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MIRAGE-e: A General Equilibrium Long-term Path of the World Economy

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Highlights

- We integrate long-term issues (energy efficiency and prices, agricultural productivity) in a new version of the Computable General Equilibrium (CGE) model MIRAGE, nicknamed MIRAGE-e.
- This version of MIRAGE implements a consistent baseline framework for CGE analysis up to the 2100 horizon by interacting with the long-term growth model MaGE.
- MIRAGE-e integrates up-to-date modelling of energy demand by firms, while introducing a parallel accounting for energy flows in physical quantities.
- We acknowledge and quantify the vast uncertainty underlaid by baseline assumptions by comparing scenarios on population (fertility, education and female participation).
- At our horizon, economies will shift towards services as they increasingly rely on skilled labour. CO_2 emissions trajectories, in absence of any emission mitigation policy, prove to be unsustainable.

Abstract

Thinking of how the relative sizes of countries and how the geography of world production and trade will be affected in the long run must be based on sound economic reasoning about the determinants of long term growth. It must also be embedded in a general equilibrium framework that takes account of the interactions among markets and sectors, as well as between countries. This paper takes stock of a three phase research project. The first step consists of deriving and estimating a three-factor (labour, capital, energy) macroeconomic growth model for a large set of individual countries, which fits two forms of technological progress (standard TFP and energy efficiency). The second step consists of recovering the sectoral detail with an energy-oriented Computable General Equilibrium model of the world economy calibrated to fit these projections. In a third step we confront the assumptions for our baseline to alternative scenarios.

Keywords

CGE model, Dynamic Baseline,Growth model, Energy.

JEL

C53, C68, O44, O47, Q43, Q56.

MIRAGE-e: A General Equilibrium Long-term Path of the World Economy[1]

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1. Introduction

Global models – in particular Computable General Equilibrium (CGE) models – are based on macroeconomic variables including especially Gross Domestic Product (GDP), Total Factor productivity (TFP), labor force, and their respective sectoral decompositions. These models are aimed at simulating medium and long term shocks to the world economy, compared to a reference case. This requires reliable projected values for these variables, which may not necessarily correspond to the reality. Some of these models can be expected to be linked to other sectoral, technological and/or biophysical models. We require information for world models as well as models for a wide range of economic activities: food, energy, and transport demand, land use changes, etc.

International research centers and organizations (*e.g.* the International Monetary Fund – IMF) provide short term GDP forecasts. These forecasts, which generally are based on macro-econometric models, are suited to the short term changes in the world economy. However, we have no clearly documented, validated, and theoretically founded long term picture of the world economy. This applies particularly to broad coverage of countries, regions, and sectors of the world economy. In this report, we build on pioneering work in the field (Burniaux and Chateau, 2008, van der Mensbrugghe, 2005, Walmsley, 2006) and tentatively combine two very different modeling frameworks, a growth model which we call Macroeconometrics of the Global Economy (MaGE) and a new version of the CEPII CGE MIRAGE model.[2]

MaGE is a theoretical long run growth model embodying energy, energy efficiency, technical progress, demography, and capital accumulation. MIRAGE is a sectoral CGE model of the world economy. MaGE is a country level model that is estimated econometrically, MIRAGE is calibrated. MaGE is based on a three-factor labor, capital, and energy production function, with two forms of technological progress. Estimations are used to project long-run growth scenarios

[1]We acknowledge insightful comments from Jean Chateau and Dominique van der Mensbrugghe. We thank the Institute for Prospective Technological Studies (IPTS) for advice and financial support. Support by CIREM.
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[2]The reference documents for MaGE and the original version of MIRAGE are respectively Fouré et al. (2012) and Decreux et al. (2007). We call the new version of MIRAGE MIRAGE-e.

for 147 countries, which are imposed on MIRAGE. Based on these constraints, MIRAGE provides a fully consistent and theoretically funded projection of changes in consumption patterns, resource allocations, and sectoral GDP composition, at the regional and country levels, for all regions in the world economy. To our knowledge, the most advanced growth and CGE models implemented in this field are the exercises conducted for the ENV-Linkage model (Burniaux and Chateau, 2008) jointly with projections by Duval and De La Maisonneuve (2010).

The time horizon is 2100 and projections are at one year intervals. We account for the 2008-09 global crisis by initializing our projection model in 2013, and relying on IMF short-term forecasts from 2010 to 2012. Regarding labor force and its age structure, we rely first on United Nations (UN) and International Labour Organization (ILO) labor projections. Note that MaGE takes account of female participation in the labor market, modeling it consistently with an estimated and projected education catch-up. Accumulation of human capital is also the main driver of TFP growth and therefore reshapes the world economy. We econometrically estimate and project the education level of workers, conditional on their age. MIRAGE is fitted with the same projections in terms of population, education, and labor force.

Capital accumulation depends on the relationship between savings and investment rate, which is complex in open economies – a dimension often overlooked in projection exercises. In MaGE we estimate a non-unitary relationship between savings and investment, departing from the assumptions of either a closed economy or full capital mobility. The savings rate depends on the life cycle, hence on the structure of the population by age, as well as income per capita. Projected savings rates are imposed on MIRAGE, while the allocation of investment across sectors remains endogenous.

In MaGE, technological progress includes energy efficiency and TFP. It is derived theoretically, and estimated econometrically at the macroeconomic level. However, in a general equilibrium, TFP is unlikely to follow the same path in agriculture, industry, and services. To address this, in MIRAGE, we model, estimate, and project TFP separately for agriculture, considering two categories of production: animal and vegetal. The results of this exercise provide an exogenous variable. We compute TFP for manufacturing and services in MIRAGE, conditional on TFP in agriculture and GDP growth, with a constraint on the productivity differential between these two sectors. Energy productivity in MIRAGE-e is also determined exogenously from MaGE.

Our paper contributes to the literature in two ways. First, it provides a detailed baseline of the world economy – although with limited country coverage due to data constraints. Second, it provides projections up to 2100. Despite the intrinsic fragility of such results, they provide a useful tool for evaluating very long run policies, such as environmental policies.

This work departs from the existing literature in two ways. Firstly, we proceed in two steps. A macroeconomic growth model is exploited to provide detailed GDP and factor accumulation projections, while sectoral breakdown and emissions results are provided by a CGE model, with both models designed to be fully consistent. Secondly, we emphasize wide coverage in terms of number of countries, combined with a versatile aggregation of sectors and regions using recursive dynamics. This contrasts with the more usual choice to have fewer countries and sectors and an inter-temporal macroeconomic framework.

Following a review of the literature related to our main modeling assumptions (Section 2), we describe our CGE framework and the implementation of our baseline model (Section 3). We describe the agricultural TFP methodology (Section 4), and then present the scenarios (Section 5) and our results (Section 6).

2. Related literature

As mentioned in the introduction, there are several contributions on the development of CGE baselines. Walmsley (2006) develops a database covering 147 countries for the period 2001-2020 fitting the dynamic GTAP model (Ianchovichina and McDougall, 2000), which is updated in Chappuis and Walmsley (2011) and extended to 2050.[3] The database is amplified with various assumptions in order to end up with 226 regions. Population is split into three age categories, which is a first step towards precise representation of the qualification and age structure of the population. Another noteworthy model is G-Cubed (McKibbin and Wilcoxen, 1999), which focuses on an inter-temporal macroeconomic framework of agents' decisions, which necessitates a narrower aggregation[4] and some simplifying assumptions (*e.g.* constant population and TFP growth rates up to 2050, no energy efficiency gains). Finally, Bagnoli et al. (2005) develop a baseline model to consider environmental impacts up to 2030. They rely on simulations of JOBS, a global recursive dynamic CGE model derived from the Linkage model (van der Mensbrugghe, 2005) but focused on environmental issues. They use three age-bins and pay attention to projecting participation rates. Productivity derives from a catching up process. Sectoral productivity growth is imposed on the model and estimated using STAN (OECD) and Groningen's data. Ultimately, the baseline is directly projected by the CGE model using these exogenous variables for 34 regions and 7 sectors. In the following, we focus on the methodological differences between energy-oriented CGE baselines and our modeling choices.

2.1. CGE Baselines

Country availability and the time span of projections vary across the existing approaches. Many models focus on the period up to year 2020 (e.g., the GTAP model) but some exercises extend to 2050 (e.g., the Linkage model) or 2100 (Chateau et al., 2012), although the link with CGE is not investigated in any of these works.

The first step in developing a baseline is building a general trajectory for world growth. There are two competing CGE model approaches. The first involves building a scenario for factor

[3]Chappuis and Walmsley (2011) relies on Fouré et al. (2010) for certain variables.
[4]G-Cubed was developed with 8 regions and 12 sectors

productivity growth in order to recover GDP from the CGE model. The second involves building a GDP scenario such that the model recovers TFP gains accordingly.

On the one hand, recovering GDP from TFP growth assumptions has the advantage that data availability is not a limiting factor. Moreover, it allows encompassing different sector-specific trajectories without over-constraining the model. On the other hand, this kind of approach is very sensitive to assumptions on TFP growth or its determinants. For instance, the EPPA model (Paltsev et al., 2005) assumes identical logistic productivity growth for all countries and sectors, and excludes capital productivity.

Imposing GDP growth trajectories and recovering productivity gains is more data demanding but enables exploitation of macro projections by other institutions. These projections are built upon the vast growth literature, although not all have been thoroughly documented.[5] For instance, the main projections used in the GTAP model and earlier versions of MIRAGE are from the World Bank.[6]

Concerning the sectoral decomposition of TFP, several approaches have been developed. First, the Linkage model (van der Mensbrugghe, 2005) uses the GDP-driven framework described above, and adds to the endogenous national TFP a sectoral component, labor-only productivity. This results in constant exogenous agriculture TFP and a constant 2 percentage points difference between industry and services sector productivity (with industry more productive).

Notwithstanding the implementation of sectoral productivity in CGE models, the literature on agricultural-specific productivity has increased since Nin et al. (2001). For instance, Coelli and Rao (2005) and Ludena et al. (2007) analyze yield in order to estimate non-parametric productivity indices based on use of agricultural inputs. They show that agricultural productivity is not constant, and also grows at diffrent rates across countries.

Our modeling strategy exploits the best parts of these approaches to productivity. We implement a more comprehensive macroeconomic framework by imposing GDP from our growth model on our CGE model, and using sector-specific constraints and exogenous agricultural productivity to enable a coherent sector disaggregation.

2.2. Environmental baselines

In the specific case of energy-oriented CGE models, we draw on two thematic strands in the existing literature. First, energy productivity and its impact on energy consumption and CO_2 emissions, and second, natural resources scarcity and its direct link with energy prices. In both cases, the assumptions focus on one of these variables while the other adjusts.

First, one can rely on CO_2 emissions (or equivalently energy demand) data from other insti-

[5] See Fouré et al. (2012) for a short review.

[6] The respective documentations are Ianchovichina and McDougall (2000) and Decreux et al. (2007).

tutions, such as the PACE model (Böhringer et al., 2009). In this case, improvements in the carbon content of goods is deduced, since no comprehensive framework for energy consumption has been developed. In addition, particular attention has to be paid to the coherence between the emissions projections' underlying growth assumptions, and the CGE macroeconomic growth projections, because energy consumption and CO_2 emissions depend heavily on economic activity.

Second, the opposite method, which consists of developing a precise scenario for autonomous energy efficiency improvements (AEEI) as in the EPPA model. AEEI measure changes in the intensity of energy use which are induced not by a change in price but by technological progress, structural change, or policy. An exogenous time trend in energy productivity is often imposed on AEEI in order to control for the evolution of reductions in demand, which scales the production sectors' use of energy per unit of output. AEEI are specific to broad regions (*e.g.*, 10 regions in EPPA) with two distinct profiles. On the one hand, China and the developed countries face a regularly increasing AEEI; on the other hand, for the other countries, AEEI first decreases (up to around 2035) and then increase at different paces. These discrepancies are motivated by the empirical observation that energy productivity has increased regularly in countries with already advanced industry and services development whereas energy productivity has stagnated or even decreased in newly industrializing countries.

The Linkage model implements a mixed framework in which energy demands are imposed to balance productivity changes, except in the case of crude oil consumption which is driven by an exogenous productivity scenario.

Another issue related to CO_2 emissions and energy consumption is a limitation inherent in CGE modeling. These two variables are measured in physical quantities, although CGE models traditionally measure variables in constant price dollars. As pointed out by Laborde and Valin (2011), using CES (Constant Elasticity of Substitution) functional forms for monetary values leads to inconsistencies in substitutions where commodities are relatively homogeneous, such as in the case of energy goods. Two approaches can be used to deal with this issue. It is possible to build a world price matrix for physical quantities of the goods (this has been done for agricultural goods measured in tons), such that it can account for changes in both value and quantity. A simpler approach is to impose coherence in the model between monetary units and physical quantities for production, consumption, and trade.

Finally, the question of natural resources depletion can also be captured in two ways. As Paltsev et al. (2005) underlines, the long run dynamics of energy prices is captured by natural resources depletion. Therefore, one can either model this depletion and deduce the corresponding energy prices, or vice versa. The first solution is chosen by the EPPA model, which incorporates resources-specific natural resources use as well as additional recoveries. The second solution requires exogenously fixing energy prices as in the ENV-Linkage model (this option is also available in EPPA), such that natural resources adjust to match the target prices. The assumption in ENV-Linkage is reliance on IEA's world price projections up to 2030 and after that, to assume a 1% growth in the oil price.

3. The MIRAGE-e model

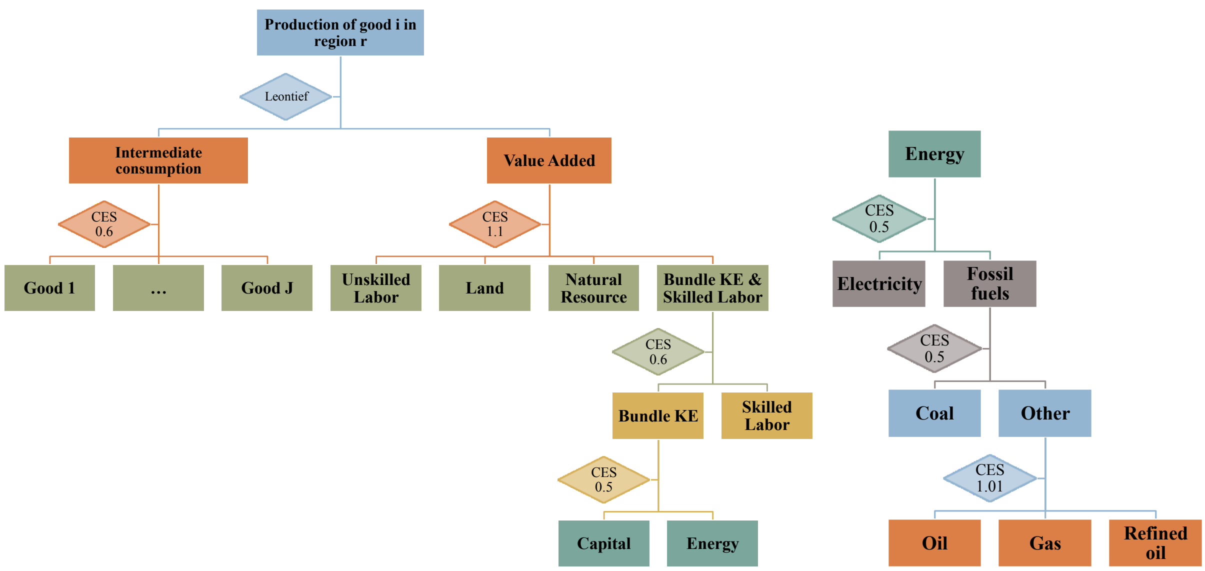
We use a new version of the multi-sectoral and multi-regional CGE model, MIRAGE (Bchir et al., 2002; Decreux and Valin, 2007), which initially was developed and then used extensively to assess trade liberalization and agricultural policy scenarios (e.g., Bouët et al., 2005, 2007). MIRAGE has a sequential dynamic recursive set-up, which is used to evaluate a long-term path for the world economy; in our case, focused on perfect competition. The MIRAGE-e version of the model relies on a different modeling of energy use, denoted by the "e" extension. Macroeconomic closure consists of imposing the shares of each region in the global current accounts imbalance, which varies year to year according to the projections from MaGE.

3.1. Representative firms

The perfect competition version of MIRAGE assumes that each sector is modeled as a representative firm, which combines value-added and intermediate consumption in fixed shares. Value-added is a bundle of imperfectly substitutable primary factors (capital, skilled and unskilled labor, land, natural resources) and energy. Nesting of the production function differs between MIRAGE and MIRAGE-e, allowing better representation of energy use in MIRAGE-e, as depicted in Figure 1.

Countries' primary factor endowments are all assumed to be fully employed, and countries' GDP growth rates are set exogenously according to MaGE's projections. Installed capital stock

Figure 1 – Production function of firms in MIRAGE-e



is assumed to be immobile (sector-specific), while investment, which represents the long run adjusting possibilities in a capital market, is allocated across sectors (perfect mobility) according to their rates of return to capital. Skilled labor is perfectly mobile across sectors, while unskilled labor and land are imperfectly mobile, the former between agricultural and other sectors, and the latter between agricultural sectors. Finally, natural resources are sector-specific.

Firms' consumption of energy from the five energy goods (electricity, coal, oil, gas, refined petroleum) is aggregated in a single firm bundle, which mainly substitutes for capital. There is no consensus in the CGE literature on the extent to which capital and energy are substitutable, or alternatively, value-added and energy are substitutable – depending on the chosen nesting. Estimations by van der Werf (2008), for example, suggest that the elasticity of substitution between capital and energy depends heavily on the sector and country considered; however, these estimations have not, to our knowledge, been based on recent data, or on the service sectors.

In CGE, the elasticity of substitution between capital and energy can vary according to the vintage of the capital (for instance from 0.12 to 1 in the GREEN model), or be fixed, at between 0.4 (EPPA model) and 0.8 (PACE model).[7] We find that energy consumption is very sensitive to the capital-energy elasticity of substitution. Calibrating this elasticity as GTAP-E provides an energy consumption for our reference scenario that is in line with International Energy Agency (IEA) projections to 2025 (IEA, 2011). We therefore adopt the GTAP-e value, that is, $\sigma_{KE} = 0.5$. The architecture of the energy bundle defines three levels of substitutions and is depicted in Figure 1 which also shows its position in MIRAGE's production function. Oil, gas, and refined oil are more inter-substitutable than coal or electricity. The values of the elasticities of substitution are determined according to the literature; electricity-fossil fuels substitution is from Paltsev et al. (2005), the two other elasticities are from Burniaux and Truong (2002).

However, in order to avoid unrealistic results, we made the assumption of "constant energy technology" in non-electricity energy production sectors (coal, oil, gas, petroleum and coal products) such that it is impossible to produce crude oil from coal, or refined petroleum from gas and electricity. For these sectors, substitution between energy sources is not allowed (Leontief formulation).

The value of energy aggregate in sector j in country r, $ETOT_{j,r,t}$, is subject to productivity improvements, $EE_{j,r,t}$ based on the growth model, as shown in Equation (1). These productivity improvements are introduced at the capital–energy bundle level, $KE_{j,r,t}$.

$$ETOT_{j,r,t} = a_E EE_{j,r,t} KE_{j,r,t} \left(\frac{PKE_{j,r,t}}{PE_{j,r,t}} \right)^{\sigma_{KE}} \quad (1)$$

In Fouré et al. (2012), energy productivity is defined differently from its equivalent in MIRAGE.

[7] The respective reference documents of the two models are Paltsev et al. (2005) and Böhringer and Rutherford (2009).

MaGE does not include TFP while MIRAGE does not include the share coefficient. By trickling-down the effect of MIRAGE's sectoral TFP, $TFP_{r,t}TFPJ_{j,r,t}$, into the capital-energy bundle CES function, we can make an analogy between the two expressions and deduce the value of energy productivity in MIRAGE, $EE_{j,r,t}$, given the MaGE energy productivity, $B_{r,t}$ and an initial value normalized to 1.

$$EE_{j,r,t} = \left(\frac{B_{r,t}}{TFP_{r,t}TFPJ_{j,r,t}}\right)^{\sigma_{KE}-1} = \frac{EProd_{r,t}}{(TFP_{r,t}TFPJ_{j,r,t})^{\sigma_{KE}-1}} \quad (2)$$

For non-electricity energy production sectors, we also set energy productivity constant in order to match our "constant energy technology" assumption, in line with the substitutions between energies in these sectors.

3.2. Representative consumer

The demand side is modeled as a representative consumer from each region that maximizes its intratemporal utility function under its budget constraint. This unique agent, which includes households and government, saves a part of his income and spends the rest on commodities according to a LES-CES *(Linear Expenditure System – Constant Elasticity of Substitution)* function. Regional propensity to save changes yearly in the dynamic baseline according to MaGE's projections. Above a minimum consumption proportion at the sectoral level, consumption choices among sectors are according to a constant elasticity of substitution. Then, within each sector, a nested CES allows a particular status for domestic products, and a product differentiation according to their geographical sources ("Armington hypothesis", Armington, 1969), using the GTAP (Global Trade Analysis Projet) Armington elasticities estimated in Hertel et al. (2007). Although the most complete version of MIRAGE allows for product differentiation across varieties, we adopt simple demand trees for agriculture, raw energies and electronic devices, to allow us to work with a tractable model.

Total demand is built from final consumption, intermediate consumption and investment in capital goods. The second and third elements follow the same rules as described above.

3.3. Energy and CO_2 emissions accounting

Using CES functional forms with variables in monetary units leads to inconsistencies when trying to retrieve physical quantities. In our case, this matters for energy consumption, production, and trade, and their consequences for CO_2 emissions.[8] Therefore, in addition to accounting relations in constant dollars, MIRAGE-e integrates a parallel accounting in energy physical quantities (in million tons of oil equivalent, $Mtoe$) allowing CO_2 emissions to be computed (in million tons of

[8]Preliminary simulations of MIRAGE-e showed that there could be a gap of more than 20% between a country's energy consumption and energy demanded if proportionality was assumed between monetary and physical values.

carbon dioxide, $MtCO_2$). Since the CES architecture does not maintain coherence in physical quantities, MIRAGE-e introduces energy- and country-specific adjustment coefficients. These two aggregation coefficients allow our basic energy accounting relationships to remain valid. This means that the quantity produced by one country[9], $EY_{e,r,t}$ must equal the demand in this country both local, $ED_{e,r,t}$ and from abroad, $EDEM_{e,r,s,t}$, as in Equation (3) ; and energy consumption (by households, $EC_{e,s,t}$ and firms, $EEIC_{e,j,s,t}$) in one country must equal its local and foreign demand (Equation (4)).

$$EY_{e,r,t} = ED_{e,r,t} + \sum_{s} EDEM_{e,r,s,t} \tag{3}$$

$$EC_{e,s,t} + \sum_{j} EEIC_{e,j,s,t} = ED_{e,s,t} + \sum_{r} EDEM_{e,r,s,t} \tag{4}$$

The corresponding adjustment coefficient, $AgDem_{e,r,t}$ (resp. $AgCons_{e,r,t}$) rescales the country's demand (resp. consumption) such that it matches the physical quantities produced (resp. demanded). In turn, only energy quantity produced is proportional to the volume production Y due to its being above rather than inside the CES. The epsilons in Equations (5) to (9) are constant conversion coefficients calibrated from the energy quantity data; they allow us to link energy quantities with corresponding volumes of demand for local good, $D_{e,r,t}$, bilateral demand, $DEM_{e,r,t}$, local final consumption, $C_{e,s,t}$ and local intermediate consumption, $EIC_{e,j,s,t}$.

$$EY_{e,r,t} = \epsilon^{Y}_{e,r} Y_{e,r,t} \tag{5}$$

$$ED_{e,r,t} = \epsilon^{D}_{e,r} AgDem_{e,r,t} D_{e,r,t} \tag{6}$$

$$EDEM_{e,r,s,t} = \epsilon^{DEM}_{e,r,s} AgDem_{e,r,t} DEM_{e,r,s,t} \tag{7}$$

$$EC_{e,s,t} = \epsilon^{C}_{e,s} AgCons_{e,s,t} C_{e,s,t} \tag{8}$$

$$EEIC_{e,j,s,t} = \epsilon^{EIC}_{e,j,s} AgCons_{e,s,t} EIC_{e,j,s,t} \tag{9}$$

Finally, CO_2 emissions are recovered as proportional to the energy quantities consumed, using energy-, sector- and country-specific factors determined by the data.

3.4. GDP projections

In order to implement our baseline exercise, we use the long-run growth projections from the MaGE model (Fouré et al., 2012). These projections are based on a three-factor (capital, labor, energy) production function at national level, for 147 countries. First, we briefly describe the methodology underlying such projections.

[9] In these equations, and in the rest of this paper, the subscript e will be an index for energy goods. In addition, r denotes (where appropriate), the country of origin of a good and s denotes its destination.

These three factors are gathered in a CES function of energy $E_{r,t}$ and a Cobb-Douglas aggregate of capital $K_{r,t}$ and labor $L_{r,t}$:

$$Y_{r,t} = \left[\left(A_{r,t} K_{r,t}^{\alpha} L_{r,t}^{1-\alpha} \right)^{\frac{\sigma-1}{\sigma}} + \left(B_{r,t} E_{r,t} \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{10}$$

were $A_{r,t}$ and $B_{r,t}$ respectively are the usual TFP – in our case the efficiency of labor and capital combined – and an energy-specific productivity. In line with the literature (see e.g. Mankiw et al., 1992), α is set to 0.3. In turn, the $\sigma = 0.2$ parameter is calibrated, within the range estimated by van der Werf (2008) but also considering that services are not included in these estimations; and the shape of energy productivity must not be reduced to an inverse function of energy price (see Fouré et al., 2013). In addition, GDP, $Y_{r,t}$, where appropriate, is considered net of oil rents to avoid a biased measure of productivity. Oil rents are added separately and are assumed to be pure rents: the volume of production is constant, but its real value (in terms of the GDP deflator) increases with the relative price of oil.

This model is fitted with UN population projections as well as econometric estimations for capital accumulation, education, female participation in the labor force, and two types of technical progresses. The energy consumption factor is not directly projected, it is recovered from the firms' optimization program.

In particular, capital accumulation follows a permanent inventory process, where the stock of capital increases each year with investment but also can be depleted. The depletion rate is set in accordance with the MIRAGE model at 6%, whereas investment-to-GDP ratios depend on savings rates through an error-correction Feldstein-Horioka-type relationship. This allows us to relax the common assumption of a closed economy. Savings rates are determined by both the demographic and economic situations in line with life-cycle theory.

The two productivity measures follow catch-up processes. While TFP growth is fueled by education levels, energy productivity growth is tempered by the levels of GDP per capita such that it mimics the impact of sectoral changes on energy productivity during a country's development process.

3.5. Closure and dynamic set-up

Thanks to the projections provided by MaGE, the new dynamic baseline of MIRAGE displays many original features regarding savings, GDP, active population, energy efficiency changes, and current account balances, all at regional level. This set of projections was completed by oil, gas, and coal world price projections from the World Energy Outlook (IEA, 2011).[10]

[10]These prices and MaGE outputs were converted into growth rates to allow implementation in the dynamics in MIRAGE, and in order to maintain coherence between our initial year and the GTAP database.

In this model, dynamics is implemented in a sequentially recursive approach. That is, the equilibrium is solved successively for each period by adjusting to projected growth in the variables described above. The time span of this long-run baseline is 96 years, starting from 2004. Over this time period, capital stocks change according to investment decisions based on rates of return to capital at sectoral level and the depreciation rate, which is assumed to be constant and uniform across regions (i.e. $\delta = 6\%$).

$$K_{j,r,s,t} = K_{j,r,s,t-1}.(1-\delta) + INV_{j,r,s,t} \tag{11}$$

Skilled and unskilled labor supplies from each region, $\bar{H}_{r,t}$ and $\bar{L}_{r,t}$ resp., are updated yearly according to the active population growth rates projected by MaGE. $g^{H}_{r,t}$ is the growth rate of the active population with at least a tertiary level of education, and $g^{L}_{r,t}$ is the growth rate of the rest of active population. It is a crude approximation since GTAP definition of skilled population is based on occupation rather than on education level; however it is manageable (see Chappuis and Walmsley, 2011).

$$\bar{L}_{r,t} = \left(1 + g^{L}_{r,t}\right) \bar{L}_{r,t-1} \tag{12}$$

$$\bar{H}_{r,t} = \left(1 + g^{H}_{r,t}\right) \bar{H}_{r,t-1} \tag{13}$$

Total population increases exogenously under the dynamic baseline inducing growth through the final demand.

Growth rates for regional GDP are set exogenous according to MaGE projections, and thus, TFP is endogenously determined. Sectoral factor productivity, calculated by large sectors (i.e. Agriculture, Manufactures and Services) also enters this dynamic baseline. Factor productivity in Agriculture is differentiated between Livestock and Crops sectors, and calibrated according to our estimates in Section 4. Factor productivity in manufactures and services are endogenous variables, which are affected by regional GDP (through TFP) and agricultural factor productivities. Factor productivity growth in manufactures is higher than in services (*i.e.*, Δg^{TFP}_{j} is greater than 0 for Manufactures and null for Services as in Equation 15), following the ENVISAGE model methodology (van der Mensbrugghe, 2008). The gap between services and manufacturing is calibrated to a 2 percentage point growth differential, according to two estimates by Bernard and Jones (1996) and Timmer et al. (2010), on the 1970-1989 and 1980-2005 periods respectively, for developed countries.

$$GDP_{r,t} = \left(1 + g^{GDP}_{r,t}\right) GDP_{r,t-1} \tag{14}$$

$$TFPJ_{j,r,t}.TFP_{r,t} = TFPAgri_{j,r,t} \qquad \text{if} \quad j \in Agri \tag{15}$$

$$TFPJ_{j,r,t}.TFP_{r,t} = \left(1 + \Delta g^{TFP}_{j}\right) TFPJ_{j,r,t-1} TFP_{r,t} \qquad \text{if} \quad j \notin Agri \tag{16}$$

where $TFP_{r,t}$ is the variable that adjusts to match the GDP target and $TFPAgri_{j,r,t}$ corresponds to agricultural (crops and livestocks) factor productivities projected according to the methodology described in Section 4.

Energy productivity, $EProd_{j,r,t}$ also increases exogenously during the baseline according to MaGE's projections for regional energy efficiency. Energy productivity directly affects energy demand per unit of output by sector as described in (Equation (2)).

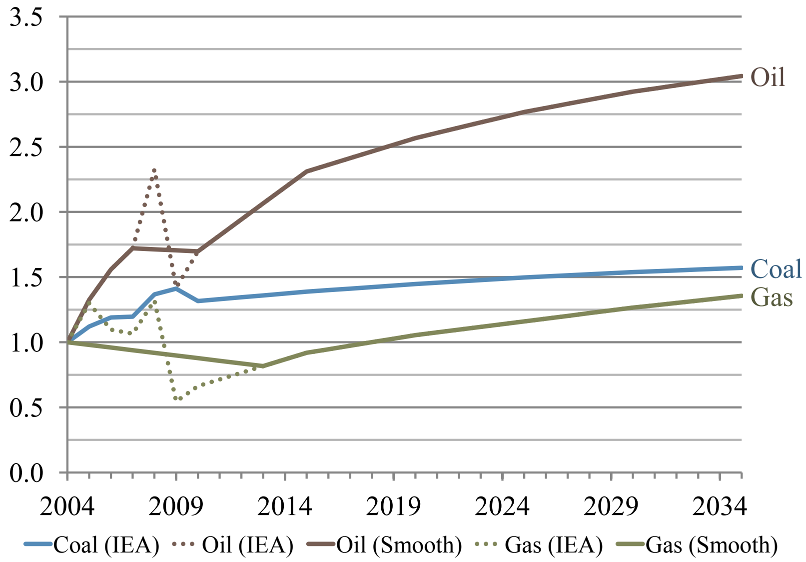
$$EProd_{j,r,t} = EProd_{j,r,t-1}.\left(1+g^{B}_{r,t}\right)^{\sigma^{KE}-1} \quad \text{if} \quad j \notin Energy \tag{17}$$

World prices of primary fossil energies (i.e. oil, coal and gas) are also assumed to be exogenous during the new dynamic baseline. They increase annually according to the World Energy Outlook projections (IEA, 2011) up to 2035 with continuing constant growth rate afterwards, leading to adjustments in the corresponding stocks of natural resources.

$$PWORLD_{e,t} = \left(1+g^{P}_{e,t}\right) PWORLD_{e,t-1} \quad \text{if} \quad e \in \{coal, oil, gas\} \tag{18}$$

where $g^{P}_{e,t}$ is the growth rate in energy prices. Each fossil energy price has its own projections, as depicted in Figure 2.[11]

Figure 2 – Energy prices, 2004=1, 2004-2035



Source: International Energy Agency (2011) and authors' computations.

As in the original version of MIRAGE, regional investment is savings-driven and is allocated across sectors according to the capital rate of return. Although it provides the possibility to work with foreign direct investment (Decreux and Valin, 2007), in this version we keep it simple and allow capital flows between regions to occur only through the channel of current account imbalances.

[11] We had to smooth the sharp variations in oil and gas prices between 2006 and 2013 to maintain a tractable model.

The new dynamic set-up in MIRAGE particularly affect macroeconomic closures. Current accounts are driven by MaGE projections and updated yearly. For consistency, savings rate are also taken from MaGE, and thus determined by demography, life cycle and purchasing power. Savings rates grow at the exogenous growth rate $g_{r,t}^{SAV}$ and current accounts are incremented by the deviation of the imbalance $\Delta SOLD_{r,t}$. Current account variations are not represented by a growth rate because the signs can change over time.

$$SAV_{r,t} = \left(1 + g_{r,t}^{SAV}\right) SAV_{r,t-1} \tag{19}$$

$$SOLD_{r,t} = SOLD_{r,2004} + \Delta SOLD_{r,t} \tag{20}$$

Equation 21 show the current account definition, $SOLD_{r,t}$, as the difference between all sectoral investments, $INV_{j,r,t}$ and national savings, $SAV_{r,t}$, as well as its implementation as a share of world GDP, $WGDP_t$.

$$SAV_{r,t}.REV_{r,t} = WGDP_t.SOLD_{r,t} + \sum_j P_t^{INVTOT}.INV_{j,r,t} \tag{21}$$

4. TFP in Agriculture

Although we have developed a methodology to compute and project long run TFP for national economies, for two reasons we consider agriculture separately. First, technical progress in agriculture seems to be lower than national TFP growth, and therefore requires further investigation. Second, the definition of agricultural sector production factors is trickier at the macroeconomic level.

Although data on labor-force in agriculture are available, there are no aggregated data on capital in agriculture, although there are sources of disaggregated data (on machinery, land, etc.). We therefore have to implement a multi-input, non-parametric methodology such as the Malmquist productivity index, based on productivity distance to the global frontier.

4.1. Data Envelopment Analysis (DEA)

Malmquist indices are designed to represent productivity growth rates at both national and sectoral levels. Computing these indices involves two steps. The basic concept on which Malmquist indices are built is a distance measure. The distances represent the gap between a country's actual production and the production it potentially could have achieved had it used the best available technology. The first step, then, is to compute these distance measures. The logic behind the mathematical formulation, which is described in Appendix A.1, is to build a piece-wise linear surface of the best performing countries to identify the technological frontier starting with data on production and production factors, and to measure the distance between each country's productivity and this frontier.

Once these distances are known, the second step is to combine them in order to build a Malmquist index $M^{t,t+1}$ for each year and each country, to represent productivity growth rates. Instead of detailing the formulation in distances, Färe et al. (1997) rely on the following decomposition.

$$M^{t,t+1} = \Delta EFF^{t,t+1}.\Delta TECH^{t,t+1} \tag{22}$$

These two components indicate different things. The first, $\Delta EFF^{t,t+1}$, is called efficiency change and represents the rate of growth in the distance to the technological frontier. The second term, $\Delta TECH^{t,t+1}$, is a technical change term and represents the contribution of the country to the evolution of the technological frontier.

This index has some interesting properties. $M^{t,t+1} \geq 1$ if progress has been made in TFP between year t and $t+1$ and $M^{t,t+1} \leq 1$ if there has been technological regression. Also, improvements (resp. deterioration) of $\Delta EFF^{t,t+1}$ or $\Delta TECH^{t,t+1}$ are equivalent to their value being greater (resp. lower) than 1.

We use data from the UN Food and Agriculture Organization (FAO) on agricultural production and inputs for the 1961–2009 period. We choose two outputs for agriculture (gross production of crops and livestock) and five different inputs based on their frequency across the world and data availability.[12] Inputs can be allocated either to crops or livestock, or be shared between these two sectors.

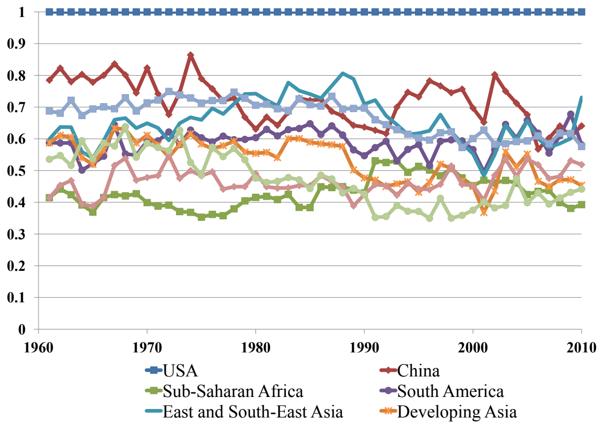
First, labor force (non-allocatable) is described by the economically active population involved in agriculture, although data for 1961–1979 needs to be recovered from the agricultural population by assuming a constant activity rate. Land input (non-allocatable) includes arable land and permanent pasture. Machinery is measured as the total number of agricultural tractors in use, although gaps are filled with agricultural tractor series. This input is allocated to crop production, as are fertilizers, whose consumption is measured in nutrients. The series for 1961–2001 is available only in weight units; we convert this to nutrients assuming a constant nutrient content for the three selected fertilizers: nitrogen, phosphate, and potash. Finally, livestock inputs (allocated to the livestock sector only) are computed using Livestock Units (LU) equivalents based on numbers of buffaloes, camels, cattle, pigs, sheep, goats, chickens, ducks, and turkeys. These data are aggregated following Ludena et al. (2007), as detailed in Appendix A.2.

Several adjustments were needed to achieve a fully operational dataset. First, we had to deal with countries whose data perimeters changed over the period (Belgium–Luxembourg in 2000, Czechoslovakia in 1993, Ethiopia PDR in 1993, USSR in 1992, Yugoslavia in 1992, Serbia–Montenegro in 2006). For these countries, we took the share of the different members for the first disaggregated year available; for the previous years we split the aggregate data between countries. Second, we aggregated data for nine broad regions (Appendix A.3) whose productivity is computed among all independent countries, and these values used for the estimations.

[12] We are aware that these are rough assumptions but the DEA method does not cope with gaps.

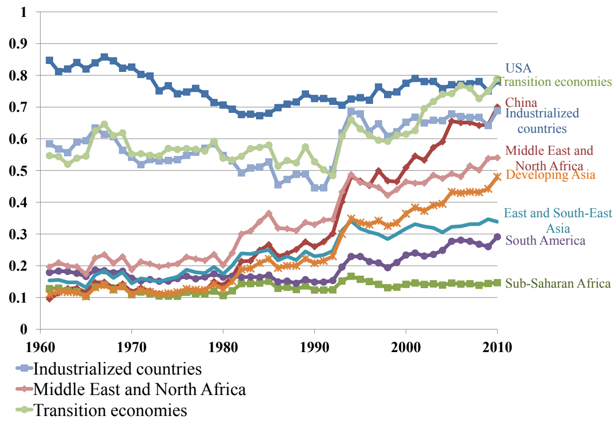
In relation to efficiency changes, Figure 3 and Figure 4 depict distances measures (growth rates of $\Delta EFF^{t,t+1} - 1$) for the different regions considered. Note that by convention we adopt a distance of 1 if the country is at the frontier and 0 if it is not productive.

Figure 3 – Distance to TFP frontier in the Crops sector, 1961-2009



Source: authors' computations.

Figure 4 – Distance to TFP frontier in the Livestock sector, 1961-2009



Source: authors' computations.

Figure 3 shows the distance to TFP frontier for the crop sectors in our nine broad world regions. The United States of America (USA) is at the frontier over the whole period, while there are other countries that do not seem to catch-up. Some zones (namely China, the industrialized countries, and sub-Saharan Africa) even show some retreat from the frontier.This stylized fact is in line with FAO data on yields observed in past decades: there is no catch-up in cereal yields between individual continents and subcontinents, and the United-States (with the exception of China before 1990). For the livestock sector, catch-up occurs along the period and more rapidly between 1985 and 2000, as shown in Figure 4, though none of our broad regions is at the technological frontier.

In contrast to efficiency change, technical change has increased on average, in all country groups. Also, the livestock sector shows efficiency increases, while the crop sector show bigger growth in technical change. Table 1 summarizes these growth rates.

Table 1 – Average productivity growth (percentage points, geometrical means 1961-2009)

Region	Crops			Livestock		
	$\Delta EFF^{t,t+1}$	$\Delta TECH^{t,t+1}$	$M^{t,t+1}$	$\Delta EFF^{t,t+1}$	$\Delta TECH^{t,t+1}$	$M^{t,t+1}$
China	-0.5	0.7	0.1	4.1	0.2	4.3
Developing Asia	-0.5	0.6	0.2	2.9	0.2	3.2
East and south-east Asia	0.0	0.5	0.5	1.7	0.2	2.0
Industrial Countries	-0.2	1.9	1.6	0.2	1.1	1.3
Middle East and North Africa	0.5	0.1	0.7	2.1	0.3	2.4
Central and South America	0.3	0.4	0.7	0.8	0.9	1.7
Sub-Saharan Africa	-0.2	1.3	1.1	0.2	0.2	0.5
Transition economies	-0.4	0.9	0.4	0.7	0.9	1.6
USA	0.0	2.0	2.0	-0.3	1.8	1.6

Source: authors' computations.

4.2. Estimating efficiency catch-up

To make regional level projections of agricultural TFP, we need to estimate a catch-up function. This will allow us to extrapolate the frontier, and project catch-up by each region towards this frontier. We follow Ludena et al. (2007) in dividing our projections and our methodology into two parts: efficiency change and technical change. According to Nin et al. (2001), we assume that catch-up measured by distance to the productivity frontier $D^{i,t}$, occurs along a logistic function – an S-shaped curve – which suggests a diffusion process:

$$D^{i,t} = \frac{1}{1 + e^{-\alpha_i - \beta_i t}} \tag{23}$$

where α_i and β_i are region-specific coefficients. That is, in 1961, each region is assumed to be at a certain state of catching up – parametrized by α_i – and would catch-up at its own speed (β_i). Reformulating this yields

$$Y_{i,t} = \log\left(\frac{D^{i,t}}{1 - D^{i,t}}\right) = \alpha_i + \beta_i t \tag{24}$$

We first perform Chow test in order to identify any structural breaks in the time series that might have occurred between 1961 and 2004 (more recent breaks are difficult to identify because of the number of the remaining observations). We conduct this test only on the speed of convergence/divergence β_i, because the constant α_i represents just the starting point of the curve. Table 2 presents the latest date when breaks in the series can be identified, at a 1% confidence level.

Table 2 – Structural breaks in distance function series

Region	Crops	Livestock
China	1961	1991
Developing Asia	1961	1990
East and Southeast Asia	1992	1992
Industrial countries	1989	1992
Middle East and North Africa	1992	1983
Central and South America	1961	1997
Sub-Saharan Africa	2000	1980
Transition Economies	1998	1999
USA	1961	1995

Source: authors' computations.

The case of China differs from the other countries, because the crops series shows only one break, in 2001. We therefore chose the period 1961-2001 instead of 2001-2009, for our estimations. Detailed information on breaks is provided in Appendix A.4.

Finally, we estimate relation (24) on the corresponding time-spans; the results are presented in Table 3. In the crop sector, we find three types of country groups. First, only two regions seem to catch-up to the frontier (MENA and the transition economies). Two zones seem to be persistently at the same distance from the frontier (East and south-east Asia, and South America). The remaining four zones seem to be involved in negative catch-up (sub-Saharan Africa, Developing Asia, the industrialised countries, and China). The USA is not included in Table 3 because it was at the frontier along the entire period. In livestock, catch-up occurs for all zones in the sample, although at different rates. The fastest-growing zone is China and the slowest is sub-Saharan Africa.

Table 3 – Efficiency change estimation results

Region	Crops				Livestock			
	Time	Constant	N obs.	R-sq.	Time	Constant	N obs.	R-sq.
MENA	0.018***	-0.848***	18	0.40	0.035***	-1.601***	27	0.83
	(-0.006)	(-0.233)			(-0.003)	(-0.119)		
Transition Economies	0.027**	-1.560***	12	0.45	0.073***	-2.332***	11	0.75
	(-0.009)	(-0.403)			(-0.014)	(-0.615)		
East and south-east Asia	-0.014	0.998**	18	0.14	0.012**	-1.263***	18	0.33
	(-0.009)	(-0.353)			(-0.004)	(-0.173)		
South America	0.002	0.326***	49	0.02	0.036***	-2.675***	13	0.79
	(-0.002)	(-0.048)			(-0.005)	(-0.238)		
Sub-saharan Africa	-0.035***	1.290***	10	0.72	0.004**	-1.983***	30	0.14
	(-0.008)	(-0.34)			(-0.002)	(-0.074)		
Developing Asia	-0.013***	0.472***	49	0.53	0.052***	-2.684***	20	0.85
	(-0.002)	(-0.052)			(-0.005)	(-0.205)		
Industrial countries	-0.016***	1.098***	21	0.45	0.016**	-0.045	18	0.23
	(-0.004)	(-0.159)			(-0.007)	(-0.295)		
China	-0.015***	1.339***	41	0.29	0.078***	-3.072***	19	0.88
	(-0.004)	(-0.091)			(-0.007)	(-0.285)		
USA					0.014**	0.601**	15	0.30
					(-0.006)	(-0.244)		

Note: Standard errors in parenthesis. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$
Source: authors' computations.

5. The scenarios

We now illustrate our methodology by decomposing the world economy into regions and sectors (see Table 4), and considering a central baseline plus two alternative scenarios.

5.1. Aggregation

The MIRAGE model is calibrated on the GTAP dataset version 7, with 2004 as the base year.[13] Our data aggregation isolates all energy sectors and combines the other sectors into the main representative sectors in agriculture, manufacturing, and services. For the regional aggregation, we retain the main developed (e.g. the EU, Japan, USA) and emerging (e.g. Brazil, Russia, China) economies, and the rest of the world is aggregated according to the relationship to energy markets (i.e. oil rich countries, see Table 4) or geographical position.

Trade policy data are from the GTAP database whose source is CEPII's Market Access Maps (MAcMap-HS6) dataset version 2. Departing from the original dataset, which assumes the

[13] The GTAP 8 version, with 2007 as a base year, is currently in development.

Table 4 – Sector and country aggregation

Regions	Sectors
Developed	**Agriculture and Primary**
Oceania[a]	Vegetal Agriculture
Japan	Animal Agriculture
Korea and Taiwan	Other Agriculture
Canada	Primary (minerals)
United States	**Energy**
European Union (27 countries)	Coal
EFTA	Oil
Developing \ Emerging	Gas
China	Petroleum and Coal Products
ASEAN	Electricity
India	**Manufacturing Products**
Brazil	Food, Beverage and Tobacco
Rest of Latin America	Textile
Russia	Metals
Rest of Europe	Cars and Trucks
Oil rich Western and Central Asia[b]	Planes Ships Bikes Trains
Other Western and Central Asia[c]	Electronic Equipment
Turkey	Machinery Equipment
Northern African Countries	Other Manufactured products
Rest of World[d]	**Services**
	Transport
	Insurance, Finance and Business
	Public Administration, Education and Health
	Other Services

[a]Australia, New Zealand and Rest of Oceania
[b]Kazakhstan, Azerbailan, Iran and Rest of Western Asia
[c]Kyrgyzstan, Armenia, Georgia and Rest of former USSR
[d]All remaining GTAP regions

reference group weighting scheme (Bouët et al., 2008) for aggregation within the GTAP classification, here we apply the standard trade-weighted averages available in GTAP (both are available in the model).

This version of MIRAGE also includes trade costs, modeled as iceberg trade costs. The data used to calibrate trade costs associated with time are from Minor and Tsigas (2008).

5.2. Scenario assumptions

The reason for modeling alternative scenarios is to enable documentation of the MIRAGE-e central baseline, and to provide a sensitivity analysis of the main determinants of this baseline. Two main channels through which long-term growth trajectories are impacted are TFP – and its driver, education – and labor force. Other determinants, such as capital formation and energy productivity, and assumptions about energy prices, have a more limited impact and are examined in another paper (Fontagné and Fouré, 2013).

Thus, our scenarios focus on three demographic-related variables – overall population, female participation in the labor force, and education level, and their interactions – and two alternative specifications organized around a central scenario. All scenarios are implemented from 2013 onwards. The reference scenario is the standard output from the MaGE model and provides the base data for MIRAGE. In scenario 1, we introduce a very dynamic population, with increased education catch-up. In scenario 2, the population is less dynamic, with less variation in female participation in the labor force and lower levels of education catch-up.

All these assumptions for the dynamic baseline scenarios are implemented within the growth model, and therefore will have an impact on MIRAGE-e through its exogenous parameters (GDP growth, savings, current account, energy productivity, female participation in the labor force). No CGE-specific assumptions, such as trade barriers, are implemented at this stage; they are investigated separately in Fontagné and Fouré (2013). Our assumptions are presented in Table 5. The three scenarios elaborated in this paper therefore, are three alternative baselines in the sense that, in each, GDP trajectories are imposed exogenously and TFP adjusts. However, for the sake of clarity we describe the central baseline as the "reference" and the alternative assumptions as "scenarios".

Table 5 – Scenarios summary

Variable \ Scenario	Reference	Scenario 1	Scenario 2
Population	Medium variant	High fertility	Low fertility
Female participation	Fouré et al. (2012)	Fouré et al. (2012)	No improvements
Education	Fouré et al. (2012)	Double convergence	Half convergence

We rely on three UN population scenarios (2010 revision). The reference case is the central scenario of the UN ("medium variant"), with scenarios 1 and 2 respectively rely on a "high fertility variant" and "low fertility variant".

In our central case as well as in scenario 1, female participation in the labor force in each five-year age band, depends on the education level of the overall population. That is, the youngest age groups (15-19 and 20-24) tend to participate less as they are in education, whereas the other age groups tend to participate if they have received more education. In scenario 2, we only extend past trends on female participation using the relations and parameters defined by the ILO for their projections up to 2020.

Education in the reference scenario relies on a catch-up process with geographic, country-group-specific speed. In scenario 1, we assume that educational attainment diffuses more in developing countries, while the level in developed countries remains the same. In scenario 2, convergence is slower and differences tend to extend to the 2100 horizon. These convergence speeds are computed such that the half-life time[14] is twice (resp. half) the reference half-life time.

6. Results

We first present the baseline calibration, focusing on the variables imposed to the CGE. GDP, population, savings rate, energy productivity and current account are outputs from MaGE, energy prices are from IEA (2011) and agricultural TFP is exogenously computed as described in Section 4. Then we focus on CGE-specific output, such as consumption, production and trade patterns, and energy and CO_2 emissions trajectories.

6.1. Baseline calibration

The main upstream factor, and the factor of most interest for our scenarios, is demographics, including fertility, education, and female participation in the labor force. Table 6 presents the results for the baseline and our two demographic scenarios. For population, we rely on the scenarios developed by the UN. These scenarios show huge contrasts: at world level in 2100, they show a variation in population of 5.7 billion people (compared to the baseline of 9.2 billion humans). The most populous region at the 2100 horizon is always sub-Saharan Africa, accounting for one-third of the world's population, twice that of India, and three times the population of China. Sub-Saharan Africa is also the biggest contributor to uncertainty in world population, given the early stages of demographic transition observed in its constituent countries.

The second demographic driver is education, for which we implement our scenarios. Table 6 also presents the share of skilled population (i.e. with at least tertiary level education). By construction, only countries far from the frontier are significantly impacted by our scenarios (unlike Russia, the USA, and Japan, which suffer a small impact). Recall that education translates into TFP gains, especially for countries catching up to the frontier.

For participation in the labor force, our scenarios encompasses three dimensions. First, fertility scenarios influence population aging: higher fertility means a larger working-aged population, and thus a higher participation rate. This effect is particularly prevalent for countries with a rapidly growing ageing population, like China whose decreased participation in the reference scenario is almost compensated for in scenario 1. Second, women's participation augments the labor force. Although in our female participation framework two effects compete (in the baseline and in scenario 1, higher education implies lower participation for the study aged population, but higher participation after the age of 25), at the horizon we consider here, the second effect predominates, because the whole working age population in 2100 has already benefitted from

[14] Half-life time is defined as the time needed to narrow the distance to the frontier by half, under the simplifying assumption that the frontier is constant. It is given by $t^{1/2} = \frac{\ln X}{\ln(1-\lambda)}$, where λ is the convergence coefficient and X is a constant that depends on the initial frontier level and country's initial position.

educational improvement. Finally, further education amplifies the effects of female participation (scenario 1 only).

Table 6 – Demographic variables in the three scenarios, 2012 and 2100

Region	Total population (million)				Share of skilled population (% of population)				Activity rate (% of population)			
	2012	2100			2012	2100			2012	2100		
		Ref	1	2		Ref	1	2		Ref	1	2
EU27	479	477	+157	-117	22	86	+4.6	-17.3	48	44	+7.3	-10.6
USA	316	478	+141	-108	54	91	+0.7	-5.1	52	50	+5.9	-10.7
Japan	126	91	+31	-23	44	91	+0.7	-4.4	51	50	+6.4	-15.4
Brazil	198	177	+87	-56	8	67	+19.8	-29.3	53	54	+10.8	-12.6
Russia	143	111	+47	-33	57	90	+1.6	-7.0	54	49	+7.1	-11.7
India	1,258	1,551	+665	-464	6	47	+29.7	-23.2	41	45	+9.1	-14.4
China	1,361	951	+414	-289	8	49	+27.1	-22.0	60	48	+10.8	-14.2
ASEAN	557	650	+261	-186	9	48	+27.4	-19.5	51	54	+9.2	-12.1
MENA	409	566	+215	-155	14	71	+16.9	-25.9	38	40	+7.7	-12.7
RoAfr	792	3,008	+807	-636	3	20	+29.4	-11.7	41	57	+5.7	-6.3
RoW	966	1,190	+483	-341	17	65	+19.1	-21.5	45	50	+8.7	-12.1
World	6,604	9,251	+3,307	-2,410	14	46	+24.9	-18.7	48	51	+7.7	-10.3

Notations: EU27 stands for European Union, USA for the United States of America, ASEAN for the Association of Southeast Asian Nations, MENA for Middle-East and North Africa and RoAfr for sub-Saharan Africa and RoW for Rest of the World.

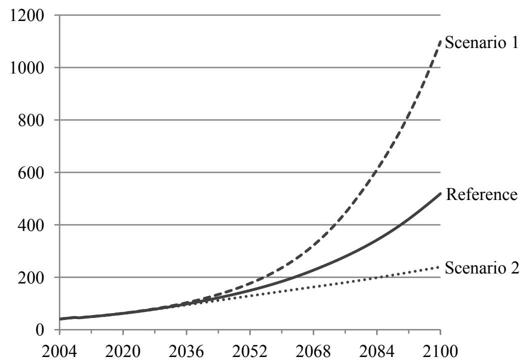
Note: Columns labelled "1" and "2" show changes of each variable with respect to the reference case "Ref", in the same units. For instance, India would have 2,216 (1,551+665) million inhabitants in 2100 in scenario 1 among which 76.7 (47+29.7) percent are skilled.

Source: authors' computations.

For GDP, MaGE, over the next century, predicts sustained growth in its reference scenario, resulting in an 11-fold increase in world GDP at constant prices and exchange rates (Figure 5). However, economic growth is unevenly distributed across regions, as shown in Figure 6. Developed countries, by definition, do not benefit much from a catching-up mechanism, and their share of world GDP shrinks to the benefit of the developing countries. For instance, in the reference scenario, the share of the European Union in world GDP falls from 31% to 11% between 2004 and 2100, while the share of sub-Saharan Africa (RoAfr) jumps from 1% to 10%.

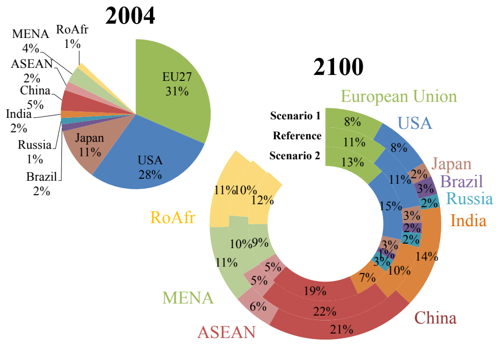
The scenarios for the demographic variables suggest a wide range of possible GDP levels by year 2100. While our reference scenario projects an 11-fold increase in world GDP between 2010 and 2100, the range could be between 5-fold and 23-fold given uncertainties about fertility, education, and labor force participation. This variability affects every country in levels, but also unevenly affects the repartition of world wealth, especially for countries relying strongly on

Figure 5 – World GDP 2004-2100 (‘000 billion constant 2004 USD)



Source: authors’ computations.

Figure 6 – Country shares in 2004 and 2100 (‘000 billion constant 2004 USD)



Source: authors’ computations.

educational catch-up such as India and China. The share of India in world GDP at the end of our simulation period ranges between 7% and 14%, whereas for China the figures are 19% and 23%.

Regarding TFP in agriculture, our estimations for the arable and pastoral sectors lead to projections that are very heterogeneous among countries and also between the two sectors. Table 7 presents average growth rates for both the Malmquist indices (M) and their efficiency and technical components; The trajectories of these indices by region are depicted in Appendix A.5. Although every country seems to show reasonable annual growth in livestock productivity – ranging from 0.26 (China) to 1.97 (USA) percent, three regions perform very badly for crops. Projections for developing Asia and sub-Saharan Africa show declining productivity over the whole period, and stagnating productivity for China. These bad performances are driven by the lack of catch-up highlighted in Section 4, which is not compensated for by the technical change component, whereas the former makes crops productivity grow in industrialized countries.

Table 7 – Average productivity growth (percentage points, geometrical average 2010-2100)

Region	Crops						Livestock					
	2010-2050			2050-2100			2010-2050			2050-2100		
	Eff	Tech	M	Eff	Tech	M	Eff	Tech	M	Eff	Tech	M
China	-0.66	0.66	0.00	-0.91	0.66	-0.25	0.83	0.22	1.06	0.03	0.22	0.26
Developing Asia	-0.80	0.63	-0.17	-0.97	0.63	-0.34	1.51	0.21	1.72	0.23	0.21	0.44
East and Southeast Asia	0.00	0.52	0.52	0.00	0.52	0.52	0.72	0.24	0.96	0.56	0.24	0.80
Industrial countries	-0.79	1.86	1.05	-1.06	1.86	0.78	0.39	1.06	1.46	0.22	1.06	1.28
Middle East and North Africa	0.72	0.15	0.87	0.41	0.15	0.55	1.06	0.27	1.33	0.30	0.27	0.57
Central and South America	0.00	0.42	0.42	0.00	0.42	0.42	1.94	0.86	2.82	0.72	0.86	1.59
Sub-Saharan Africa	-2.56	1.32	-1.28	-3.16	1.32	-1.89	0.37	0.22	0.59	0.36	0.22	0.58
Transition Economies	1.13	0.87	2.02	0.50	0.87	1.38	0.55	0.90	1.45	0.03	0.90	0.93
USA	0.00	2.02	2.02	0.00	2.02	2.02	0.24	1.83	2.07	0.14	1.83	1.97

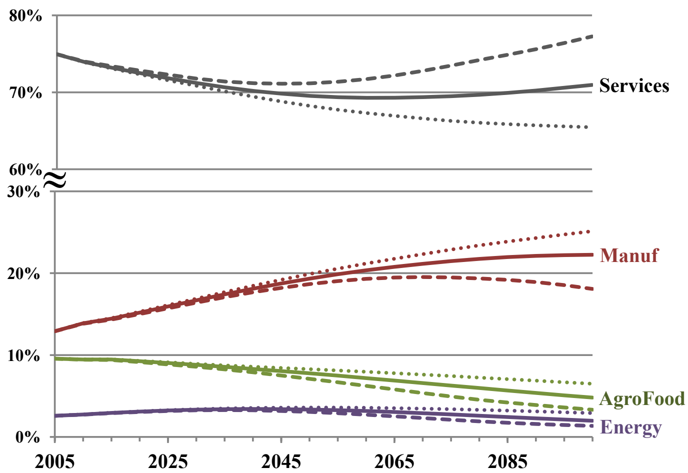
Note: "Eff" stands for the efficiency component and "Tech" for the technical component of the Malmquist indices.

Source: authors' computations.

6.2. Production and consumption: A shift towards services

The sectoral composition of the world economy evolves in a non-linear way, as shown in Figure 7. While in our three scenarios the share of agricultural goods in world consumption decreases steadily, the share of industry grows asymptotically, and even reverses after 2065 in scenario 1. The share of services is U-shaped.

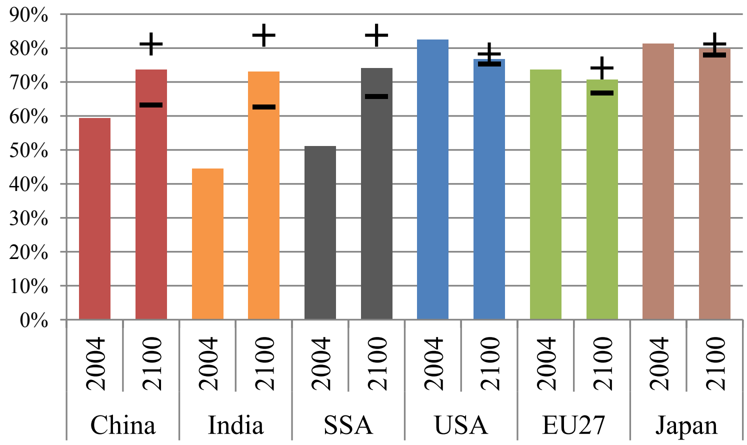
Figure 7 – Share in world consumption by large sector, 2005-2100



Note: Large dash: scenario 1 ; Small dash: scenario 2
Source: authors' computations.

In the first phase, between 2004 and 2060, developing countries which show the highest initial share of food in consumption and the highest economic growth, dominate the evolution towards manufactured goods, while the weight of developed countries decreases. In the second phase, consumption of services in these developing countries continues to rise steadily (see Figure 7). Since consumers' preferences are constant in MIRAGE-e (except when minimal consumption thresholds are binding), this effect comes from the distribution of skills: as the skilled population increases, the price for skill-intensive services tends to reduce. For instance, production prices in China present an inverted U-shape for Public Administration, but the reverse for Textiles. In India, the balance between skilled and unskilled people leads to a constant decrease in Finance, Insurance and Business Services, as well as Other Services. In contrast, prices for Indian Textiles and Other Manufactured Goods begin to rise by around 2040. As a consequence of this mechanism, the shift towards services is more pronounced in scenario 1 – where skills increase faster, and less pronounced in scenario 2.

Figure 8 – Share of services in consumption, selected countries and the world, 2004 and 2100

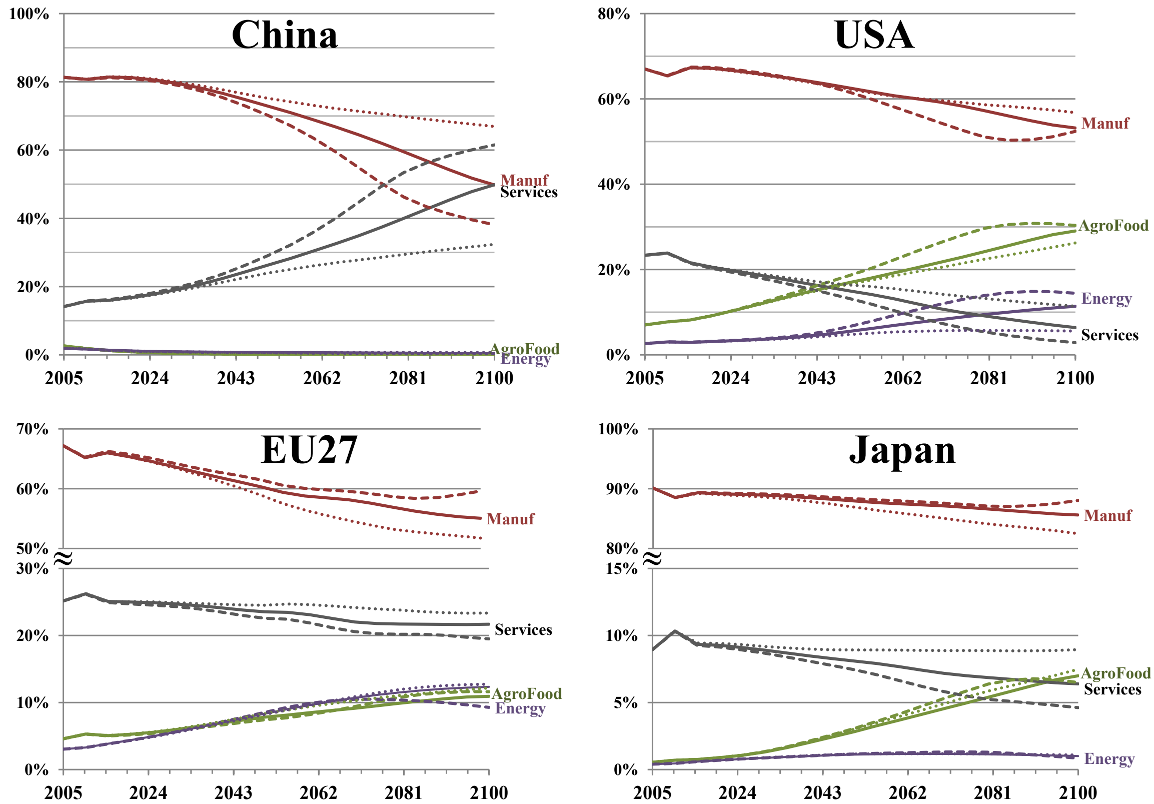


Note: +: scenario 1 ; -: scenario 2
Source: authors' computations.

6.3. World trade patterns: A reshaping of international markets towards skill-intensive goods

The shift in consumption patterns described in Section 6.2 is accompanied by changes in countries' comparative advantage, and thus with the location of production. This shapes countries' export specializations, as depicted in Figure 9. The increase in education in China (and its variation across our scenarios), results in its competitive advantage being profoundly reshaped towards the skill-intensive sectors. This contributes to explaining the shift in services production towards the emerging economies, but also influences the composition of manufactured goods exports.However, projections for specific sectors (*e.g.* the balance between electronics and textile in China) to the 2100 horizon are difficult because of the lack of information on technological developments – such as those that occurred over the last 80 years. The structure of exports for the developed economies shows less variation than for the developing countries – both over time and across scenarios; nevertheless, two effects seem to emerge. First, the specialization of developed countries is conditional on competition from the developing countries, especially in the market for skill-intensive goods. Hence, the decrease in the importance of services in exports for the USA, the EU, and Japan. This contraction of specialization in services however is softened at the end of the period. Second, with sustained world growth over the next century, global demand for primary goods, such as food and energy, should increase drastically. This increase in demand tends to favor those countries showing the highest agricultural productivity, namely, the USA and the EU.

Figure 9 – Export specialization for China, USA, EU and Japan, 2005-2100



Note: Large dash: scenario 1 ; Small dash: scenario 2
Source: authors' computations.

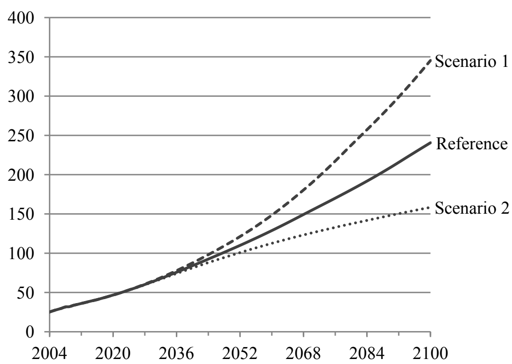
6.4. Energy and CO_2 emissions: an unsustainable path

As Figure 11 highlights, the shift in CO_2 emissions towards the emerging world was underway even in 2004, in contrast to the shift in GDP. This is due mainly to energy productivity, which is higher in developed countries (EU, EFTA and Japan in particular) as emphasized in Fouré et al. (2012). The BRIC countries, ASEAN and MENA already account for 58% of world emissions, and only 30% of world GDP. These countries show an increase to 84% of emissions in 2100, with a more limited variation across scenarios than for GDP. The shares of all regions remain roughly stable and China continues to be the biggest emitter, at around three times the amount emitted by the USA which is in second place.

Although population scenarios do not significantly change the world repartition of CO_2 emissions, the impact on total volumes is sizeable. According to our scenarios, world emissions could multiply by between 6 and 14 times in 2100 compared to 2005. The reference case, which corresponds to a "business as usual" scenario without any emissions mitigation policy, depicts around 250 thousand billion tons of CO_2 emissions (10 times more than in 2004), which seems very far from sustainable.

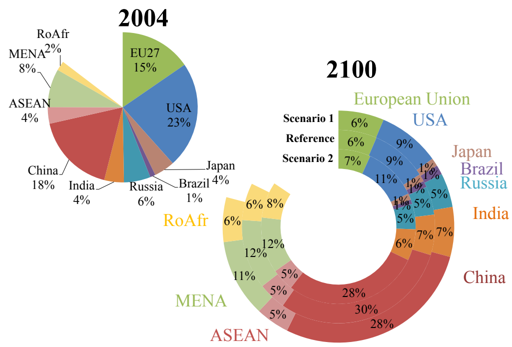
Our CO_2 emissions trajectories are in the upper range among comparable exercises (MIT, 2012; IPCC, 2008), mainly due to our relatively high GDP growth scenarios. For instance, MIT assumes that world GDP will increase 7.5-fold between 2010 and 2100, compared to our 11-fold increase depicted in Figure 10. As a result, it could seem that in MIRAGE-e, the world carbon intensity does not change, but this is due to a composition effect based on the emergence of less efficient countries as important contributors to the world economy. As well as this difference, the impact of renewable energy sources, and the downward impact of climate change on production (in particular agricultural yield) is not accounted for in our model. Nevertheless, the baselines scenarios in CGE are intended as "business as usual" scenarios with no policy included. In this sense, we provide a "worst-case" scenario against which environmental policy can be evaluated. In such a world, if we refer to the orders of magnitude suggested by the IPCC (2008), average world temperatures could rise by up to 6.5 °C.[15]

Figure 10 – World CO_2 emissions 2004-2100 ('000 MtCO2)



Source: authors' computations.

Figure 11 – Country shares in 2004 and 2100 ('000 MtCO2)



Source: authors' computations.

Given our levels of GDP growth, such non-sustainable increases in CO_2 emissions are rooted in the conjunction between countries' energy productivity and demand for fossil energy. The price incentives we implement cause emissions go in both directions but are not sufficient to induce

[15] At least, this increase would lie within the upper part of the 2.5–6.5 °C range presented, "A1F1" being the scenario we are the closest to.

a clear shift from CO_2-intensive fuels. Gas is the least expensive fossil energy (and the least emissive), but coal is second and is the most polluting (see Figure 2 in Section 3.5). Although the final energy mix (*i.e.* excluding electricity generation and petroleum refining) tends to shift away from refined petroleum, towards gas and electricity as shown in Figure 12, the share of coal in demand remains stable, with only a slight decrease due to its moderated price trajectory. Oil remains negligible as a final energy because its purpose is almost only to be refined. The only significant difference among scenarios is the border between electricity and refined petroleum. Higher (lower) population accelerates (resp. moderates) this shift due to the rescaling of both firms' and households' demands for energy. For instance, this leads to higher pressure on refined petroleum markets, with prices bound to stability, compared to the central scenario. This way of modeling energy markets in reference scenarios (*i.e.* imposing an exogenous price) is rough and requires direct feedback on demand and prices (this feature is however present if one models a policy deviation from baseline).

Figure 12 – World final energy mix (MtCO2)

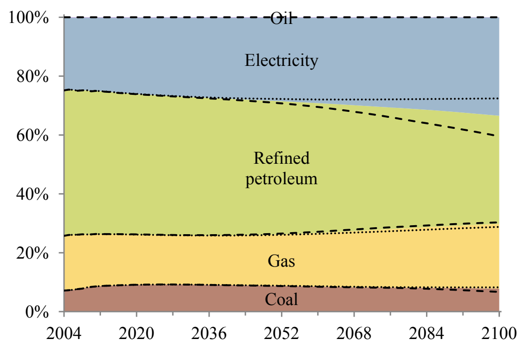
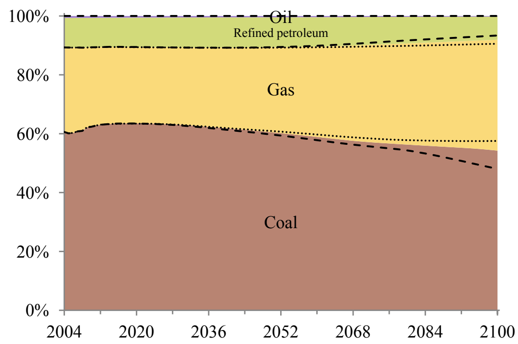


Figure 13 – World electricity generation mix (MtCO2)



Electricity generation is depicted in Figure 13; it shows an increase in the share of gas (which has the slowest increase in price), at the expense of coal and refined petroleum. However, this change is not enough to reduce emissions since coal remains at around 50% of the electricity generation mix in 2100 compared to 60% in 2004. Here again, demographic scenarios emphasize the same mechanisms as in final demand, but regarding coal and gas rather than electricity and refined petroleum.

As a consequence, the large increase in CO_2 emissions can be attributed to the absence of environmental incentives in the price of energy, especially coal whose CO_2 emission factor is the highest of all the fossil energies and whose equilibrium price does not increase much. Finally, renewable electricity sources, such as wind, hydro, and solar power, are not explicit in MIRAGE but are incorporated in the initial energy intensity of the electricity sector. We therefore underestimate their possible contribution to electricity generation

7. Conclusion

We have developed a consistent long-term baseline framework at the 2100 horizon by combining the growth model MaGE with a new version of the CGE MIRAGE – MIRAGE-e. This includes energy efficiency and prices, sectoral productivity, macroeconomic closure, and the integration of growth determinants in a CGE model. Although very tentative, this framework is a necessary first step for encompassing long-run issues in general equilibrium models, such as global emissions mitigation issues or the bi-directional implications of trade agreements, and the reshaping of the world economy.

Our central scenario emphasizes the hugely increasing presence of large developing countries or regions (mainly China, India, and sub-Saharan Africa) on global markets, as both suppliers and consumers. The magnitude of this change however is very sensitive to demographic and education assumptions, since developing economies are more vulnerable to uncertainties about these growth fundamentals.

Nevertheless, our models confirm that, whatever assumptions are used, world CO_2 emissions are far from sustainable at the 2100 horizon in the absence of any emissions mitigation policy. This also underlines one of the limits of our framework and suggests some further developments: at current levels of greenhouse gas emissions and expected rises in temperature, the absence of feedback on economic growth in general, and agricultural productivity in particular, should not be ignored.

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Appendix

A.1. Distance functions and Malmquist Index

The goal of DEA is to build a piece-wise linear surface, for each year t and country i, corresponding to the maximum production that country i could have achieved with its inputs (output-oriented DEA). That is, to find which countries use their inputs the most efficiently in order to derive a productivity frontier. DEA methods have been used to compute Malmquist TFP indices at a national level (see Färe et al., 1997) or for agriculture-specific TFP (see Coelli and Rao, 2005; Ludena et al., 2007).

DEA uses a distance function to compute TFP improvements. Suppose that we have a set of all feasible inputs/outputs vectors S^t. For a country which produces a vector of outputs y^t with its inputs x^t, the output-oriented distance function to the frontier at date s can be defined following Färe (1988):

$$\begin{aligned} D^s\left(x^t, y^t\right) &= \inf\left\{\theta \ s.t. \ \left(x^t; y^t/\theta\right) \in S^s\right\} \\ &= \sup\left\{\theta \ s.t. \ \left(x^t; \theta y^t\right) \in S^s\right\} \end{aligned} \quad (25)$$

This implies that $D^s\left(x^t, y^t\right) \leq 1$ if and only if $\left(x^t, y^t\right)$ is a feasible input/output combination at date s ; and $D^s\left(x^t, y^t\right) = 1$ if and only if $\left(x^t, y^t\right)$ is at the technology frontier.

Most times, numerical estimations are required to compute the frontier and distances to it. The frontier is approximated by a piece-wise linear surface delimited by the countries which are the most efficient at date s and the distances of the other countries are computed by a maximization program (for sector m^* in country k^* at date t, relative to period s technology):

$$D^s\left(x^t, y^t\right)^{-1} = \max_{\theta, z^k}(\theta) \quad (26)$$

$$\text{s.t.} \begin{cases} y_m^{k^*,t} \leq \sum_k z^k y_m^{k,s} & \text{for} \quad m \neq m^* \\ \theta y_{m*}^{k^*,t} \leq \sum_k z^k y_{m^*}^{k,s} & \\ \sum_k z^k x_{n_{m^*}}^{k,s} \leq x_{n_{m^*}}^{k^*,t} & \text{for} \quad n \in A \\ \sum_k z^k x_n^{k,s} \leq x_n^{k^*,t} & \text{for} \quad n \notin A \\ z^k \geq 0 & \text{for} \quad k = 1, ..., K \end{cases}$$

In order to simplify the notations, we write θ instead of $\theta_{m^*}^{k^*,t,s}$ which is the inverse of the distance we want to compute; and z^k instead of $z_{m^*}^{k,k^*,t,s}$ which determines to which point countries k^* is projected at the frontier. In addition, we used a refinement introduced by Nin et al. (2004) which benefits from the information about which inputs are allocatable to a specific sector ($\in A$) and which are not ($\notin A$).

We solve these programs numerically using GAMS. The program solves, for each year t and each $s \in \{t-1; t; t+1\}$, the maximization programs of all countries and sectors at the same time using a linear objective function and the additional constraint that all $\theta_{m^*}^{k^*,t,s}$ are positive: [16]

$$\beta = \sum_{m^*,k^*} \theta_{m^*}^{k^*,t,s} \tag{27}$$

Färe et al. (1997) define the Malmquist index of productivity growth as the geometrical mean of two indices, respectively based on technological frontier at date t and $t+1$, for constant returns to scale:

$$M^{t,t+1} = \sqrt{\left(\frac{D^t(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)}\right)\left(\frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^{t+1}(x^t, y^t)}\right)} \tag{28}$$

This formula can be rewritten more conveniently as:

$$M^{t,t+1} = \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)}\sqrt{\left(\frac{D^t(x^{t+1}, y^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1})}\right)\left(\frac{D^t(x^t, y^t)}{D^{t+1}(x^t, y^t)}\right)} \tag{29}$$

which splits the Malmquist index into an efficiency (distance to the frontier) term $\Delta EFF^{t,t+1}$ and a technical change term $\Delta TECH^{t,t+1}$. This index has some interesting properties. $M^{t,t+1} \geq 1$ if there has been progress in TFP between year t and $t+1$ and $M^{t,t+1} \leq 1$ if technological regression has occurred. Furthermore, improvements (resp. deterioration) of the two components $\Delta EFF^{t,t+1}$ and $\Delta TECH^{t,t+1}$ are associated with values greater (resp. lower) than 1.

A.2. Computing livestock

Table A.1 – Aggregation coefficient for animal stock by region

Region	Buffaloes	Camels	Cattle	Chickens	Ducks	Goats	Pigs	Sheep	Turkeys
Asia	0.50	0.50	0.50	4.4	4.72	0.05	0.26	0.05	23.38
SSA	0.46	0.46	0.46	3.3	6.22	0.04	0.17	0.04	10.64
Eastern Europe	0.63	0.63	0.63	4.8	7.75	0.04	0.30	0.04	18.78
Rest of America	0.74	0.74	0.74	5.3	7.18	0.05	0.26	0.05	19.15
MENA	0.51	0.51	0.51	4.2	8.50	0.06	0.27	0.06	11.12
OECD	1.00	1.00	1.00	5.5	8.44	0.06	0.30	0.06	27.91
Former USSR	0.54	0.54	0.54	4.5	7.75	0.06	0.27	0.06	21.60

Notes: SSA stands for Sub-Saharan Africa and MENA for Middle east and North Africa.
Source: Ludena et al. (2007).

[16] We are then left with 139 programs. We also tried, as a comparison, solving a program for each sector and country (for a total of 38086 programs), but the results were the same.

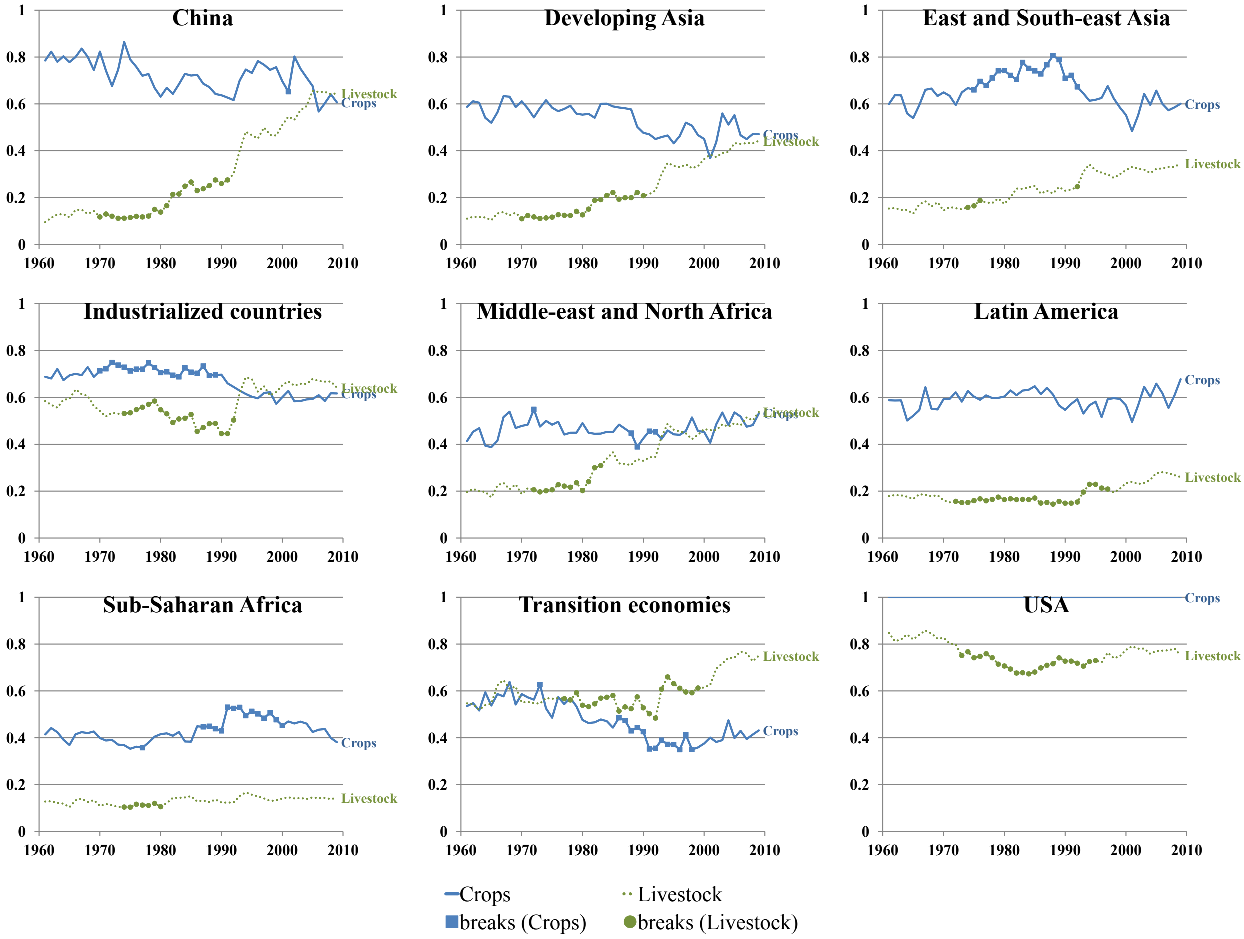
A.3. Region Aggregation

Table A.2 – Malmquist indices regional aggregation

Industrialised countries	**China**	**Latin America**
Australia	China	Argentina
Austria	**Developing Asia**	Bolivia
Belgium	Bangladesh	Brazil
Canada	China	Chile
Switzerland	Indonesia	Colombia
Germany	India	Costa Rica
Denmark	Iran, Islamic Republic of	Ecuador
Spain	Cambodia	Guatemala
Finland	Korea	Mexico
France	Lao People's Democratic Republic	Nicaragua
United Kingdom	Sri Lanka	Panama
Greece	Malaysia	Peru
Ireland	Pakistan	Paraguay
Italy	Singapore	Uruguay
Japan	Thailand	Venezuela
Luxembourg	Turkey	Rest of Central America
Netherlands	Vietnam	Caribbean
Norway	Rest of East Asia	Rest of South America
New Zealand	Rest of South Asia	**Sub-Saharan Africa**
Portugal	Rest of Southeast Asia	Botswana
Sweden	Rest of Western Asia	Ethiopia
United States of America	**East and South-east Asia**	Madagascar
Rest of EFTA	Indonesia	Mozambique
South Africa	Cambodia	Malawi
USA	Korea	Nigeria
United States of America	Lao People's Democratic Republic	Senegal
Transition economies	Malaysia	Tanzania
Albania	Philippines	Uganda
Bulgaria	Singapore	South-Central Africa
Belarus	Thailand	Central Africa
Czech Republic	Vietnam	Rest of Eastern Africa
Croatia	Rest of East Asia	Rest of South Africa Customs Union
Hungary	Rest of South Asia	Rest of Western Africa
Kazakhstan	Rest of Southeast Asia	Zambia
Kyrgyzstan	**Middle-east and North Africa**	Zimbabwe
Poland	Egypt	
Romania	Iran, Islamic Republic of	
Russian Federation	Morocco	
Slovakia	Tunisia	
Slovenia	Turkey	
Ukraine	Rest of North Africa	
Rest of Europe	Rest of Western Asia	
Rest of Former Soviet Union		

A.4. Breaks in distances series

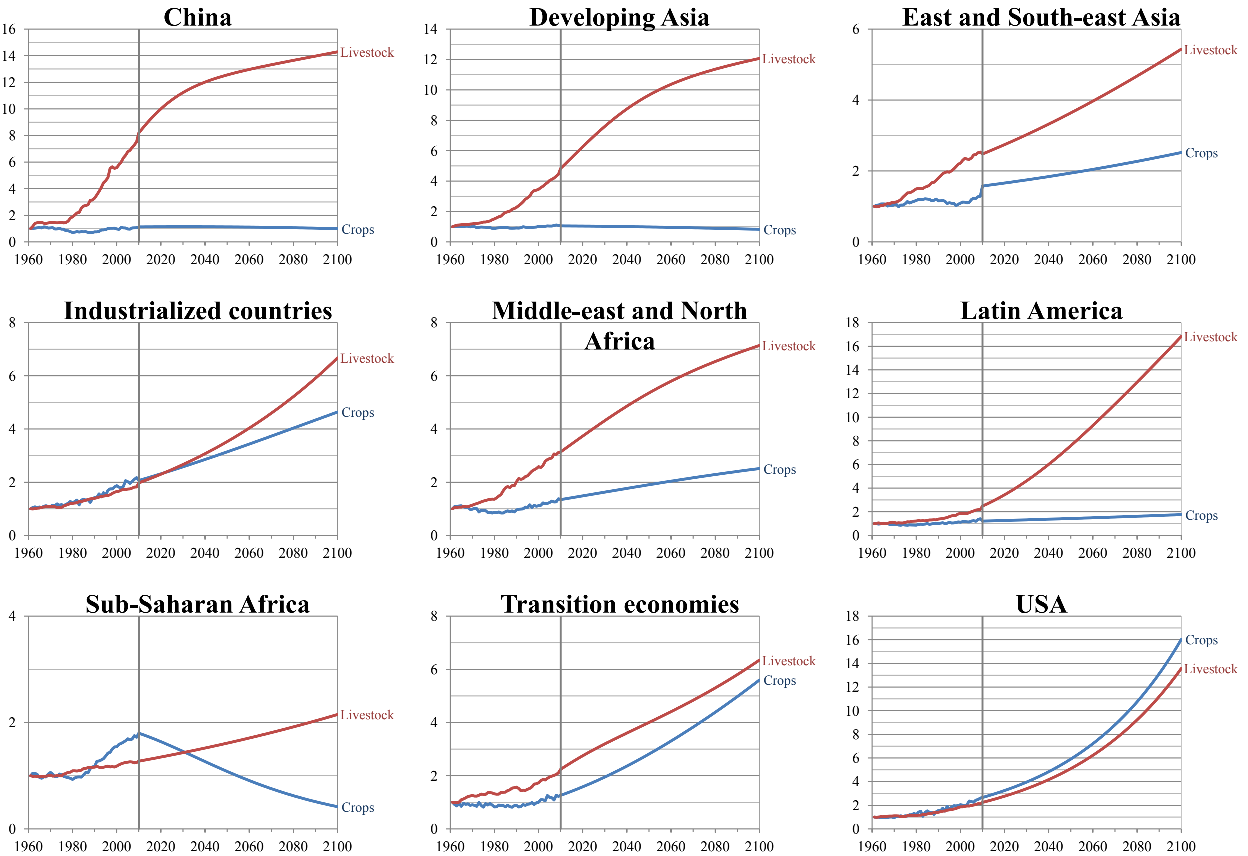
Figure A.1 – Breaks in distance function series by region



Source: authors' computations.

A.5. Projection by region

Figure A.2 – Projected malmquist indices by region (2004=1)



Source: authors' computations.