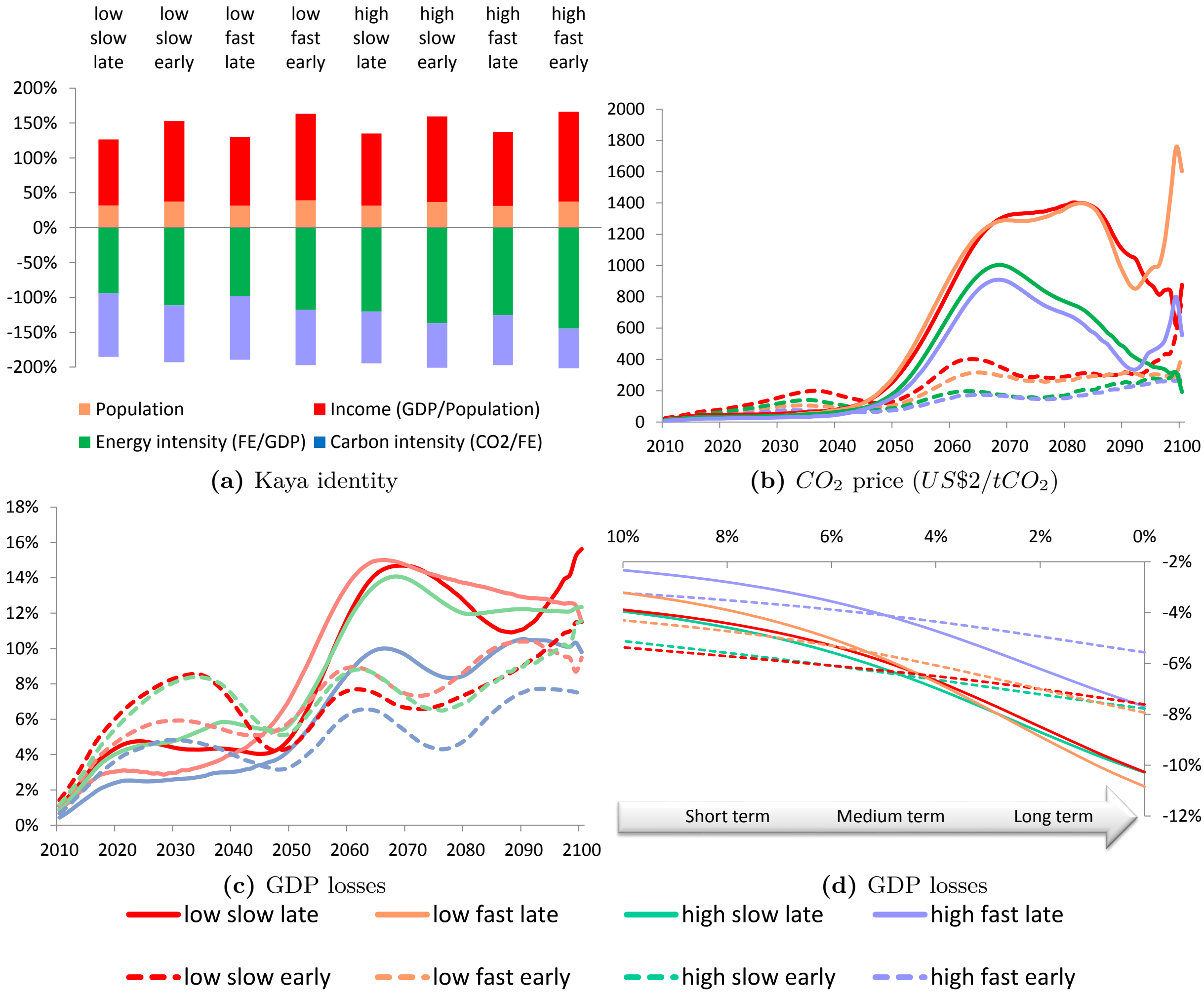
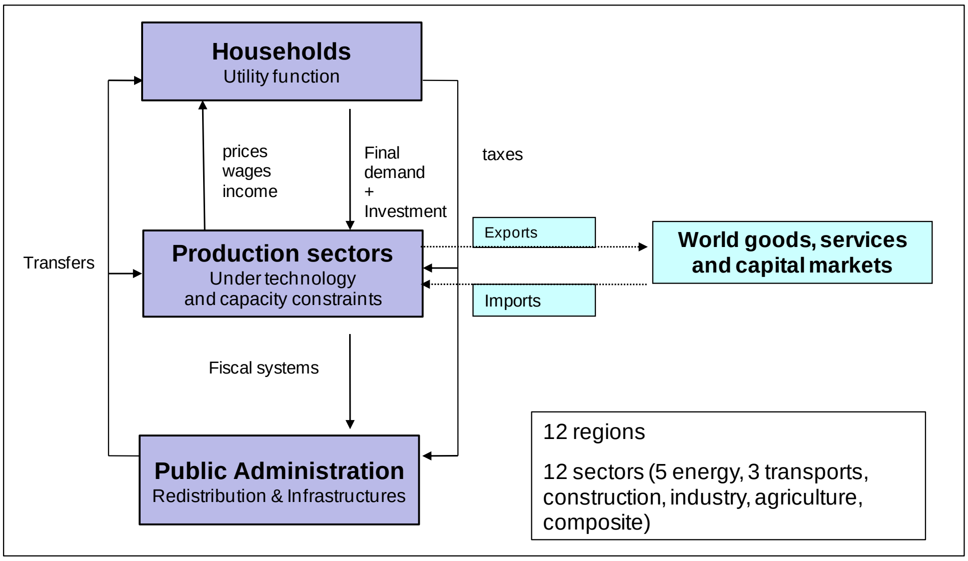


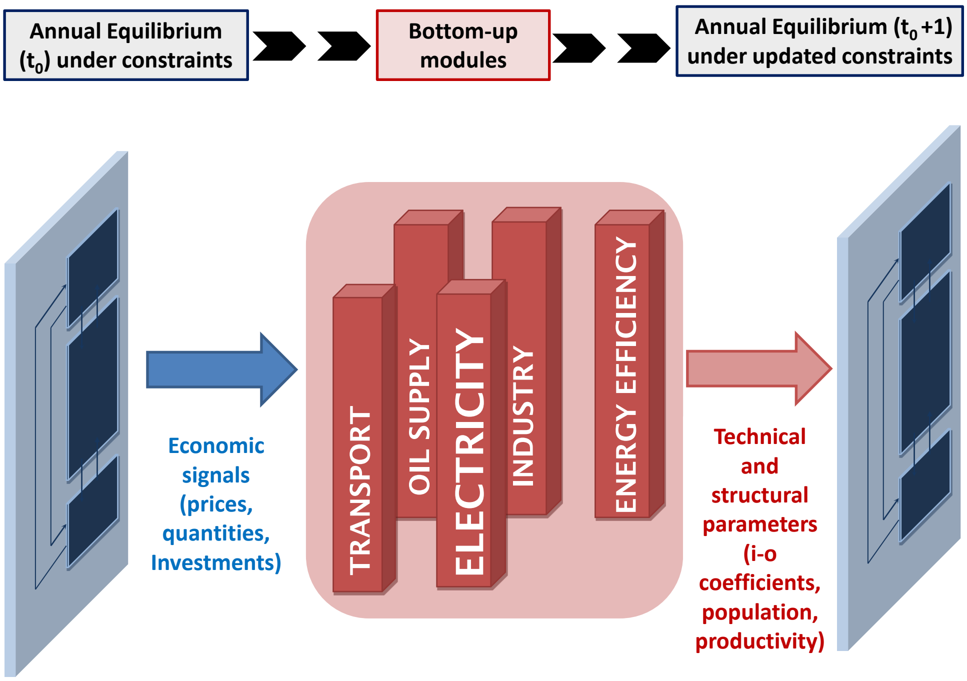
Figure 7: Early and late action, high and low energy efficiency

Appendices

Imaclim-R model schematics



(a) Static equilibrium



(b) Model dynamics

Figure A: IMACLIM-R model schematics

Default setting

Emissions profiles

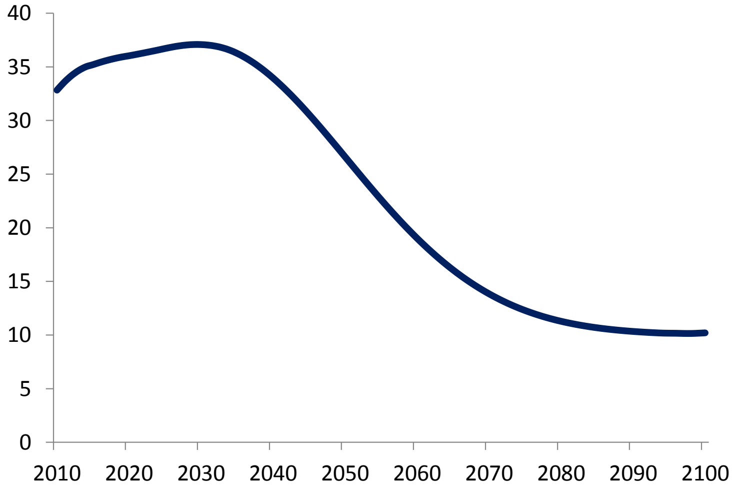


Figure B: Default emissions profile constraint ($GtCO_2$)

High vs. low (default setting)

Sectoral demand - industry and services

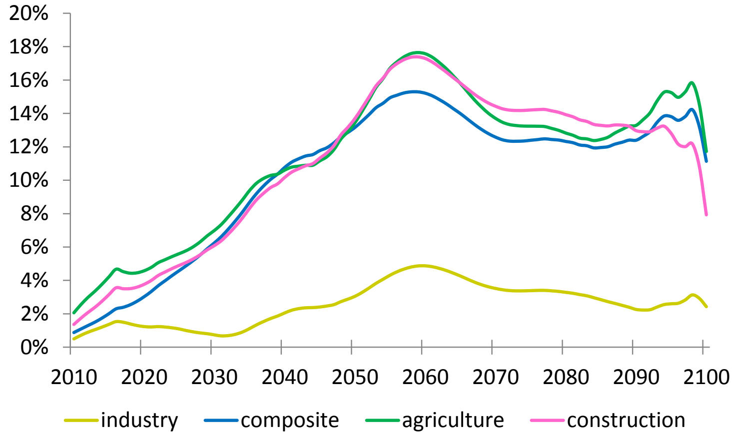


Figure C: Sectoral demands - industry and services

Electricity mixes

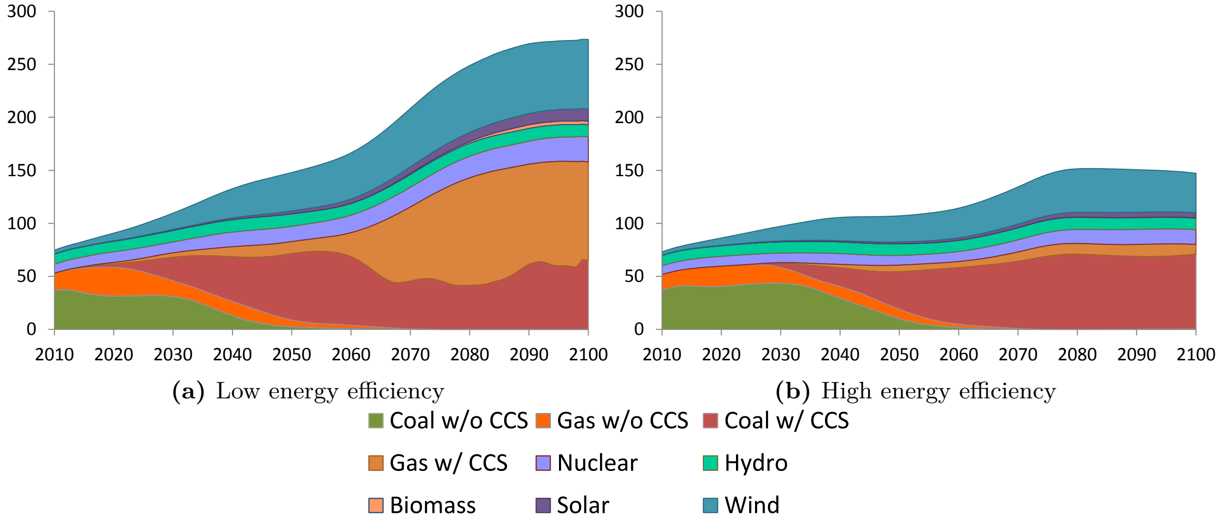


Figure D: Electricity mixes

Mobility

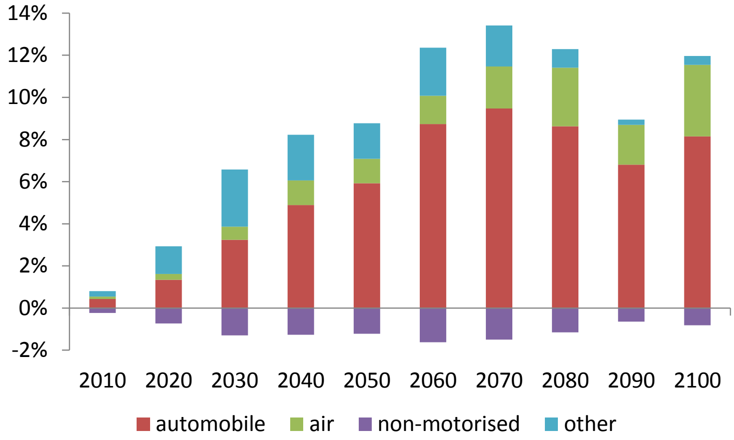


Figure E: Mobility (Changes in pkm (%))

Industry and services factors decomposition

Output (values)	Industry		Composite	
% change (USD)	2050	2100	2050	2100
Output	3%	2%	13%	11%
Energy consumption	-46%	-58%	-33%	-53%
Non-energy consumption	5%	5%	10%	6%
Labour	17%	21%	19%	21%
Profits	10%	-1%	13%	11%
Taxes	14%	15%	16%	15%

Table A: Impact of energy efficiency on industrial and composite output

Prices (unitary values)	Industry		Composite	
% change (USD)	2050	2100	2050	2100
Output	-20%	-22%	-2%	0%
Energy consumption	-58%	-68%	-42%	-58%
Non-energy consumption	-18%	-19%	-5%	-5%
Labour	-9%	-8%	3%	9%
Profits	-15%	-24%	-2%	-1%
Taxes	-11%	-12%	1%	3%

Table B: Impact of energy efficiency on industrial and composite prices

Quantities	Industry		Composite	
% change (USD)	2050	2100	2050	2100
Output	29%	31%	13%	11%
Energy consumption	-40%	-63%	-35%	-57%
Non-energy consumption	19%	24%	8%	6%
Labour	26%	29%	16%	13%
Profits	-	-	-	-
Taxes	-	-	-	-

Table C: Impact of energy efficiency on industrial and composite quantities

Industry decomposition

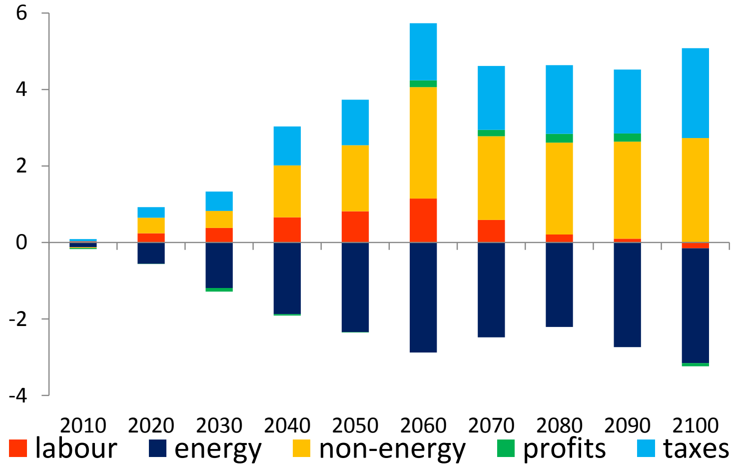


Figure F: Difference in expenditures items for industry from low to high (trillions $US\$$)

Energy prices

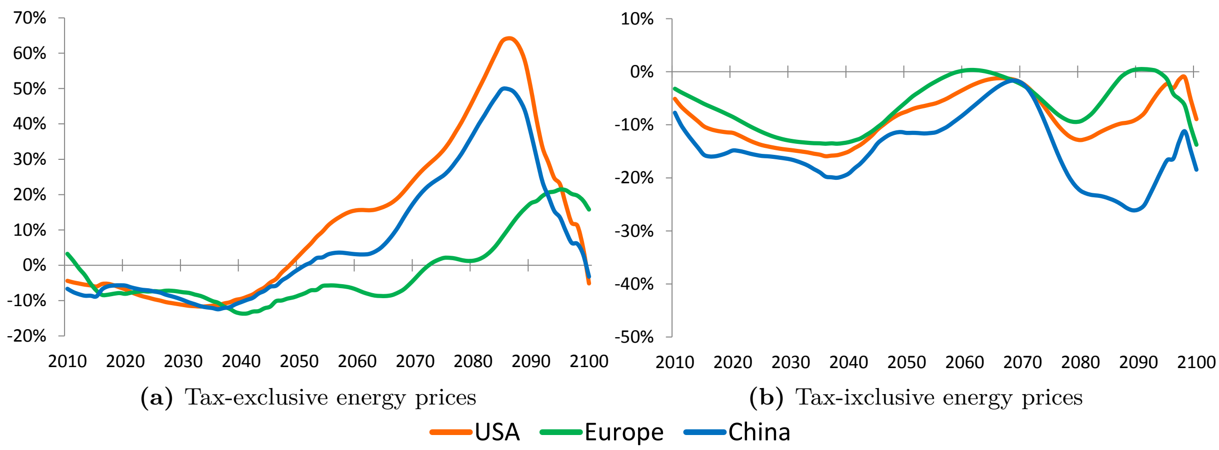


Figure G: Industry energy prices

Early vs. late action

Emissions profiles

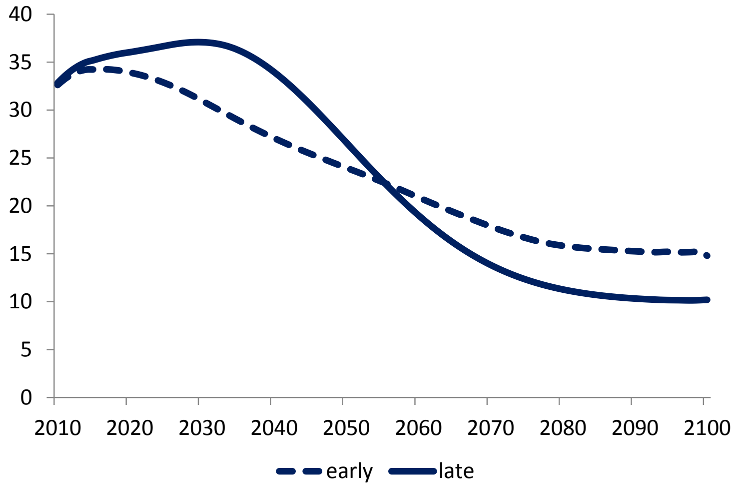


Figure H: Early vs. late (default) emissions profile constraint ($GtCO_2$)

All scenarios

Final energy intensity

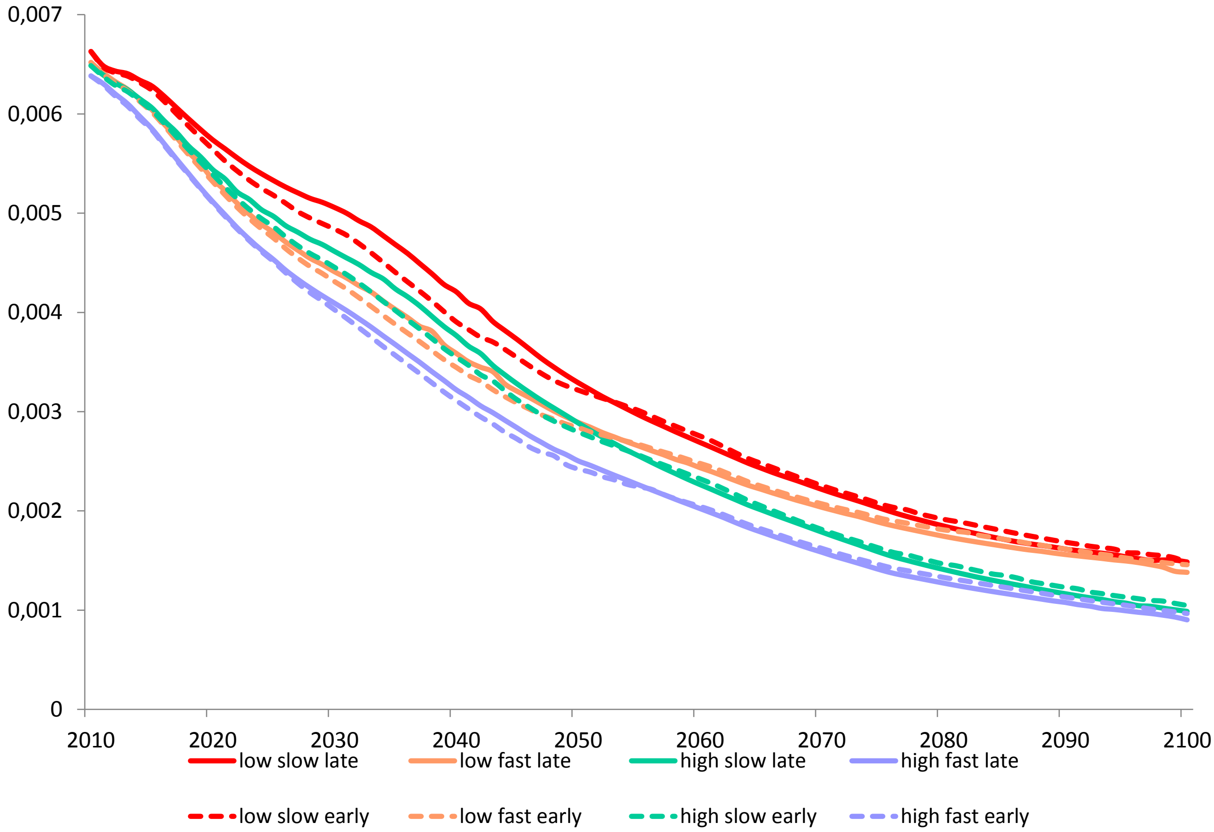


Figure I: Energy intensity

Discounted GDP losses

			Discount rate											
EE level	Convergence	Action	0%	1%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
low	slow	late	-10.3%	-9.9%	-9.4%	-8.5%	-7.6%	-6.7%	-5.9%	-5.3%	-4.8%	-4.4%	-4.1%	-3.9%
low	fast	late	-10.8%	-10.4%	-9.9%	-8.9%	-7.8%	-6.7%	-5.8%	-5.0%	-4.4%	-3.9%	-3.5%	-3.2%
high	slow	late	-10.3%	-9.9%	-9.5%	-8.7%	-7.8%	-7.0%	-6.2%	-5.6%	-5.0%	-4.6%	-4.2%	-4.0%
high	fast	late	-7.7%	-7.3%	-7.0%	-6.2%	-5.4%	-4.7%	-4.1%	-3.6%	-3.1%	-2.8%	-2.5%	-2.3%
low	slow	early	-7.6%	-7.5%	-7.3%	-7.0%	-6.7%	-6.5%	-6.3%	-6.1%	-5.9%	-5.7%	-5.5%	-5.4%
low	fast	early	-7.9%	-7.7%	-7.5%	-7.0%	-6.5%	-6.1%	-5.7%	-5.3%	-5.0%	-4.7%	-4.5%	-4.3%
high	slow	early	-7.8%	-7.6%	-7.5%	-7.2%	-6.9%	-6.6%	-6.4%	-6.1%	-5.8%	-5.6%	-5.4%	-5.1%
high	fast	early	-5.6%	-5.4%	-5.3%	-4.9%	-4.6%	-4.4%	-4.1%	-3.9%	-3.7%	-3.5%	-3.4%	-3.2%

Table D: Discounted GDP losses