Originally published as:

Bibas, R., Méjean, A., Hamdi-Cherif, M., Energy efficiency policies and the timing of action: an assessment of climate mitigation costs, Technological Forecasting and Social Change, In press

DOI: 10.1016/j.techfore.2014.05.003

Energy efficiency policies and the timing of action: an assessment of climate mitigation costs

Ruben Bibas* Aurélie Méjean* Meriem Hamdi-Cherif*

Abstract

This paper assesses the sensitivity of climate change mitigation costs to energy efficiency policies, and gives policy insights for the timing of climate action. A hybrid general equilibrium model (Imaclim-R) is used to investigate numerically the interaction between technical change and economic growth. Energy efficiency in productive sectors lowers energy prices. Lower energy prices increase demand due to lower prices of non-energy goods and higher household revenues. 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. Late action shows high long-term costs, even when combined with policies to enhance innovation and accelerate diffusion. Early action could reduce the cost uncertainty induced by the controversy surrounding the appropriate discount rate for policy assessment, while late action would require additional measures to reduce long term costs, notably in sectors with significant inertia.

Keywords: Energy Efficiency; Climate Policy; General Equilibrium; Endogenous Technical Change
JEL Classification: C68 ; F0 ; H23 ; Q01 ; Q4 ; Q5 .

*CIRED – International Research Center on Environment and Development, 45 bis, Avenue de la Belle Gabrielle, 94736 Nogent-sur-Marne, France. Corresponding author: ruben.bibas@centre-cired.fr

1 Introduction

The nature of the interaction between energy and economic growth is still an unresolved issue in the economic literature. Some econometric studies have identified energy use as a determinant and possible limiting factor of economic growth, for instance [1]. Other studies have questioned the causal relationship between energy use and economic output, see [2] for a review. The relationship between energy prices and economic growth is less controversial. Econometric analyses have shown the correlation between oil price shocks and short-term economic downturns [3]. The oil price shocks also gave rise to a vast literature focusing on the links between energy and long-term economic growth, and on the role of technical change and capital substitution to sustain growth in an economy relying heavily upon nonrenewable energy resources, see [4] for a review. At the same time, high energy prices may bias innovation towards energy efficient technologies, see [5] for a review. This bias would allow energy-saving technical change to reduce overall energy use and CO_2 emissions while sustaining long-term economic growth.

Energy efficiency could thus play a crucial role in addressing climate change and energy security issues [6]. Policy-makers in many countries have acted on that premise and implemented energy efficiency policies. For instance, the European Union aims at increasing energy efficiency by 20% by 2020, while China set the objective at 16% by 2015. Specific measures include mandatory energy requirements in buildings in Europe and part of the United States and light-vehicles standards in Europe, Japan and the US. Also, most industries in these countries are regulated through standards, or participate in voluntary programmes. Such energy efficiency policies usually target specific sectors at the micro level, and their impact on overall economic growth is ambiguous.

This paper sheds light on this unresolved issue and aims at answering the following questions: How do the effects of technological innovation propagate from the micro to the macro level and affect overall energy efficiency and economic growth? More precisely, how do the level of energy efficiency at the sectoral level and the diffusion of technological innovations impact macroeconomic indicators? How do these mechanisms affect climate change mitigation costs? How do the dynamics of technological innovation and diffusion interact with the timing of mitigation strategies?

Two main strands of the economic literature focus on technical change. On the one hand, at the micro level, the literature studies the determinants of technological innovation and diffusion (see [7] for a review in the context of environmental issues). On the other hand, at the macro level, the literature studies the link between technical change and growth. For instance, [8] reviews the link between the environment, technical change and economic growth, with a particular focus on optimal growth pathways. [9] questions the traditional way in which models have addressed this issue and separated top-down and bottom-up modelling approaches. In that, traditional models heeded the conclusions of [10] that the evolution of the energy sector has little impact on economic growth. Following [9] and [11], we introduce a model with endogenous technical change and economic growth. This hybrid general equilibrium model Imaclim-R offers a tool to test the links between technical change and the contents of economic growth, coupling of a top-down structure and bottom-up modules. This dynamic recursive model allows to assess the short and long term consequences of climate change mitigation policies.

The paper is structured as follows. Section 2 presents a selected 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 used in this analysis. A series of numerical experiments is then performed to assess the sensitivity of macroeconomic indicators to energy efficiency at the sectoral level. Section 4 presents the mechanisms at play as energy efficiency improvements propagate through the economy. 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 Technical change in energy-economy models

2.1 Technical change and energy efficiency: some empirical facts

Technical change includes both the change in the amount of inputs to produce a unit of output and the change in the structure of the output. In other words, technical change encompasses the choice of techniques (e.g., from the plough to the tractor) and structural change (e.g., industrialisation and growth of the share of services in the economy). Input substitution can be distinguished from technical change and refers to the evolution of the inputs structure to produce a unit of output, considering a fixed set of techniques. Induced technical change is the alteration of the rate and direction of technical change in response to policy [12]. Technical change can be induced by investments in Research and Development (R&D), learning-by-doing, relative price changes, technology transfers, behavioural change, see [5]. While R&D investments may influence the rate and direction of technical change, learning-by-doing can reduce the unit cost of a particular good as a function of experience. Technical change may also occur when a change in the relative prices of factors spurs innovation directed at reducing the use of a factor which has become relatively expensive [13].

Because of the emissions they induce, energy inputs are critical for assessing of climate change mitigation policies. Empirical studies show that higher energy prices have been associated with energy efficiency improvements. For instance, [14] shows that energy prices and energy intensity of industrial production have been negatively correlated in eight energy intensive US 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. [15] also identifies rising energy prices as one of the key factors of energy intensity reduction in the Chinese industrial sector between 1997 and 1999. High fossil energy prices (for instance driven by carbon pricing) may drive firms to invest in new knowledge to develop less carbon intensive processes and products [16]. A rise in energy prices may also drive households to purchase energy-efficient equipment, products and services.

Energy efficiency improvements may also be driven by technology diffusion policies. For instance, basic oxygen furnaces replaced open hearth furnaces for steel production as a more efficient technology in terms of energy and other inputs in former Eastern Germany after the reunification [17, 18]. The diffusion of energy efficient technologies across regions is often seen as critical to mitigate climate change. In particular, the Clean Development Mechanism (CDM) of the Kyoto Protocol has been used as a tool to facilitate the transfer of low carbon technologies towards industrializing countries [19]. Dedicated technology policies can induce the diffusion of innovations. For instance, the large diffusion of high efficiency motors in the US occurred thanks the implementation of demand-side management programs at the initiative of many electricity utilities. Increased energy efficiency followed the development of better insulation and magnetic materials (e.g., low-carbon silicon steel plates and light aluminium alloys). Introduced to the market in the 1970s, they represented 20% of the US market in the mid-1990s. Their share was only 1% in Europe because of the lack of market transformation initiatives [20].

However, the rebound effect following energy efficiency improvements may well lead to higher emissions. In the residential sector, energy-saving technical change may indeed lead to greater energy consumption by households as a result of lower energy prices. This is the case for China, as shown by [21]. This rebound effect is the object of extensive study, see for instance [22–24]. At the aggregate level, the impact of energy efficiency on economic growth is ambiguous as well. The estimation of elasticities on past data shows that the improved conversion of energy into physical work accounts for most of the growth attributed to technological progress [25]. Technology transfers do not necessarily translate into an increase of the productivity of all factors, see for instance [26] for a review of the relationship between technological progress, energy efficiency and economic growth. Again in the case of the Chinese industrial sector, imported technology may be labour and energy-saving but capital-using, [15].

2.2 Modelling technical change and energy efficiency

In accordance with these findings, some models have paid particular attention to the effect of energy prices, the mechanisms of technological innovation and diffusion, and rebound effects to model energy efficiency and economic growth. In aggregate models, input substitution is understood as a movement along a production function, while technical change is a 'shift' of the production function [27]. Technical change was first modelled through the evolution of a technical change index (Solow's residual [28], also called Total Factor Productivity) which translates a change in the quantity of output for given inputs. [29] later introduced an autonomous energy efficiency improvement coefficient (AEEI) in energy-economy models to account for historical non-price related technical change. This coefficient translates energy efficiency improvements induced by non-price signals like norms or technical standards, by behavioural change following the evolution of lifestyles, or by structural changes (e.g., an increasing share of manufactured vs. energy-intensive industrial goods) [30]. The calibration of the AEEI coefficient is difficult and has been largely criticized in the literature, e.g., [31]. Exogenous trends of energy efficiency improvements greatly influence model results, in particular in macroeconomic models where it determines emissions and economic growth. For instance, low (respectively high) AEEI values may lead to overestimating (respectively underestimating) future energy demand and climate change mitigation costs [32]. More fundamentally, ambitious climate policies could significantly alter technology and consumptions patterns and are likely to change the structure of economic growth. The calibration of AEEI on past trends therefore might not remain valid over time [33]. Models with endogenous technical change have been developed to address the shortcomings of exogenous technical change [34]. These models include some or all of four key elements: capital vintages, R&D, technological learning, and the heterogeneity of energy consumption choices.

Many models represent the evolution of technical systems through successive generations of capital [35, 36]. In this setting, new technologies can only penetrate the mix of installed capacities if they coincide with new investments to satisfy demand, replace end-of-life capital or replace capital that is no longer profitable. More broadly, the development of economy-wide technical characteristics depends on specific sectoral developments, which for instance depend on the typical lifetime of capital in each sector (e.g., sectors with long capital lifetimes will usually evolve slowly even if more efficient technologies emerge). Modelling generations of capital thus allows for the representation of technical inertia, which depends on the speed of capital capacities renewal and the speed of innovation diffusion [37]. It also ensures that technological characteristics at the sectoral level and economy-wide technical change are consistent. Besides, capital vintages link endogenous technological change and the availability of investments. This modelling feature is particularly relevant since the inertia of technical systems determines the short and long term costs of climate mitigation [38].

Technical change induction mechanisms have been examined by [39], [40] and [41]. Based on these theoretical advances, some energy-economy models associate technical change with a stock of knowledge that evolves with R&D investments, see [42] for a review. Investments in R&D can impact the shape of the production function [43], the conversion factor between CO_2 emissions and economic output or energy [16], or both [44] and [45]. R&D investments are usually assumed to remain with a constant budget, and R&D investments in energy technologies occur at the expense of R&D investments in other sectors [46, 47]. Ignoring such crowding-out effects for the allocation of investment in R&D between sectors might lead to underestimating climate mitigation costs [43]. Models sometimes represent positive externalities, such as spillovers, between sectors or regions for R&D and technological learning [48]. For instance, the regional aggregate production functions benefit from a stock of "global" knowledge in [44].

Energy-economy models usually represent technological learning mechanisms through experience or learning curves. Learning curves translate the evolution of the cost of a technology as a function of cumulated experience (cumulative production or installed capacity is often used as a proxy for experience). Many econometric studies have identified learning rates of explicit energy technologies, see [49–51] for reviews. Some models use also cost asymptotes to be more realistic [52, 53]. Many models use technological learning to represent endogenous technical change. In some models, cumulative abatement and R&D investments jointly drive the improvements in energy productivity and the carbon intensity of energy [45]. Using global learning curves for some low carbon technologies, [54] shows the importance of positive externalities as inter-regional spillover reduce climate mitigation costs.

Note that another form of technical change derives from the sectoral and regional disaggregation of energy-economy models. Technical change at the global level, as reflected for instance in the energy and carbon intensity of the economy, depends on technical change in various sectors and regions. Economy-wide technical change therefore depends on this level of disaggregation. Technical change at the sectoral level is affected by the heterogeneity of energy consumption choices (e.g., the energy intensity of production and household energy use).

2.3 Modelling the relationship between energy efficiency and economic growth

The previous section outlined how models represent energy efficiency. In this section, we discuss the challenges faced when linking technical change, energy efficiency 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 [55] for a review.

As briefly mentioned in section 2.2, 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 [56], which mimic the set of available techniques and the technical constraints on an economy [57, 58] and often use constant 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 exceeding feasible technical limits in the case of large departures from the reference equilibrium [9, 59], 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 [60].

Bottom-up models embark detailed representation of energy production technologies. 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) that favour learning in low-carbon technologies. Bottom-up studies explicitly track the set of available and operated techniques and distinguish the changes in emissions and system costs due to substitution effects or technological change [61]. However, this bottom-up approach does not account for the interaction between the energy sector and economic growth. In particular, [14] 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 [62, 63]. Therefore some authors have attempted to couple bottom up models to conventional macroeconomic growth models [11, 64]. The hybrid Computable General Equilibrium (CGE) model Imaclim-R aims at bridging the gap between these branches of the literature and allows to capture the macroeconomic feedbacks between energy use and supply and the structure of the economy.

3 Methods: technical change in a hybrid modelling framework

3.1 Imaclim-R: beyond the aggregate production function

3.1.1 The hybrid framework

Imaclim-R is a recursive, dynamic, multi-region and multi-sector hybrid general equilibrium model of the world economy [65][1]. Hybrid matrices [9] ensure a description of the economy in consistent money values and physical quantities [66]. It is calibrated for the year 2001 by modifying the set of balanced input-output tables provided by the GTAP-6 dataset [67] to make them fully compatible with 2001 IEA energy balances (in Mtoe) and data on passengers' mobility (in passenger-km) from [68][2]. This hybrid accounting framework represents the material and technical content of production processes and allows for abandoning standard aggregate production functions. At a given year, technologies are fixed and

[1] 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).

[2] The update of Imaclim-R towards more recent databases is in progress.

no substitution between inputs can occur. Input-output coefficients evolve each year according to the engineering information contained in the dynamic modules. The evolution of the production frontier over time is determined by the joint transformation of economic and technical systems. This recursive structure relies on a systematic exchange of information between an annual macroeconomic equilibrium and technology-rich dynamic modules.

The static equilibrium models short-term macroeconomic interactions each year under technology, capacity and investment constraints (cf. appendix A.1). Each yearly equilibrium is calculated assuming Leontief production functions with fixed intermediate consumption and labour inputs (these coefficients are fixed at a given date but vary over time), decreasing static returns due to increasing labour costs at high utilization rate of production capacities [69], and fixed mark-up in non-energy sectors. A representative household maximizes utility through a trade-off between consumption goods, mobility services and residential energy use, assuming fixed end-use equipment at any given year. Market clearing conditions can lead to a partial utilization of production capacities. Fixed short-term mark-up pricing is used to model imperfect markets. Following [70], our modelling framework also accounts for imperfections in labour markets by using regional wage curves which relate real wages to the unemployment rate[3]. 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 region.

Every year, dynamic modules[4] use the information stemming from the previous static equilibrium to assess the response of technical systems and determine investment needs for building new production capacity (cf. appendix A.2 and A.3 for schematics and a detailed table). Investment dynamics in Imaclim-R World are described in [72]. Investment demands are expressed by each sector: for energy sectors, investment demands follow a bottom-up module, while non-energy sectors express demands to fulfill an expected production to capacity ratio of 80%. Fixed shares of households' and firms' revenues are allocated to investment supply after each equilibrium. The share of these resources dedicated to investment follows an exogenous trend. Then, this fixed amount is assigned according to investment requests from each sector: energy sectors see their requests fully met because of the assumption that the bottom-up description (which is more refined than that of the other sector) already includes the specific sectoral mechanisms for investment, while other sectors receive investment in proportion of their investment demand. The bottom-up modules for energy sectors describe the competition between explicit technologies based upon their profitability. Investment demand thus reflects microeconomic mechanisms. In non-energy sectors, the adjustment of investment levels translates the relative scarcity of production capacities. Indeed, the further the sector is from the aimed 80% production to capacity ratio, the largest the expressed investment demand and the largest both the adjustment and the allocated investment to bring the production to capacity ratio closer to 80%. The possible mismatch between optimal and allocated investments can lead to the underemployment of production factors. This may result in suboptimalities in climate and energy policies, or gains if such policies correct pre-existing suboptimalities. Once investments have been allocated among sectors, dynamic modules build new capacities and send new Leontief coefficients back to the static module to determine the next equilibrium. Each year, technical choices are flexible but only modify at the margin these coefficients and labour productivities embodied in existing equipment. In other words, capacity vintages exhibit little flexibility and only investment in new capacity is fully flexible[5]. This putty-clay assumption is key to represent the inertia of technical systems.

3.1.2 Modelling economic growth

In Imaclim-R, the natural growth rate is given by exogenous assumptions on active population[6] and labour productivity[7]. The growth rate of labour productivity is prescribed over time for each region and

[3]The wage curve for each region is implemented through the relation: $\frac{w}{pind} = aw \cdot \frac{w_0}{pind_0} \cdot f(\frac{z}{z_0})$; where w is the salary, $pind$ the price index and z unemployment [71].

[4]Including demography, bottom-up modules for energy sectors and reduced forms of other economic sectors.

[5]Some retrofit options exist, such as EEI described in the following section.

[6]Derived from UN medium scenarios and International Labour Organization.

[7]The natural growth rate is the growth rate that an aggregated one-sector economy would follow under full employment of production factors [73].

sector[8]. The effective economic growth rate may depart from this exogenous trend. Indeed, the structure and rate of effective growth for each region 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 Leontief 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 if investment shortages occur. These mechanisms result in the endogenous evolution of capital and energy productivities.

3.2 Technical change in energy and non-energy productive sectors

For all sectors, the first source of technical change is labour productivity improvements following an exogenous trend. For energy sectors, explicit resources and technologies are modelled. Technological improvements stem from learning-by-doing for technologies (learning rates are given in [77]). Endogenous technical change in non-energy productive sectors (industry, services, agriculture) is modelled through two main channels in Imaclim-R. First, energy efficiency improvements (EEI) in productive sectors are induced by energy prices. Second, energy substitution may occur in all sectors, driven by energy prices and technology costs. Transport by private car is modelled via explicit technologies, allowing for learning-by-doing. The model tracks vintages of the car fleet, allowing for the representation of inertia. In other transport sectors, technical change is modelled through EEI, driven by exogenous trends (AEEI) and fuel price elasticities. The mechanism by which learning-by-researching leads to technical change is not represented in Imaclim-R World (e.g., investments in knowledge stocks. At the aggregate level, energy efficiency improvements and energy substitution may result in structural changes of economic activity.

3.2.1 Energy efficiency improvements in productive sectors

Energy efficiency improvements (EEI) in Imaclim-R are endogenous. For each productive sector, 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 endogenous energy price index, given an exogenous coefficient for EEI at constant energy prices. When the energy prices index increases, the coefficient for EEI increases linearly, up to an asymptote. Conversely, when the energy price index decreases, the coefficient for EEI decreases until reaching an asymptote. For each sector, the energy intensity of the followers is assumed to converge towards the performance of the leader. The speed of convergence also depends on the energy price index: when the energy price index increases, the speed of convergence increases up to an asymptotic level, and conversely when the energy price index decreases. Note that Imaclim-R does not differentiate between technology improvements and behavioural changes as technologies are not explicit in productive sectors.[9] EEI affect newly installed capacities. They also result in the retrofitting of existing capacity vintages exists, but to a limited extent, since it implies only marginal change on technology, processes and behaviour. Such mechanisms have been observed for instance in China where energy intensity of clinker production declined in the 1980s, thanks to the development of improved vertical kilns and the retrofitting of non-mechanized kilns [78].

[8]Exogenous labour productivities satisfy a convergence hypothesis [74] and are informed by historical data [75] and best guess assumptions [76]. 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.

[9]For energy sectors, the model features bottom-up sectoral models which do differentiate specific technologies as well as the behavioural determinants of investment decisions.

In terms of the calibration of energy efficiency, some issues arise for the parametrization of the leader trend and for the speed of convergence of the followers. Some emerging economies may appear to be more energy efficient in some sectors at calibration year[10]. To address this issue, the energy intensity of the concerned sectors in these regions is allowed to reach higher levels than the initial energy intensity of the leader, before converging towards the leader. The energy efficiency parameters are calibrated so that EEI rates in the baseline correspond to the values prescribed in the modelling protocol, see [80]. EEI include technology improvements, fuel switching and price-driven behavioural changes [6].

EEI are assumed to be in part free, and in part to coincide with an increase in the mark-up rate of firms, linking EEI to the capital share in production costs. The free part of EEI corresponds to 1/3 of total EEI. The increase in capital costs is estimated and set to completely offset the energy costs saved with more energy-efficient equipment (therefore translating the constraint that EEI investments should be profitable). EEI in productive sectors are not biased towards low carbon energy. The use of fossil and non-fossil energy decreases uniformly but may result in lower emissions 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, for instance due to the introduction of a carbon price.

Figure 1 outlines the economic channels through which energy efficiency lowers unitary energy consumption and impacts economic growth. EEI induce lower energy consumption per unit of output ($IC_{ener}^{unitary}$ in $Mtoe/USD$) in each productive sector. This may result in higher or lower aggregated energy consumption (IC_{ener}), depending on the relative effect of lower unitary energy consumption and higher sectoral production (Q) due to lower prices. Lower prices can indeed increase consumption through the rebound effect. Lower overall energy consumption affects energy prices through two channels: a decrease in tax-exclusive prices due to lower energy use (IC_{ener}) and a relaxation of the required carbon tax to reach a set climate objective thanks to lower emissions. Overall, lower energy consumption results in lower tax-inclusive energy prices. As EEI are driven by the energy price index, lower energy prices may in turn counterbalance EEI. On the production side, lower unitary energy requirements ($IC_{ener}^{unitary}$) decrease production costs and prices (p), driving up demand and production (Q).

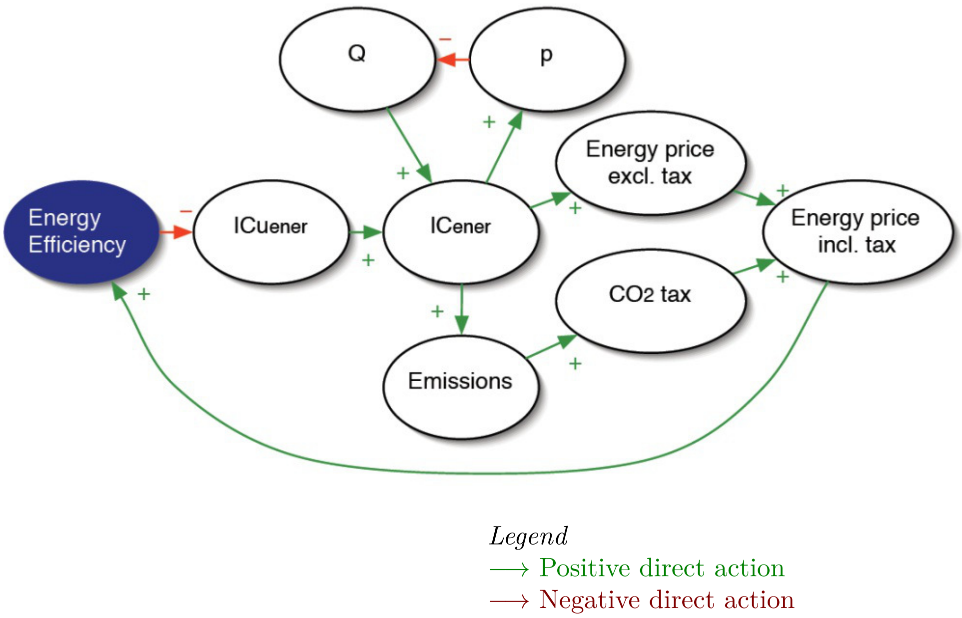


Figure 1: Influence diagram

[10]The hybridization of IEA energy matrices and GTAP input-output tables reveals that 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 this precaution. [79] also reports that some African countries display a very high energy output to input ratio (Uganda is 380 times more “efficient” than Japan).

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. road, rail, air or water) are driven by relative prices, given the explicitly modelled constraints on energy production and end-use equipment and infrastructure. 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. 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 section 2.2. It is used in Imaclim-R to model electricity and oil production technologies [77], and for demand technologies (e.g. cars). In energy production sectors, learning-by-doing in low-carbon technologies (triggered by carbon prices) may improve the carbon efficiency of energy transformation through the substitution from fossil energy to low carbon-alternatives. For those sectors using fossil fuels, carbon pricing will increase the energy price index. The substitution between energy sources 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).

At the macro level, carbon pricing policies can induce a change in the structure of demand both at the household and firm levels. Altering energy prices may change the nature of the goods produced, therefore the structure of each sector and the relative weight of each sector in total economic output.

3.3 Analyzed scenarios

The relationship between energy efficiency and economic growth under climate constraint is explored in climate policy scenarios restraining emissions to a budget of 2400 $GtCO_2$ for the 21^{st} century. This budget was set to be compatible with a 550 $ppm\ CO_2e$ climate target [80]. This paper analyses eight scenarios along three dimensions: high or low energy efficiency of the leader, slow or fast convergence towards the leader, early or late climate action. Table 1 summarizes the eight scenarios.

Section 4 carefully examines energy efficiency variants to understand the mechanisms through which energy efficiency propagates to the economy and affects climate change mitigation costs. To that end, two scenarios are analyzed: low energy efficiency with slow convergence and high energy efficiency with fast convergence, both in the late action setting. The scenarios are labelled high and low energy efficiency in 4, as they were calibrated following the AMPERE protocol.

Section 5 explores the interaction between energy efficiency policies and the timing of mitigation. Section 5.1 examines the role of the speed of convergence towards the leader through the study of four scenarios (high or low energy efficiency, slow or fast convergence). Then, section 5.2 then explores the interaction of the timing of action with energy efficiency policies, adding the four corresponding scenarios under early climate action. Early and late action correspond to two exogenous emissions trajectories with the same CO_2 budget over the period 2010-2100 (cf. appendix B). The emission trajectories used here were derived using a heuristic method satisfying the prescribed 2100 emissions budget. The late action setting corresponds to the low short-term target of 37.3 $GtCO_2$ in 2030 used in AMPERE WP2 scenarios. The early action scenario corresponds to immediate abatement to curb emissions below 2010 levels, resulting in emissions close to 30 $GtCO_2$ in 2030. .

Section where scenario appears for the first time (scenarios are then used throughout all subsequent sections)				
	Late action		Early action	
	Slow convergence	Fast convergence	Slow convergence	Fast convergence
High energy efficiency	section 5.1	section 4	section 5.2	section 5.2
Low energy efficiency	section 4	section 5.1	section 5.2	section 5.2

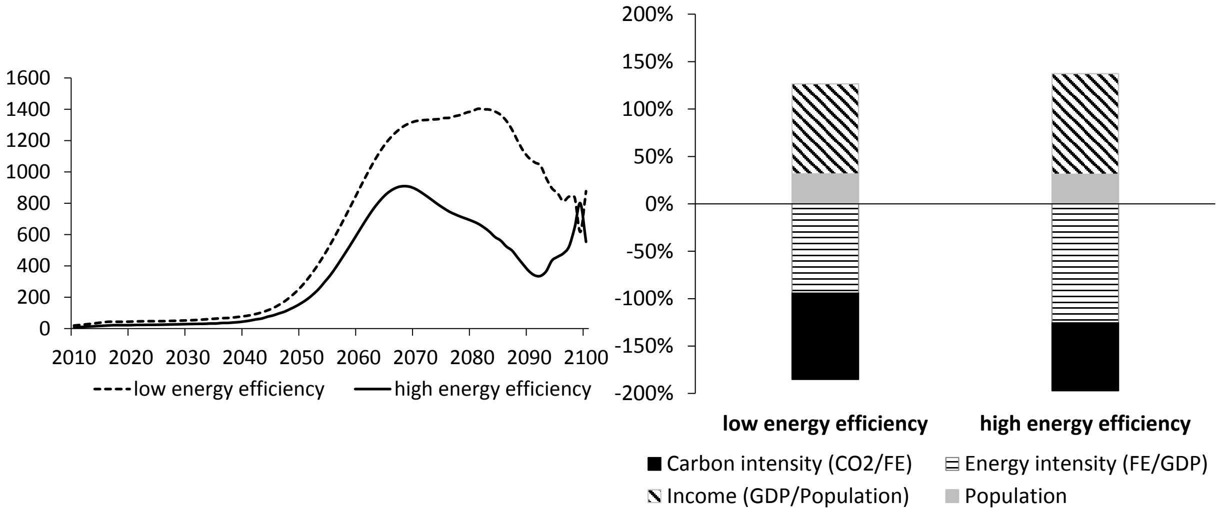
Table 1: Summary table of the examined scenarios

4 Energy efficiency as a key determinant of economic growth

4.1 Energy vs. carbon efficiency improvements

We explore the interactions between energy efficiency and economic growth under a climate constraint. In the modelled scenarios, the CO_2 price is determined endogenously each year to satisfy the CO_2 emission constraint. The CO_2 price (figure 2a) and climate policy costs directly relate to the shape of the emissions constraint (cf. appendix 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 occurs. 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 emission trajectory, see [77] for an analysis.

The Kaya decomposition of emissions factors (figure 2b) presents energy and macroeconomic determinants of CO_2 emissions. Emission changes can be explained through the evolution of three variables: GDP, the final energy intensity of GDP and the carbon intensity of the final energy[11]. This decomposition shows a larger contribution of energy efficiency improvements in emission reductions in the high energy efficiency scenario (-126% vs. -94%), with a smaller contribution of the carbon intensity of energy (-72% vs. -91%). Besides, high energy efficiency reduces the stringency of the carbon constraint, allowing for higher GDP growth (+106% vs. +95% for GDP per capita).



(a) CO_2 price ($US\$/tCO_2$)

(b) Kaya decomposition of the scenarios (2100 vs. 2002)

Figure 2: CO_2 price and Kaya decomposition - high and low energy efficiency

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

[11] Population and lifestyles are identical in all scenarios.

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 lower reliance on carbon intensity improvements to meet the emissions constraint.

4.2 Energy efficiency improvements in productive sectors allow for higher emissions from transport and residential energy use

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[12]. 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 3. This points to a change in the structure of economic output.

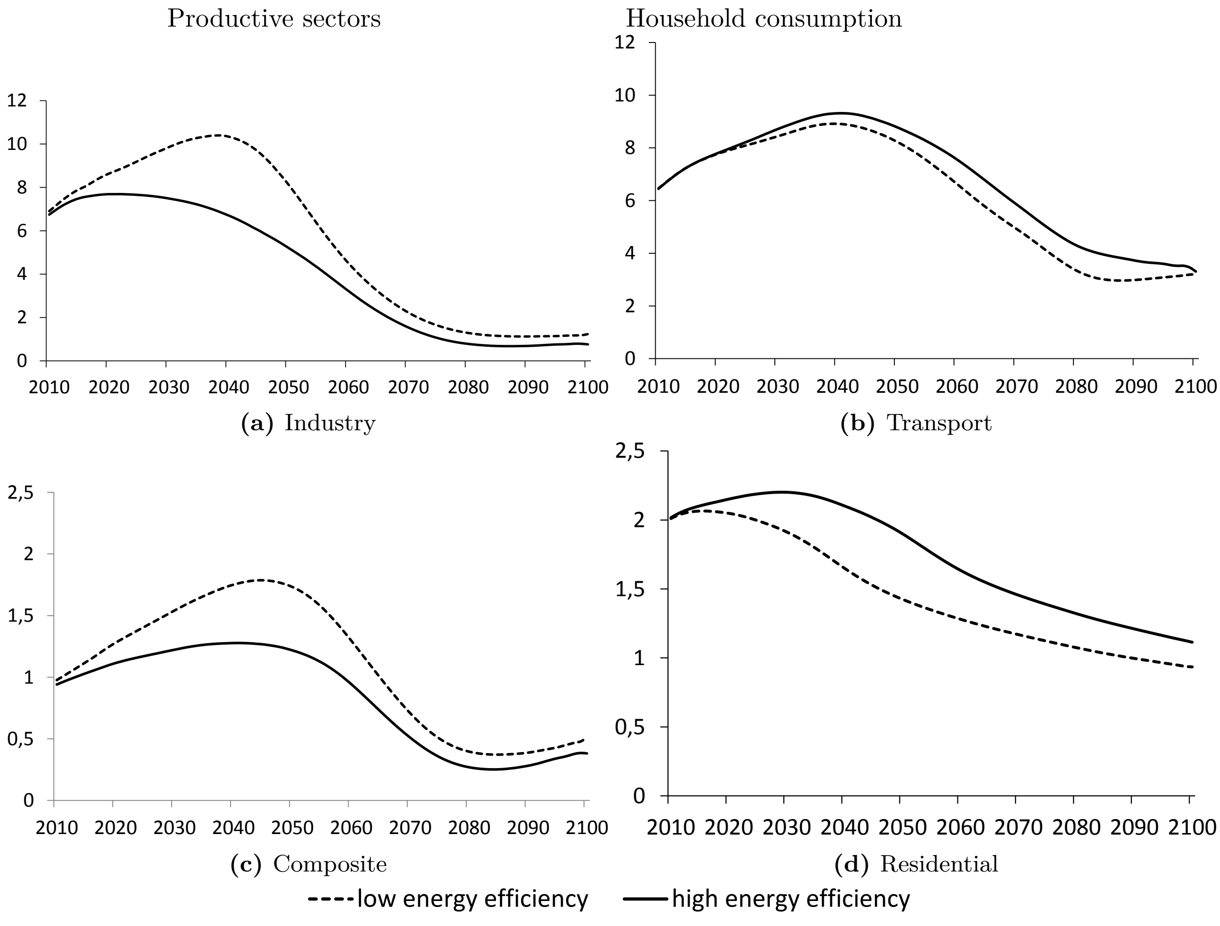


Figure 3: CO_2 emissions in largest emitting sectors - high and low energy efficiency scenarios ($GtCO_2$)

The industry and composite sectors decarbonise faster in the high energy efficiency scenario, despite higher demand for industrial and composite goods in most regions (appendix C.1), 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

[12]For instance, demand for transportation and fuel consumption of vehicles are relatively inelastic to energy prices in the short term [81].

level of the energy efficiency of the leader region[13] 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 (appendix C.2). 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[14]. 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 (appendix C.3) and higher CO_2 intensity of transport, mainly driven by larger automobile use due to lower petrol prices and higher income[15]. In fact, the share of automobile in transport is higher in high energy efficiency scenarios, leading to a different transport structure over time. Low carbon prices also delay the decarbonisation of electricity production, both in terms of overall emissions and CO_2 intensity of electricity production[16]. Higher emissions from electricity production are due to higher coal use without CCS, despite lower electricity production (appendix C.2).

Energy efficiency improvements thus induce lower final energy consumption and emissions in all productive sectors and therefore the contribution of the transport and residential sectors to meet the emissions constraint is reduced. The industry accounts for over 70% of emissions from productive sectors in the base year. The following section illustrates the mechanisms at play in this sector 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 interaction of energy efficiency with the drivers of industrial output. It illustrates the economic channels through which energy efficiency lowers unitary energy consumption and impacts industrial output, as presented in figure 1, and 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[17] and production taxes. Equation 1 presents this decomposition[18]. Each component is examined in turn to explain the drivers of industrial production growth. The impact of energy efficiency assumptions on each component[19] is summarised in tables B, C and D for industry (in appendix C.4).

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

[13]In 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 0.3% per year in the low energy efficiency case.

[14]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.

[15]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.

[16]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.

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

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

[19] 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.

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$
$IC^{unitary}$	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$/US$

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 ($IC_{ener}^{unitary}$ in toe/ton of Steel). From a sectoral viewpoint (independently of any general equilibrium or intertemporal effect), energy efficiency improvements translate 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[20], which relaxes tensions on energy markets and results in lower tax-exclusive energy prices in the first half of the period (figure Ia in appendix C.7). Second, lower energy needs command lower carbon prices to reach the same climate objective, particularly in the second half of the period (figure 2a). Both effects act to lower tax-inclusive energy prices (figure Ib in appendix C.7). Energy efficiency improvements therefore result 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 in terms of 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$, appendix C.1) 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 productivity over time, they directly follow sectoral output. Following the wage curve specification (see section 3.1), 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.

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

4.3.4 Profits

Investments in energy efficiency improvements are paid for by an increase of the mark-up rate (cf. section 3.2.1), which induces higher margins[21], 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[22], 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[23]. The increase in investments from firms is relatively small, as higher profits from higher production are compensated by lower prices.

4.3.5 The interaction between energy efficiency and economic output

The results presented in tables B, C and D (in appendix C.4) account for general equilibrium effects, and therefore include demand changes and intersectoral adjustments. In 2050, high energy efficiency 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. These results hold for a set of scenarios with technology variants (including differing assumptions on the availability of nuclear, renewables, coal resources, CCS, bioenergy and electric vehicles). For instance, we show the positive effect of energy efficiency improvements on industrial output in all these scenarios (see the sensitivity analysis in appendix C.6).

4.4 Economy-wide impacts of energy efficiency

The case study of industry has shown that energy efficiency improvements reduce energy requirements in this sector while increasing output. The mechanisms described above occur in all productive sectors (appendix C.1). 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[24], 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.

Energy efficiency improvements in productive sectors reduce total final energy consumption, primary energy and electricity production (figure 4). Energy efficiency also reduces labour requirements in energy sectors. However, higher demand for non-energy goods drives overall employment, which, together with higher wages in all productive sectors[25], triggers 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. Growth may thus depart from its natural rate, as described in section 3.1.2. In the climate scenarios considered, high energy efficiency result in higher GDP and consumption overall (figure 4). The impact of energy efficiency on growth and costs is further examined in section 5.

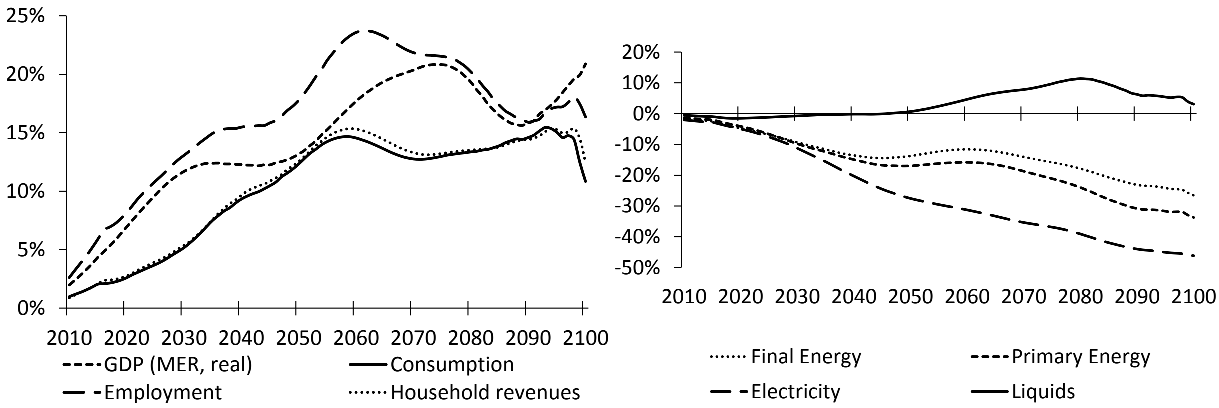
[21] The profits include all capital expenditures (investments, amortization and depreciation).

[22] Saving rates are exogenous and identical in all scenarios.

[23] Auto-investment rates are exogenous and identical in all scenarios.

[24] 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.

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



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

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

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

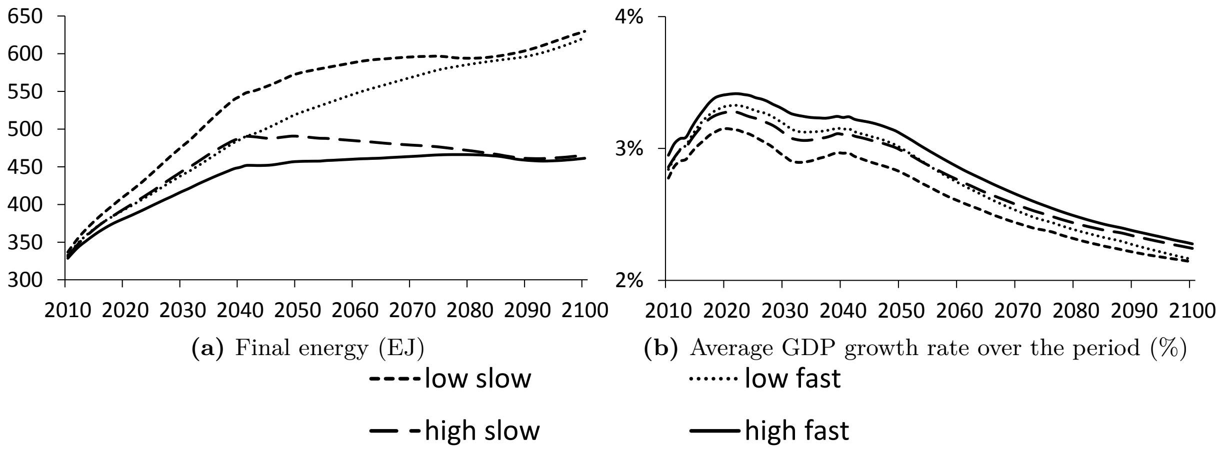
Energy efficiency in productive sectors drives household consumption up. While energy efficiency improvements are clearly beneficial over the period in terms of economic growth, the results have shown their heterogenous effect in terms of the timing of sectoral emissions. This section investigates the 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. 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).

GDP is an endogenous result in our model (see section 3.1.2). Our baseline GDP was calibrated by adapting the exogenous trends of labour productivity following the study protocol [82]. In our scenarios, baseline GDP grows between 2.1% and 2.2% per year over 2010-2100, following an intermediate pathway compared to the SRES scenarios [83]. 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 coincides with a low level of final energy consumption, resulting in a low final energy intensity of GDP. The 2010-2100 average economic growth rate (i.e. the point corresponding to year 2100 on figure **??**) is influenced by the rate of energy efficiency improvements of the leader and is 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.



(a) Final energy (EJ) **(b)** Average GDP growth rate over the period (%)

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

5.1.2 On climate policy scenarios

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

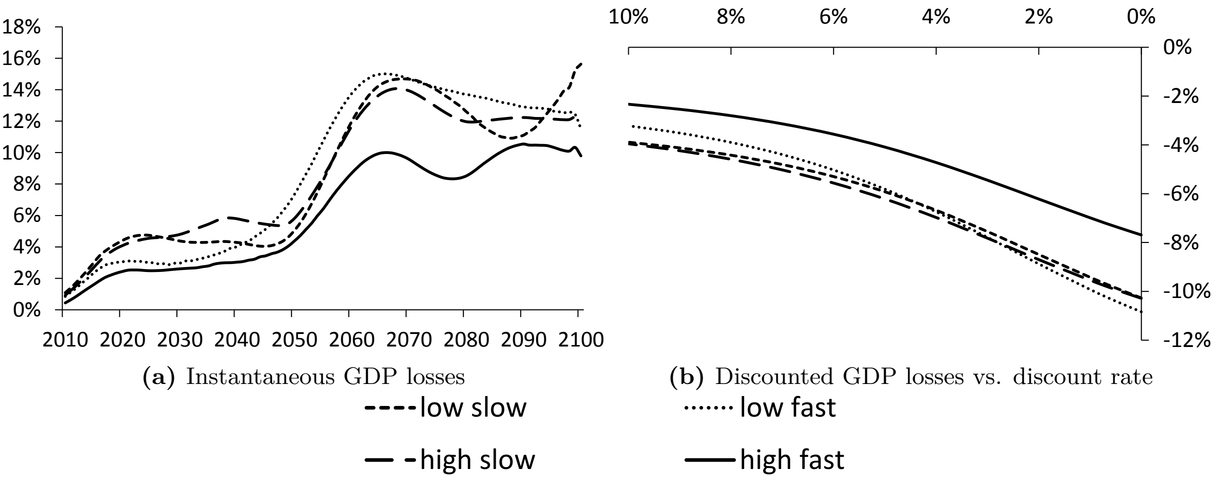
Empirical studies report such effects for CDM projects, for instance in wind power [84] and steel production [85]. [86] hints at the potential gains allowed by energy efficiency from technology diffusion from the most efficient country. [87–89] review implemented CDM projects documentation and find that 40% of projects involved technology diffusion, mainly occurring in the energy and industry sectors. Latecomers can catch up with technological innovations of industrialised countries through leapfrogging [90, 91]. Successful technological leapfrogging has occurred in emerging Asian countries, for instance the Korean steel [92] and car industries [93] and wind power in China and India [94–96]. The standardisation of transportation fuels in South America is another successful example [97, 98]. Besides, R&D agreements may improve the efficiency of international climate cooperation [99, 100].

In our study, faster convergence always reduces policy costs in the case of an energy efficient leader. The speed of convergence however has non-trivial effects on the timing of climate mitigation costs in the case of a relatively inefficient leader. Slow convergence translates into a higher carbon price until 2040 and induces short term losses compared to the fast convergence case. After that date costs are lower in the slow convergence scenario (figure 7). Indeed, with a slower convergence, a larger contribution to emissions reductions is required from the transportation and residential sectors to meet the emission constraint. This commands higher CO_2 prices, which affect economic output, as described in section 4. When looking at discounted costs[26], the benefits of fast convergence remain ambiguous for the case of an inefficient leader: slower convergence induces higher discounted costs when focusing on the short term and lower discounted costs when focusing on the long term (cf. appendix D.2). This 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 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,

[26]Discounted costs are plotted as a function of discount rates. High discount rates translate a short term focus with higher weight given to short term costs while low discount rates translate a long term focus with similar weight given to short and long term costs.



(a) Instantaneous GDP losses

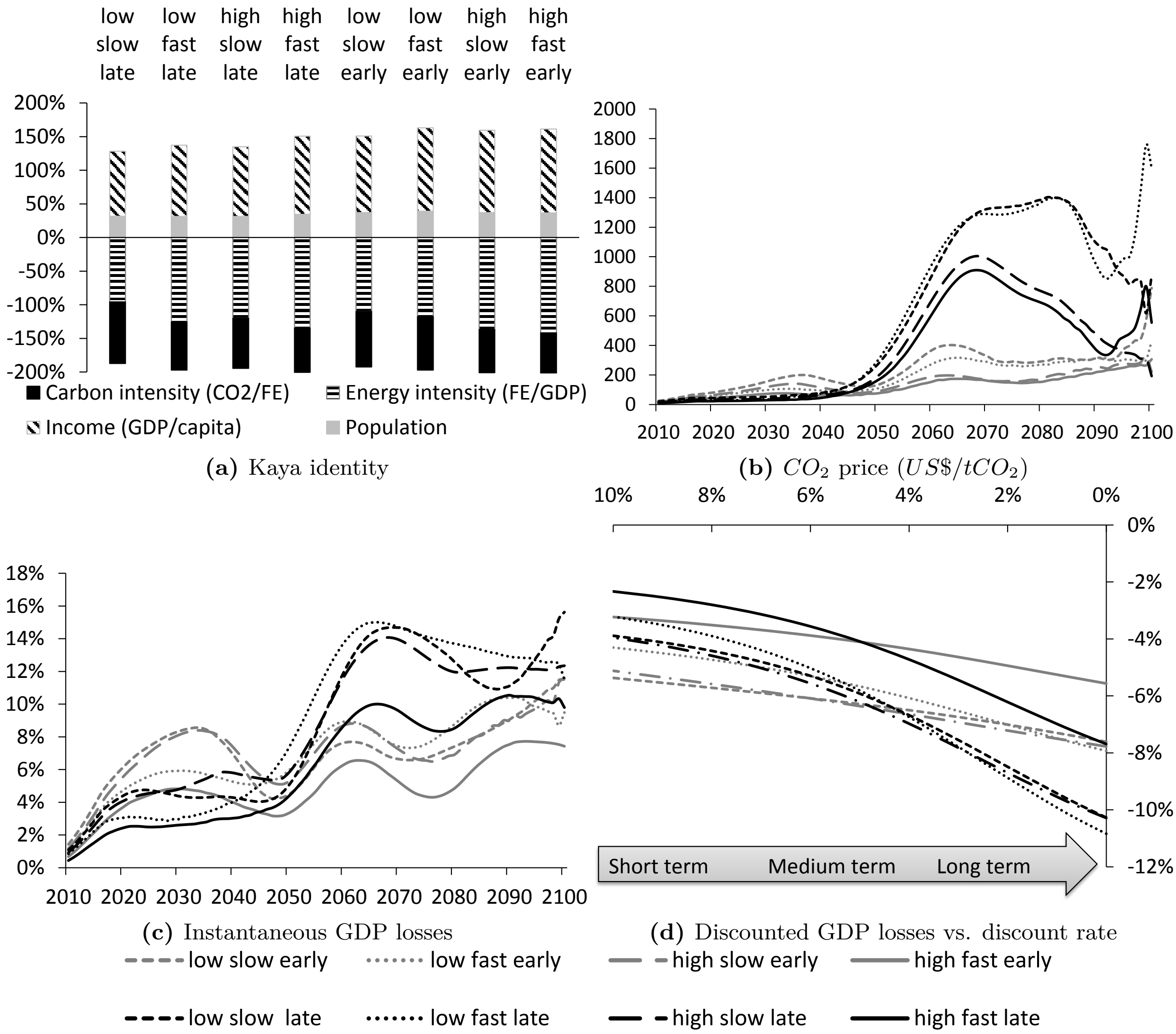
(b) Discounted GDP losses vs. discount rate

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

two emission profiles are tested (appendix B), 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 commands higher CO_2 prices in the short term compared to the late action case, but significantly lower CO_2 prices in the longer term. High short term CO_2 prices have triggered the early decarbonisation of the economy. Technical systems are better prepared to abate emissions and face a slower decarbonisation constraint in the medium term.

The results show that even in the case of early climate action, a very energy efficient leader does not reduce climate costs if other regions converge only slowly towards that level (high slow early vs. low slow early). 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 rates above 2% (the gap between low slow late and low fast late as compared to the gap between low slow early and low fast early). Early action thus acts as a trigger of energy efficiency improvements in the case of a relatively inefficient leader (as confirmed in appendix D.1). 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 due to the speed of convergence of the followers. 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 (cf. figure 7d, detailed table in appendix D.2). 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 a low rate of innovation in the leading countries.

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%), and shows significantly lower maximum losses over the considered discount rates. This result shows that early action should be preferred given the controversy surrounding the appropriate discount rate for assessing climate policies.



(a) Kaya identity

(b) CO_2 price ($US\$/tCO_2$)

(c) Instantaneous GDP losses

(d) Discounted GDP losses vs. discount rate

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

5.3 Policy recommendations

The timing of the action reveals a trade-off between short-term and long-term costs, translated into the choice of the discount rate. This discussion echoes the conclusion of the IPCC that when choosing between mitigation strategies, policy makers must weigh the potential costs of early action against the risk of delaying abatement [101]. If early action always appears more favourable in the long term while late action always appears favourable in the short term, a relevant question is therefore how we value present and future costs to choose between both options today. Policy-makers who use social discount rates of 4 to 5% will consider early and late climate action as equivalent options based on their economic costs. In that case, one option cannot be favoured over the other on a mere option value basis, according to our results.

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 that enhance the energy efficiency of leader regions and that accelerate the convergence of other regions towards the leader. The results presented in section 4 illustrate the impact of decarbonising productive sectors through improved energy efficiency on the carbon intensity of the transportation and residential sectors. Additional measures to mitigate the 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. Indeed, the structure of household demand is a significant driver of long term costs due to the high level of inertia of the capital stock: housing and transport infrastructures are long-lived and shifting to a low carbon capital stock may take decades. Reducing the carbon intensity in these sectors through policies complementary to carbon pricing (e.g., incentives to public transport) could therefore reduce the effect of the carbon constraint on these sectors.

6 Conclusion

This study has explored the links between energy efficiency improvements and economic growth using a hybrid general equilibrium model with endogenous technical change. The novelty of our approach is to combine within a consistent framework bottom-up modules with a macroeconomic top-down model. This allows us to represent the interactions between technical change at the sectoral, intersectoral and macro level, with a focus on energy efficiency in non-energy productive sectors. We thus model the evolution of the production frontier while overcoming the limitations of the standard aggregate production function.

Energy efficiency is endogenously modelled via (i) substitution and learning by doing in energy supply technologies; (ii) price-induced investment decisions in technologies for mobility and residential energy demand; and (iii) price-induced energy demand in productive sectors. This study features scenarios with alternatives on (iii) to analyze the role of energy efficiency in productive sectors. We investigate the channels through which energy use and prices impact economic growth in a carbon-constrained world, 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 these sectors conceals the less obvious result that the constraint is shifted away from household energy use. Higher final energy use in the residential sector is driven by higher household revenues and lower energy prices. 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 coincides with a low level of final energy consumption, hence a low final energy intensity of GDP over the whole period. Innovation in energy efficiency drives 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 greatly increases these costs. Energy efficiency policies aimed at innovation and knowledge diffusion 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 costs, even when combined with policy measures to enhance the energy efficiency of leader regions and accelerate technology transfers. Early and late climate action show similar economic costs with social discount rates of 4 to 5%. They may therefore be considered as equivalent options for policy design. 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 robust strategy if policy makers disagree on the appropriate discount rate for assessing climate policies.

Several limitations should be addressed in future work. The non-energy productive sectors are modeled in a very aggregate manner. Further modelling should therefore focus on adding a detailed bottom-up disaggregation of industry, services and agriculture production processes to refine the representation of energy efficiency. This study focused on the mechanisms of the interaction between energy efficiency improvements and economic growth. Also, A sensitivity analysis should be carried out to refine the analysis on the option value of energy efficiency for global climate mitigation strategies as well as for economic growth. Finally, the labour productivity should be endogenized to examine these issues with a fully endogenous growth engine. In particular, the link between energy efficiency, capital deepening and labour productivity should be further examined.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 265139 (AMPERE). The authors acknowledge funding by the Chair "Modeling for sustainable development". The authors wish to express their gratitude to Olivier Sassi for his seminal work on the topic and Julien Lefèvre for helpful discussions.

Bibliography

[1] J. Kraft and A. Kraft, "Relationship between energy and GNP," J. Energy Dev.;(United States), vol. 3, no. 2, 1978. 3

[2] I. Ozturk, "A literature survey on energy-growth nexus," Energy Policy, vol. 38, no. 1, pp. 340–349, 2010. 3

[3] J. D. Hamilton, "Oil and the macroeconomy," 2008. 3

[4] J. A. Krautkraemer, "Nonrenewable resource scarcity," Journal of Economic Literature, vol. 36, no. 4, pp. 2065–2107, 1998. 3

[5] 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, pp. 873–937, North-Holland, 2010. 3, 4

[6] IEA and OECD, World energy outlook 2012. 2012. 3, 9

[7] A. B. Jaffe, R. G. Newell, and R. N. Stavins, "Technological change and the environment," in Handbook of environmental economics (K.-G. Mäler and J. Vincent, eds.), vol. 1, pp. 461–516, Amsterdam, The Netherlands: North Holland, 2003. 3

[8] A. Xepapadeas, "Economic growth and the environment," in Handbook of environmental economics (K.-G. Mäler and J. Vincent, eds.), vol. 3, pp. 1105–1145, Amsterdam, The Netherlands: North Holland, 2005. 3

[9] F. Ghersi and J. C. Hourcade, "Macroeconomic consistency issues in e3 modeling: The continued fable of the elephant and the rabbit," The Energy Journal, no. Special Issue #2, pp. 39–62, 2006. 3, 6

[10] W. W. Hogan and A. S. Manne, "Energy economy interactions: the fable of the elephant and the rabbit?," Working Paper EMF, vol. 1.3, July 1977. 3

[11] R. Crassous, J. C. Hourcade, and O. Sassi, "Endogenous structural change and climate targets modeling experiments with imaclim-r," Energy Journal, vol. 27, pp. 161–178, 2006. 3, 6

[12] L. Clarke, J. Weyant, and J. Edmonds, "On the sources of technological change: What do the models assume?," Energy Economics, vol. 30, no. 2, pp. 409–424, 2008. 4

[13] J. R. Hicks, The theory of wages. London: Macmillan, 1963. 4

[14] D. C. Popp, "The effect of new technology on energy consumption," Resource and Energy Economics, vol. 23, no. 3, pp. 215–239, 2001. 4, 6

[15] K. Fisher-Vanden, G. H. Jefferson, M. Jingkui, and X. Jianyi, "Technology development and energy productivity in china," Energy Economics, vol. 28, pp. 690–705, Nov. 2006. 4

[16] W. D. Nordhaus, "Modeling induced innovation in climate-change policy," Technological change and the environment, pp. 182–209, 2002. 4, 5

[17] G. J. M. Phylipsen, K. Blok, and E. Worrell, Handbook on International Comparisons of Energy Efficiency in the Manufacturing Industry: In Commission of the Ministry of Housing, Physical Planning and the Environment. Univ., Department of Science, Technology and Society, 1998. 4

[18] K. Schumacher and R. D. Sands, "Where are the industrial technologies in energy-economy models? an innovative CGE approach for steel production in germany," Energy Economics, vol. 29, no. 4, pp. 799–825, 2007. 4

[19] F. Lecocq and P. Ambrosi, "Policy MonitorEdited by maureen CropperThe clean development mechanism: History, status, and prospects," Review of Environmental Economics and Policy, vol. 1, pp. 134–151, Jan. 2007. 4

[20] E. L. F. d. Almeida, "Energy efficiency and the limits of market forces: the example of the electric motor market in france," Energy Policy, vol. 26, no. 8, pp. 643–653, 1998. 4

[21] K. Fisher-Vanden and M. S. Ho, "Technology, development, and the environment," Journal of Environmental Economics and Management, vol. 59, pp. 94–108, Jan. 2010. 4

[22] S. Sorrell and J. Dimitropoulos, "The rebound effect: Microeconomic definitions, limitations and extensions," Ecological Economics, vol. 65, no. 3, pp. 636–649, 2008. 4

[23] J. C. Van den Bergh, "Energy conservation more effective with rebound policy," Environmental and resource economics, vol. 48, no. 1, pp. 43–58, 2011.

[24] K. Turner, "'Rebound'effects from increased energy efficiency: a time to pause and reflect," Energy Journal, 2012. 4

[25] D. Lindenberger and R. Kümmel, "Energy and the state of nations," Energy, vol. 36, no. 10, pp. 6010–6018, 2011. 4

[26] R. U. Ayres and B. Warr, The economic growth engine: how energy and work drive material prosperity. Edward Elgar Publishing, 2010. 4

[27] D. W. Jorgenson and K. J. Stiroh, "Information technology and growth," The American Economic Review, vol. 89, no. 2, pp. 109–115, 1999. 5

[28] R. M. Solow, "Technical change and the aggregate production function," The review of Economics and Statistics, vol. 39, no. 3, pp. 312–320, 1957. 5

[29] A. S. Manne and R. G. Richels, Global CO2 emission reductions: the impacts of rising energy costs. Springer, 1992. 5

[30] H. Dowlatabadi and M. A. Oravetz, "US long-term energy intensity: Backcast and projection," Energy Policy, vol. 34, no. 17, pp. 3245–3256, 2006. 5

[31] A. Löschel, "Technological change in economic models of environmental policy: a survey," Ecological Economics, vol. 43, no. 2, pp. 105–126, 2002. 5

[32] C. Azar and H. Dowlatabadi, "A review of technical change in assessment of climate policy," Annual review of energy and the environment, vol. 24, no. 1, pp. 513–544, 1999. 5

[33] 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, vol. 27, no. 1, pp. 271–308, 2002. 5

[34] T. Barker, I. Bashmakov, A. Alharthi, M. Amann, L. Cifuentes, J. Drexhage, M. Duan, O. Edenhofer, B. Flannery, and M. Grubb, “Mitigation from a cross-sectoral perspective,” Climate change, pp. 619–690, 2007. 5

[35] R. M. Solow, “Investment and technical progress,” in Mathematical methods in the social sciences, pp. 89–104, Stanford, CA: Stanford University Press, 1959. 5

[36] J.-M. Burniaux, J. P. Martin, G. Nicoletti, and J. O. Martins, “GREEN a multi-sector, multi-region general equilibrium model for quantifying the costs of curbing CO2 emissions: a technical manual,” tech. rep., OECD Publishing, 1992. 5

[37] O. Sassi, L’impact du changement technique endogène sur les politiques climatiques. PhD thesis, 2008. 5

[38] M. Ha-Duong, M. J. Grubb, and J.-C. Hourcade, “Influence of socioeconomic inertia and uncertainty on optimal CO2-emission abatement,” Nature, vol. 390, pp. 270–273, Nov. 1997. 5

[39] R. E. Lucas Jr, “On the mechanics of economic development,” Journal of monetary economics, vol. 22, no. 1, pp. 3–42, 1988. 5

[40] P. M. Romer, “Endogenous technological change,” Journal of political Economy, pp. S71–S102, 1990. 5

[41] P. Aghion and P. Howitt, Endogenous Growth Theory, vol. 1. MIT Press Books, 1998. 5

[42] K. Gillingham, R. G. Newell, and W. A. Pizer, “Modeling endogenous technological change for climate policy analysis,” Energy Economics, vol. 30, no. 6, pp. 2734–2753, 2008. 5

[43] L. H. Goulder and S. H. Schneider, “Induced technological change and the attractiveness of CO2 abatement policies,” Resource and Energy Economics, vol. 21, no. 3, pp. 211–253, 1999. 5

[44] P. Buonanno, C. Carraro, and M. Galeotti, “Endogenous induced technical change and the costs of kyoto,” Resource and Energy economics, vol. 25, no. 1, pp. 11–34, 2003. 5

[45] V. Bosetti, C. Carraro, and M. Galeotti, “The dynamics of carbon and energy intensity in a model of endogenous technical change,” The Energy Journal, pp. 191–205, 2006. 5

[46] D. Popp, “ENTICE: endogenous technological change in the DICE model of global warming,” Journal of Environmental Economics and Management, vol. 48, no. 1, pp. 742–768, 2004. 5

[47] D. Popp, “R&D subsidies and climate policy: is there a “free lunch”?,” Climatic Change, vol. 77, no. 3-4, pp. 311–341, 2006. 5

[48] L. Clarke, J. Weyant, and A. Birky, “On the sources of technological change: Assessing the evidence,” Energy Economics, vol. 28, no. 5, pp. 579–595, 2006. 5

[49] C.-O. Wene, Experience curves for energy technology policy. OECD, 2000. 5

[50] A. McDonald and L. Schrattenholzer, “Learning rates for energy technologies,” Energy policy, vol. 29, no. 4, pp. 255–261, 2001.

[51] L. Neij, “Cost development of future technologies for power generation—A study based on experience curves and complementary bottom-up assessments,” Energy policy, vol. 36, no. 6, pp. 2200–2211, 2008. 5

[52] D. Anderson and S. Winne, “Modelling innovation and threshold effects in climate change mitigation,” Tyndall Centre for Climate Change Research, Working Paper, vol. 59, 2004. 5

[53] F. S. Tomoda, K. Akimoto, and T. Homma, “Analysis of technological portfolios for CO2 stabilizations and effects of technological changes,” The Energy Journal, no. Special Issue# 1, pp. 141–162, 2006. 5

[54] S. Rao, I. Keppo, and K. Riahi, “Importance of technological change and spillovers in long-term climate policy,” The Energy Journal, vol. 27, pp. 123–139, 2006. 5

[55] 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. 6

[56] R. M. Solow, “A contribution to the theory of economic growth,” The Quarterly Journal of Economics, vol. 70, p. 65–94, Feb. 1956. 6

[57] E. R. Berndt and D. O. Wood, “Technology, prices, and the derived demand for energy,” The review of Economics and Statistics, vol. 57, no. 3, pp. 259–268, 1975. 6

[58] D. W. Jorgenson and B. M. Fraumeni, “Relative prices and technical change,” Modeling and Measuring Natural Resources Substitution, MIT Press, Cambridge, 1981. 6

[59] J. R. McFarland, J. M. Reilly, and H. J. Herzog, “Representing energy technologies in top-down economic models using bottom-up information,” Energy Economics, vol. 26, no. 4, pp. 685–707, 2004. 6

[60] C. Böhringer, “The synthesis of bottom-up and top-down in energy policy modeling,” Energy economics, vol. 20, no. 3, pp. 233–248, 1998. 6

[61] I. Sue Wing, “Representing induced technological change in models for climate policy analysis,” Energy Economics 28, vol. 28, pp. 539–562, 2006. 6

[62] M. Grubb, “Policy modelling for climate change: the missing models,” Energy Policy, vol. 21, no. 3, pp. 203–208, 1993. 6

[63] J. C. Hourcade, M. Jaccard, C. Bataille, and F. Ghersi, “Hybrid modeling: New answers to old challenges,” The Energy Journal, vol. 2, no. Special issue, pp. 1–12, 2006. 6

[64] 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, vol. 10, no. 1-2, p. 5–24, 2010. 6

[65] 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, pp. 1–20, 2012. 6, 29, 30

[66] R. D. Sands, S. Miller, and M. K. Kim, “The second generation model: Comparison of SGM and GTAP approaches to data development,” PNNL report, vol. 15467, 2005. 6

[67] B. V. Dimaranan, “The GTAP 6 data base,” Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, 2006. 6

[68] A. Schafer and D. G. Victor, “The future mobility of the world population,” Transportation Research Part A: Policy and Practice, vol. 34, no. 3, pp. 171–205, 2000. 6

[69] C. Corrado and J. Mattey, “Capacity utilization,” The Journal of Economic Perspectives, vol. 11, no. 1, pp. 151–167, 1997. 7

[70] D. G. Blanchflower and A. J. Oswald, “An introduction to the wage curve,” The Journal of Economic Perspectives, vol. 9, no. 3, pp. 153–167, 1995. 7

[71] 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, vol. 11, no. 1, pp. 768–788, 2011. 7

[72] R. Bibas, “Capital description and investment dynamics in Imaclim-R World,” Technical report, CIRED, 2014. 7

[73] E. Phelps, "The golden rule of accumulation: a fable for growthmen," The American Economic Review, vol. 51, no. 4, p. 638–643, 1961. 7

[74] R. J. Barro and X. Sala-i Martin, "Convergence," Journal of political Economy, pp. 223–251, 1992. 8

[75] A. Maddison, Monitoring the world economy, 1820-1992. Development Centre studies, OECD Development Center, 1995. 8

[76] 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, vol. 420, 2005. 8

[77] R. Bibas and A. Méjean, "Potential and limitations of bioenergy options for low carbon transitions," Climatic change, vol. Forthcoming, 2013. 8, 10, 11, 29

[78] F. Liu, M. Ross, and S. Wang, "Energy efficiency of china's cement industry," Energy, vol. 20, no. 7, pp. 669–681, 1995. 8

[79] P. Conforti and M. Giampietro, "Fossil energy use in agriculture: an international comparison," Agriculture, ecosystems & environment, vol. 65, no. 3, pp. 231–243, 1997. 9

[80] K. Riahi, E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, M. Schaeffer, J. Edmonds, M. Isaac, V. Krey, T. Longden, G. Luderer, A. Méjean, D. L. McCollum, S. Mima, H. Turton, D. P. van Vuuren, K. Wada, V. Bosetti, P. Capros, P. Criqui, M. Hamdi-Cherif, M. Kainuma, and O. Edenhofer, "Locked into copenhagen pledges–implications of short-term emission targets for the cost and feasibility of long-term climate goals," Technological Forecasting and Social Change, 2013. 9, 10

[81] P. Goodwin, J. Dargay, and M. Hanly, "Elasticities of road traffic and fuel consumption with respect to price and income: a review," Transport Reviews, vol. 24, no. 3, pp. 275–292, 2004. 12

[82] E. Kriegler, K. Riahi, Nico Bauer; Valeria Jana Schwanitz; Nils Petermann;, Valentina Bosetti; Adriana Marcucci; Sander Otto; Leonidas Paroussos; Shilpa Rao; Tabaré Arroyo, Curras; Shuichi Ashina; Johannes Bollen; Jiyong Eom; Meriem Hamdi-Cherif; Thomas Longden; Alban, Kitous; Aurélie Méjean; Fuminori Sano; Michiel Schaeffer; Kenichi Wada; Pantelis Capros; Detlef van, and Vuuren; Ottmar Edenhofer, "Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy," Technological Forecasting & Social Change, vol. Special issue: Climate Stabilization, 2013. 16

[83] N. Nakicenovic, J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T. Y. Jung, and T. Kram, "Special report on emissions scenarios: a special report of working group III of the intergovernmental panel on climate change," tech. rep., Pacific Northwest National Laboratory, Richland, WA (US), Environmental Molecular Sciences Laboratory (US), 2000. 16

[84] I. Haščič and N. Johnstone, "CDM and international technology transfer: empirical evidence on wind power," Climate Policy, vol. 11, no. 6, pp. 1303–1314, 2011. 17

[85] T. Okazaki and M. Yamaguchi, "Accelerating the transfer and diffusion of energy saving technologies steel sector experience—Lessons learned," Energy Policy, vol. 39, no. 3, pp. 1296–1304, 2011. 17

[86] E. Worrell, L. Bernstein, J. Roy, L. Price, and J. Harnisch, "Industrial energy efficiency and climate change mitigation," Energy Efficiency, vol. 2, no. 2, pp. 109–123, 2009. 17

[87] E. Haites, M. Duan, and S. Seres, "Technology transfer by CDM projects," Climate Policy, vol. 6, no. 3, pp. 327–344, 2006. 17

[88] A. Dechezleprêtre, M. Glachant, and Y. Ménière, "The clean development mechanism and the international diffusion of technologies: An empirical study," Energy Policy, vol. 36, no. 4, pp. 1273–1283, 2008.

[89] S. Seres, E. Haites, and K. Murphy, "Analysis of technology transfer in CDM projects: An update," Energy Policy, vol. 37, no. 11, pp. 4919–4926, 2009. 17

[90] J. Goldemberg, "Leapfrog energy technologies," Energy Policy, vol. 26, no. 10, pp. 729–741, 1998. 17

[91] J. Watson and R. Sauter, "Sustainable innovation through leapfrogging: a review of the evidence," International Journal of Technology and Globalisation, vol. 5, no. 3, pp. 170–189, 2011. 17

[92] A. P. D'costa, "State, steel and strength: Structural competitiveness and development in south korea," The journal of development studies, vol. 31, no. 1, pp. 44–81, 1994. 17

[93] S.-C. Yoon, "Systemic problems in technology transfer in emerging markets," International Journal of Technology and Globalisation, vol. 4, no. 4, pp. 341–349, 2009. 17

[94] A. Lema and K. Ruby, "Between fragmented authoritarianism and policy coordination: Creating a chinese market for wind energy," Energy Policy, vol. 35, no. 7, pp. 3879–3890, 2007. 17

[95] J. I. Lewis, "Technology acquisition and innovation in the developing world: wind turbine development in china and india," Studies in comparative international development, vol. 42, no. 3-4, pp. 208–232, 2007.

[96] P. Ru, Q. Zhi, F. Zhang, X. Zhong, J. Li, and J. Su, "Behind the development of technology: The transition of innovation modes in china's wind turbine manufacturing industry," Energy Policy, vol. 43, pp. 58–69, 2012. 17

[97] E. Dantas, "The evolution of the knowledge accumulation function in the formation of the brazilian biofuels innovation system," International Journal of Technology and Globalisation, vol. 5, no. 3, pp. 327–340, 2011. 17

[98] T. Lopes de Souza and L. Hasenclever, "The brazilian system of innovation for bioethanol: a case study on the strategic role of the standardisation process," International Journal of Technology and Globalisation, vol. 5, no. 3, pp. 341–356, 2011. 17

[99] H. De Coninck, C. Fischer, R. G. Newell, and T. Ueno, "International technology-oriented agreements to address climate change," Energy Policy, vol. 36, no. 1, pp. 335–356, 2008. 17

[100] R. G. Newell, "International climate technology strategies," Harvard Project on International Climate Agreements Discussion Paper, no. 2008-12, 2008. 17

[101] IPCC, Climate change 1995: Economic and social dimensions of climate change: Contribution of Working Group III to the second assessment report of the Intergovernmental Panel on Climate Change, vol. 53150. Cambridge University Press, 1996. 19

[102] 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, vol. 101, no. 3, pp. 663–668, 2010. 29

Appendices

A Imaclim-R model schematics

A.1 Imaclim-R static equilibrium schematics

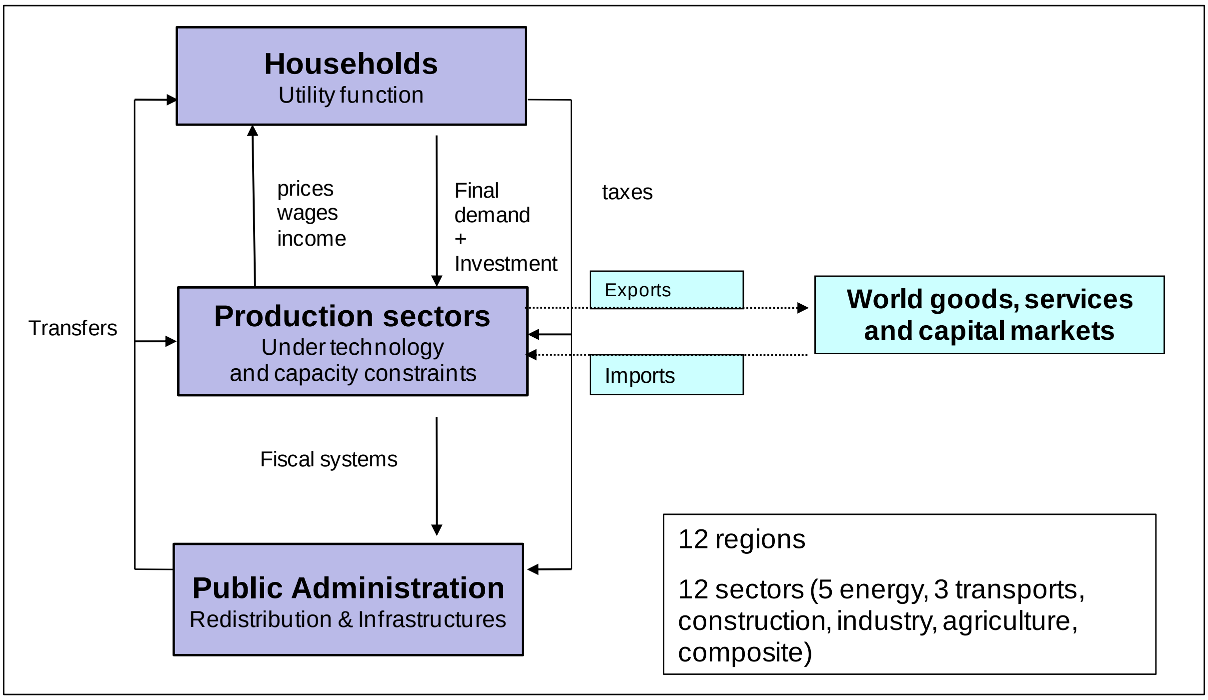


Figure A: Static equilibrium

A.2 Imaclim-R model dynamics schematics

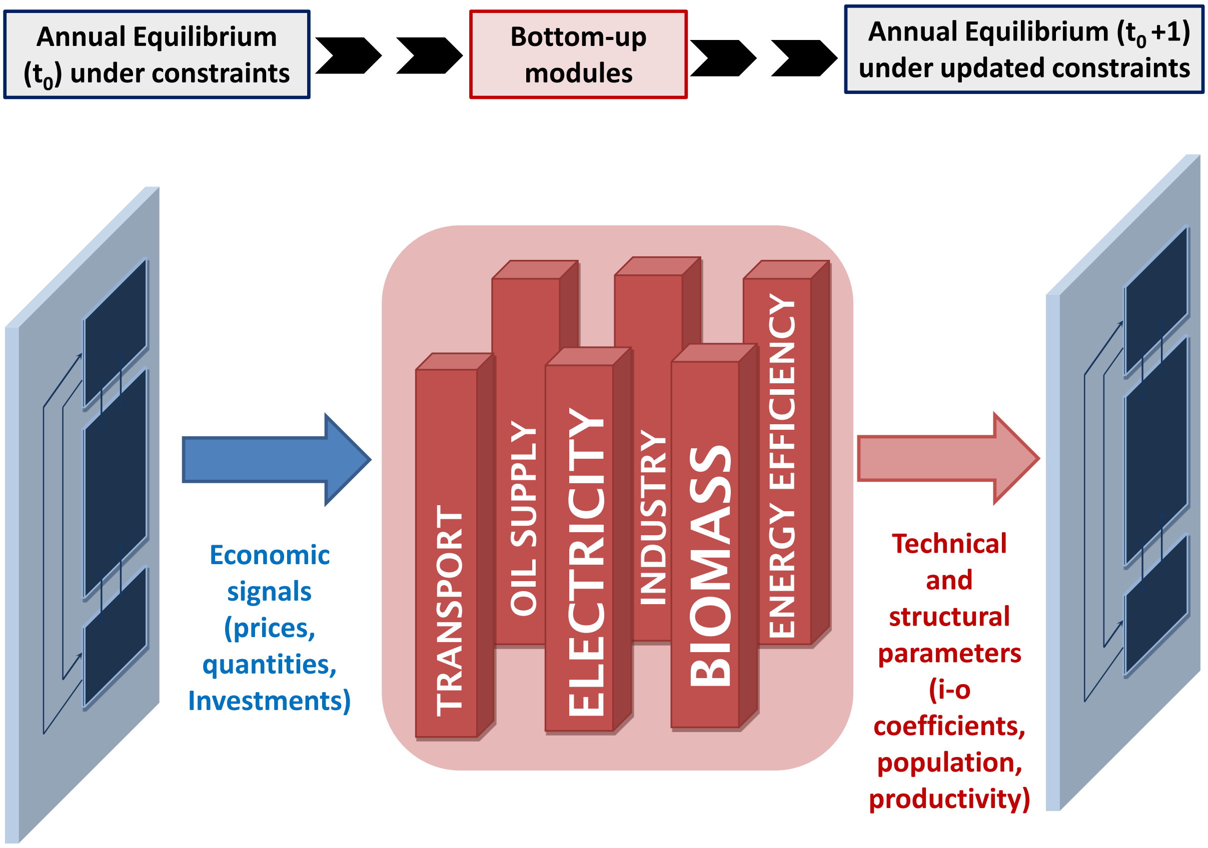


Figure B: Model dynamics

A.3 Imaclim-R dynamic modules

Cf. table A in following pages.

SUPPLY		
	Sector	Description
Primary energy	Coal	Regional investment depends on the amount of reserves in that region and on the production to capacity ratio. Coal prices increase with production growth (with asymetric elasticities for upwards and downwards trends).
	Gas	Regional investment depends on the amount of reserves in that region and on the production to capacity ratio. Gas prices follow oil prices. This evolution was calibrated on the World Energy Model (IEA, 2007) and is valid until a threshold oil price. High oil prices induce a decoupling of oil and gas prices. Gas prices then depend on production costs and scarcity rents.
	Oil	The oil module specifications include (i) market power for key suppliers, (ii) the geological nature of oil reserves (7 conventional and 5 non-conventional categories of reserves), (iii) imperfect expectations due to uncertainties on the technical, economical and geopolitical determinants of oil markets. The pace of capacity expansion is constrained by geological characteristics (inertia in the exploration process and depletion effects). [102] provides more details.
Energy transformation	Electricity	The electricity generation module specifications include (i) load curves constraints, (ii) explicit technologies, (iii) explicit capital vintages, (iv) technology-specific constraints (including nuclear acceptability and intermittent renewables integration) (v) projection of optimal investments over a 10-year period with imperfect expectations (on demand, fuel and electricity prices, carbon tax, costs), (vi) actual investment decisions for the current year to account for existing capacities. Technologies include oil (without CCS), gas, coal and biomass with and without CCS, wind, solar, hydro, nuclear. The discount rate used is equal to 10%. [77] provides more details.
	Liquid fuels	Liquid fuels include: (i) refined oil, (ii) biofuels supply following supply curves (described in [77]) and (iii) coal-to-liquid which supplements the production after a threshold oil price. Currently no technology in IMACLIM enables the use of liquid fuels with CCS, in particular biofuels currently cannot be combined with CCS.
Non-energy sectors	All	Good production is described in an aggregate manner. The sector aims at meeting the expected demand to reach a production to capacity ratio of 80%.
	Goods production	Energy efficiency improvements (EEI) are endogenous and follow two main mechanisms. First, the most energy-efficient region follows a trend of innovation, the rate of which is influenced by energy prices. Then, the followers catch-up with a convergence speed determined by energy prices. EEI are in part free and in part paid for by an increase of firms' markup rate. EEI apply to the aggregate sector (no explicit technologies are modelled). Newly-built capacities are affected in full, while already installed capacities are only marginally retrofitted. The construction sector follows the energy efficiency gains of the industry sector. Relative energy prices drive substitution between energy carriers. See section 3.2 for more details.
	Transport	The maximization of households' utility determines mobility demand and modal choices. These depend on modal speed which is driven by congestion. Investments in transport infrastructures determine the efficiency of passenger transport modes. "Basic needs" represent a constrained mobility including commuting, which is insensitive to energy prices and translates location and infrastructure constraints. The freight transport content of production is represented through Leontief (input-output) coefficients. [65] provides more details.

DEMAND	
Demography	The evolution of total and active population follows exogenous scenarios for following exogenous scenarios (UN median scenarios).
Consumption goods	The evolution of goods' consumption in the static equilibrium is determined by the maximization of the utility function, under constraints on (i) revenue (ii) transport time budget (iii) basic needs (iv) inelastic demand for housing services. For the dynamic evolution, the progressive switch from industry to services is controlled by saturation levels of per capita consumption of industrial goods (in physical terms, not necessarily in value terms) via an asymptote. For developing countries, these saturation levels represent various types of catch-up to the consumption style of developed countries.
Residential uses	Residential energy consumption depends on the energy service level per m^2 (heating, cooling, etc.) and the total housing surface. The technical characteristics of the existing stock of end-use equipment and buildings and the increase in energy service demand condition the energy coefficients per m^2, which reflect the energy service level. These coefficients evolve according to exogenous trajectories calibrated on the outputs of the POLES model. These trajectories encompass changes in residential energy consumption due to (i) cost variations of energy services (ii) rising income which increases energy consumption for services other than basic needs and (iii) physical characteristics of buildings (surface, insulation, architectural design). We also account for the diffusion of very low energy buildings at very high energy prices. They are represented by a unique alternative housing with an annual energy consumption of 50 kWh/m^2 (80 % electricity and 20% gas). Housing surface per capita has an income elasticity, and region-specific asymptotes for the floor area per capita. This limit reflects spatial constraints, cultural habits as well as assumptions about future development styles.
Mobility demand	**Freight transport** The energy intensity of freight transport is driven by an exogenous trend and a short-term fuel price elasticity. They capture autonomous and endogenous energy efficiency gains as well as short-term modal shifts, with the long-term price response resulting from the sequence of those short-term adjustments. Total energy demand is driven by freight mobility needs, which in turn depend on the level of economic activities and their freight content. **Passenger transport** The maximization of households' utility under the assumption of constant travel time and budget constraints breaks down mobility needs into four travel modes (ground-based public transport, air transport, private vehicles and non-motorized modes). When mobility demand exceeds the normal load conditions of a given type of infrastructure, speed decreases. In the absence of further investment, households will reallocate their travel time budget to more efficient modes. This allows to represent the induction of mobility demand by infrastructures and the rebound effect following energy efficiency gains on vehicles. Energy efficiency in private vehicles results from households' decisions on the purchase of new vehicles, based on a mean cost minimization criterion between different types of available technologies (including standard, hybrid and electric vehicles) according to capital costs (which undergoes learning-by-doing) and unitary fuel consumption. In each region, the motorization rates increase with disposable per capita income through variable income-elasticity, capturing agents' localization choices. In addition, the impact of local location choices is represented through basic needs of mobility, which represent the travels imposed by daily journeys (especially, for commuting to work and access to services). [65] provides more details.

Table A: Description of dynamic modules

B Constrained emissions profiles

Figure C presents the constrained emissions profiles for the scenarios with climate policies. The late action profile corresponds to the default profile presented in section 4.

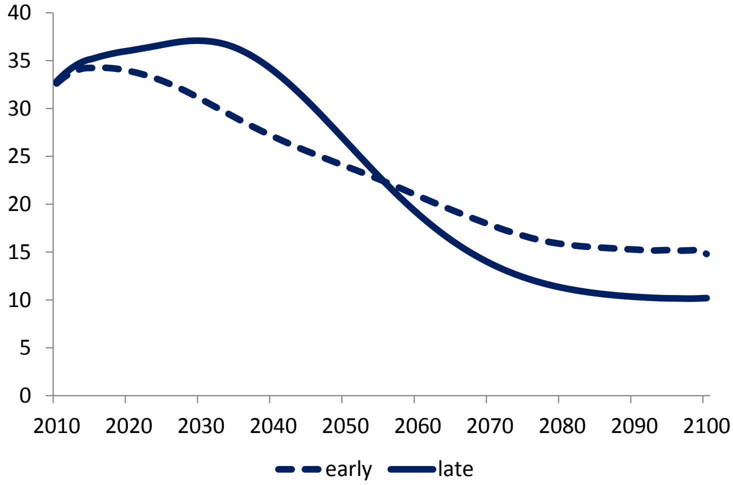


Figure C: Early vs. late (default) emissions profile constraint ($GtCO_2$)

C High vs. low (default setting)

C.1 Sectoral demands

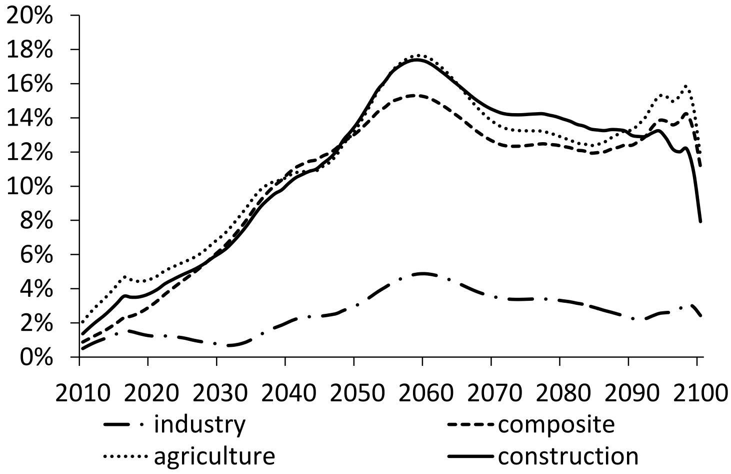


Figure D: Sectoral demands - industry and services

C.2 Electricity mixes

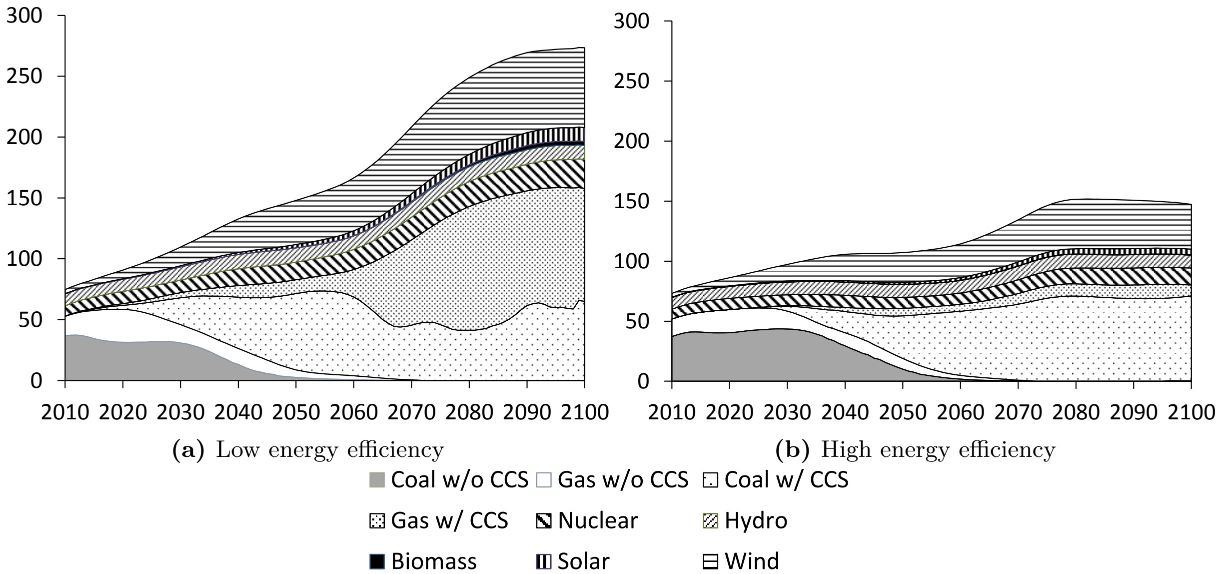


Figure E: Electricity mixes (EJ)

C.3 Mobility

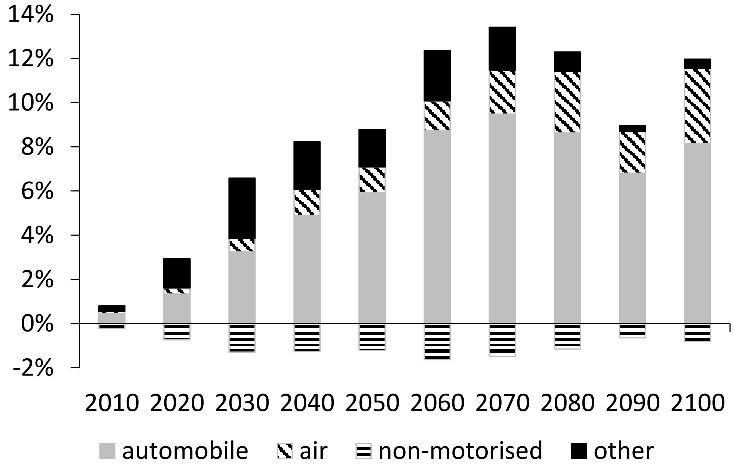


Figure F: Mobility (Changes in pkm (%))

C.4 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 B: 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 C: 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 D: Impact of energy efficiency on industrial and composite quantities

C.5 Industry decomposition

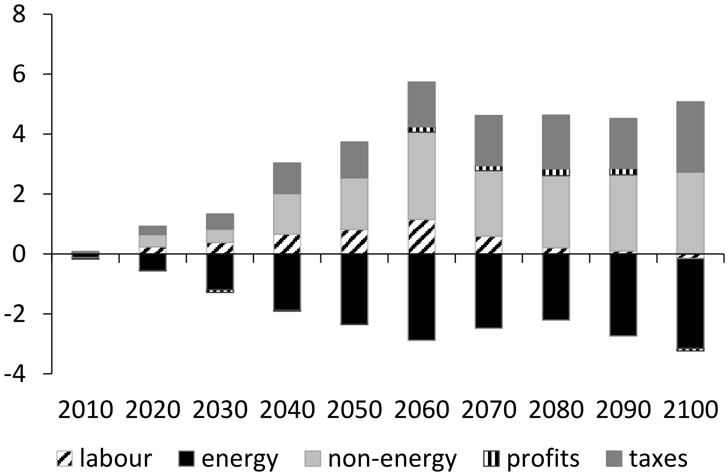


Figure G: Difference in expenditures items for industry from low to high (trillions $US\$$)

C.6 Sensitivity analysis of energy efficiency effects

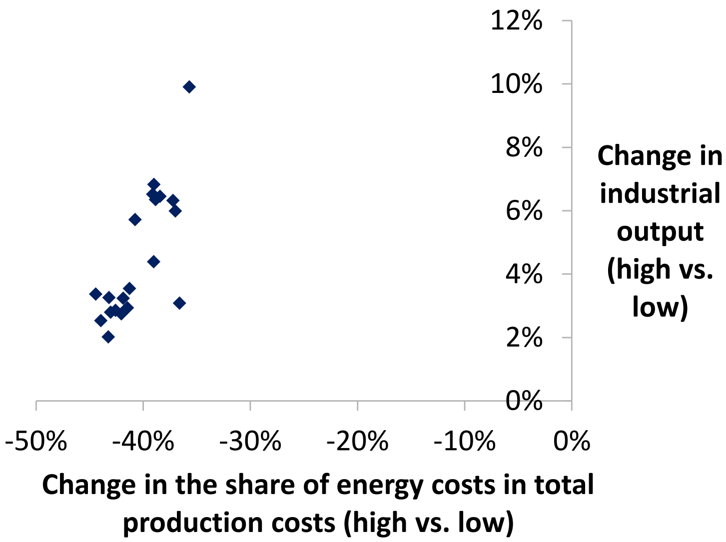


Figure H: Sensitivity analysis – high vs. low scenarios

C.7 Energy prices evolution

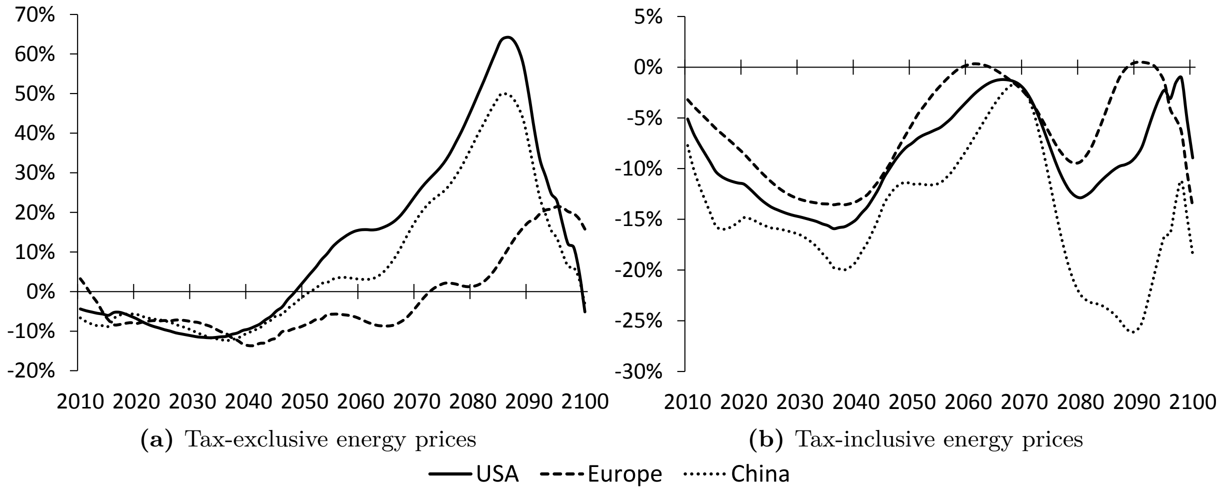


Figure I: Industry energy prices evolution

D All scenarios

D.1 Final energy intensity

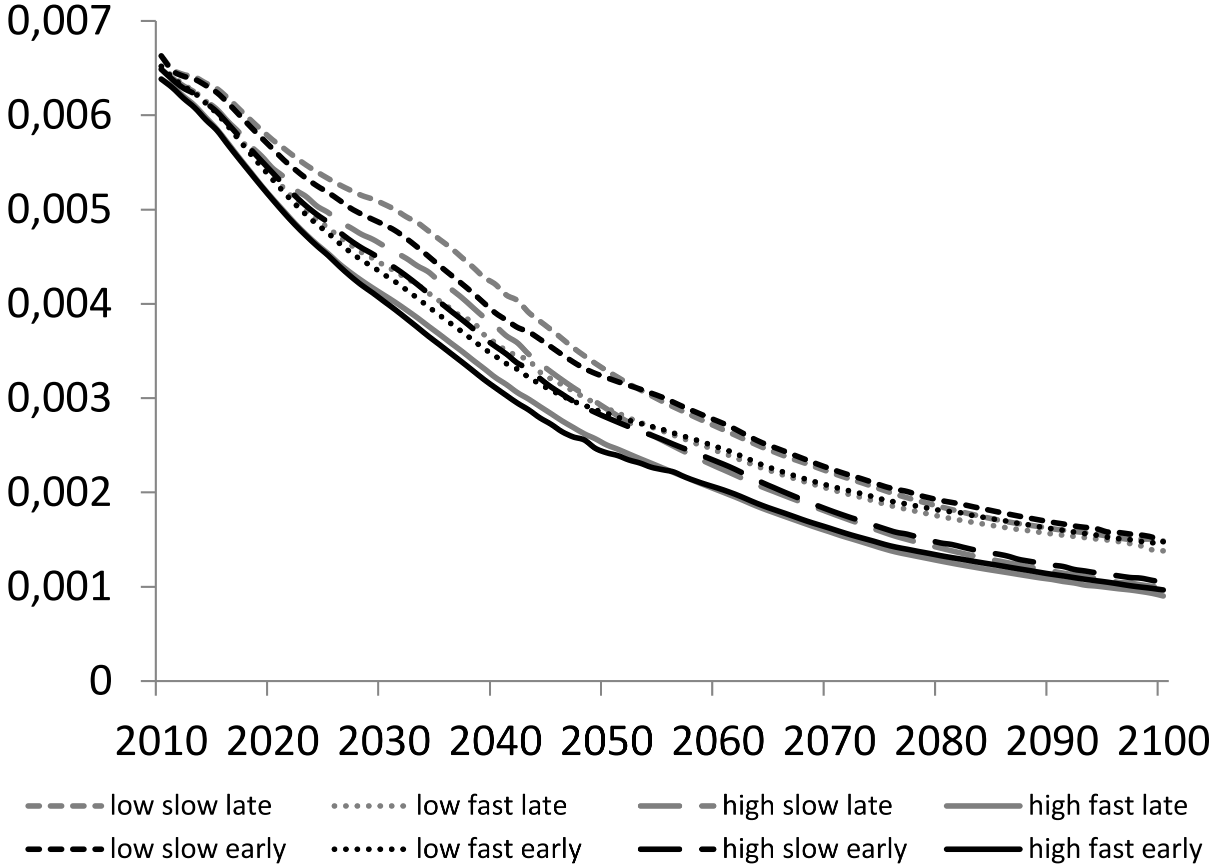


Figure J: Energy intensity ($EJ/billion\ USD2005$)

D.2 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 E: Discounted GDP losses (% w.r.t. baseline)