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MaGE 3.1: Long-Term Macroeconomic Projections of the World Economy

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Highlights

- What will the global economy look like in a generation? The answer depends on the multiple forces driving long-term growth (demography, education, diusion of technical progress, energy costs, investment and saving behaviour, international capital mobility) and requires a comprehensive framework to conceptualise them.

- We estimate a the three-factor (capital, energy, labour) MAcro-econometric model of the Global Economy (MaGE), with a database covering 170 countries using state-of-the-art methods.

- The model projections to 2050 illustrate the expected changes in the World economy and their driving forces. In light of the projected volume of energy consumption, making these projections compatible with climate imperatives calls for increased technology sharing at the international level in order to decouple economic growth from energy use.

Abstract

What will the global economy look like in a generation? The answer depends on the multiple forces driving long-term growth (demography, education, diffusion of technical progress, energy costs, investment and saving behaviour, international capital mobility) and requires a comprehensive framework to conceptualise them. We re-estimate the three-factor (capital, energy, labour) MAcro-econometric model of the Global Economy (MaGE), initially developed by Fouré et al. (2013), with a database covering 170 countries using state-of-the-art methods. We thus establish the long-term structural relationships that drive the dynamics of the World economy. The model projections to 2050 illustrate the expected changes in the World economy and their driving forces. In light of the projected volume of energy consumption, making these projections compatible with climate imperatives calls for increased technology sharing at the international level in order to decouple economic growth from energy use.

Keywords

Growth Models, Long-term Growth, Energy Use, Total Factor Productivity, Energy efficiency.

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O.04, E01, F01, F64.

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RESEARCH AND EXPERTISE
ON THE WORLD ECONOMY

Introduction[1]

What will the global economy look like in a generation? The COVID-19 pandemic, global warming, food security, the potential depletion of numerous raw materials and migratory pressures remind decision-makers that our economies are confronted with global problems, calling for the long term and raising intergenerational questions. To guide economic policies, it is therefore essential to have a coherent framework for reflection. The same requirement applies to the quantification of economic policies envisaged to make growth sustainable in the long term: having a reference trajectory for the world economy, based on the least uncertain economic and demographic data, is essential if one wants to simulate the impact of such policies in the distant future. The purpose of the exercise described in this paper is to propose such modelling framework, and to discuss the basic trends in the world economy over a generation.

Long-term growth is multidimensional: countries' economic trajectories depend, among other things, on their demographics, educational progress, the diffusion of technical progress, the availability and cost of energy, savings and investment behaviour, and the international mobility of capital. As simple extrapolation of past growth rates is not an option, two approaches can be considered. Multi-disciplinary prospective analysis develops scenarios and tries to identify weak signals that could lead to bifurcations. In contrast, macroeconomic projections, such as those proposed in this article, are limited to observable data and determine dynamic trajectories based on the functional relationships established between these data. Indeed macroeconomic projections can be used thereafter to construct alternative scenarios inspired by more multidisciplinary approaches, but this is not what this paper aims to do. In the following, we actually report on a new estimation of the MaGE (Macroeconometrics of the Global Economy) model (Fouré et al., 2013). The newly estimated long-term structural relationships will be used to discipline the projections of GDP (and its components) and provide an updated picture of the world economy at the 2050 horizon.

Having a comprehensive framework for reasoning requires the use of a model of the economy. As in any such exercise, there is a trade-off between information and understanding, which involves simplifications and assumptions. The model needs to be informed by widely available data, and it requires a theoretical framework that links macroeconomic variables to other data used, such as demographic data.

The standard framework of conditional convergence (Barro and Sala-i Martin, 2004) and growth accounting (Easterly and Levine, 2001) is used here: each country is expected to converge to its own steady-state level of GDP per capita, which is determined by various factors, such as demographics, investment or TFP, that differ across countries. Each component can then be projected in order to obtain the projected trajectory of GDP and hence GDP per capita of each country. This standard framework is adapted here to work with three factors of production, labour, capital and energy. Since energy is considered here among the primary factors, the assumption of unit elasticity of substitution implied by the Cobb-Douglas production function must be reconsidered: capital and labour can hardly substitute for the scarcity of energy in the economy. To preserve the simplicity of the modelling framework, we retain a constant nested elasticity of substitution function (David and van de Klundert, 1965) between energy and a (Cobb-Douglas) bundle of two factors—capital and labour —in line with the preferred nesting of van der Werf (2008). Similar nesting was suggested by Manne et al.

[1]This is an updated version of the CEPII working paper N 2021-12, December 2021

(1995) for evaluating the impact of policies aiming to abate Greenhouse Gas emissions, although adding a Cobb-Douglas aggregation of non-electric and electric energy. Another influential modelling framework relying on such nesting is the Massachusetts Institute of Technology Emissions Prediction and Policy Analysis model – EPPA (Paltsev et al., 2005). We explicitly derive two different types of productivity, total productivity of capital and labor factors (in the following: Total Factor Productivity – TFP), versus energy efficiency. The capital-labor ratios are determined by considering on the one hand the usual life-cycle assumption that aggregate savings depend on the demographic structure, and on the other hand the gap between savings and investments arising from the imperfect international mobility of capital. Finally, income valuation effects are introduced through a Balassa-Samuelson effect.

Each functional relationship of the model is estimated on historical data going back to 1950 for some series and covering 170 countries, i.e. the maximum coverage compatible with the available databases.

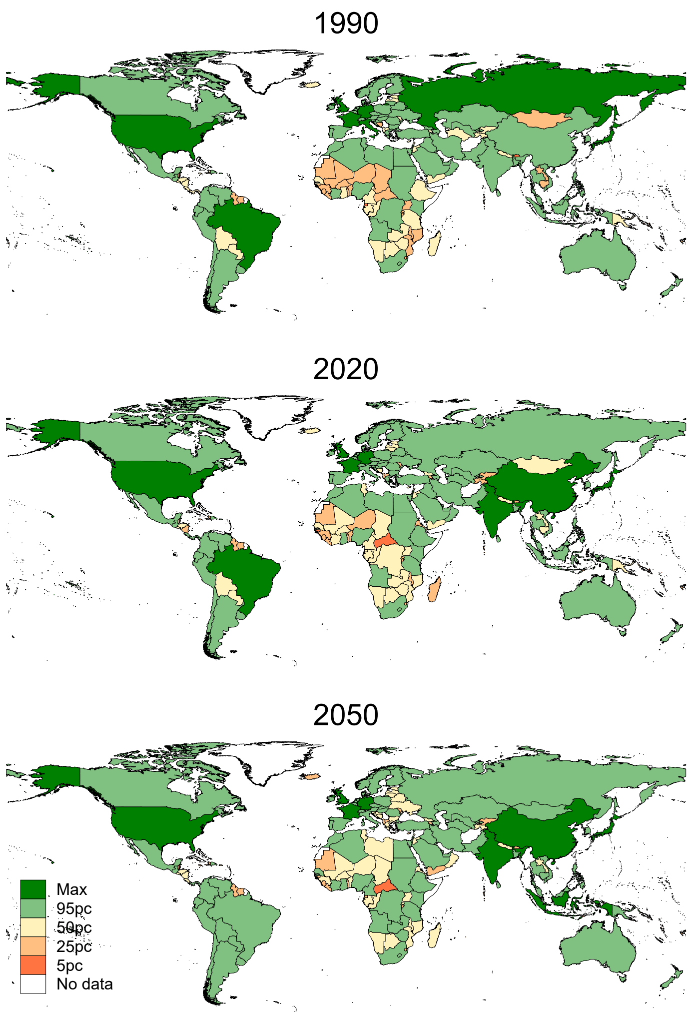
The last step of the analysis consists in projecting the estimated functional relationships in the long term, thus making the assumption that the observed behaviors and dynamics of the past (for example, the shift in time of the technological frontier in energy efficiency) will be preserved. In line with these modelling choices, the question we ask here is therefore: "given what we know about the functional relationships between observables, what should be the economic trajectory of the different countries, all other things being equal, when their demographics, their education effort, and the price of energy vary at different rates over time?"

The picture that emerges from our work is one of a changing world, as shown in figure 1. Whereas a generation ago, economic activity was concentrated in developed countries (such as the United States, Europe, and Russia) and Brazil, the current generation is already witnessing the rise of emerging economies such as China and India and a relative decline of Russia. For the next generation, this trend will continue and be accompanied by the rise of other South Asian countries (e.g., Indonesia and the Philippines). On the other hand, the developed countries of Europe will gradually see their relative importance retreat at the global level. Among the BRICS, the evolution is very heterogeneous, with Russia and Brazil rapidly sliding down the world ranking. Finally, an important dynamic in the developing world is given by the countries of Sub-Saharan Africa, certain of which are beginning to ascend in the world ranking.

This paper adds to the literature tackling long-term economic projections for the world economy. Duval and de la Maisonneuve (2010) is an important step towards theory-based macroeconomic projections. They rely on a decomposition of cross-section differences in GDP per capita in 2005 using a constant returns to scale Cobb-Douglas production function featuring physical capital, human capital, labour and TFP. Turning to projection, TFP is following till 2025 a catching up process calibrated on the observed catch up on the 1995-2005 period, and an ad-hoc pace between 2025 and 2050. Johansson et al. (2013) follow the same logic and use the projections to figure out inherent global imbalances that may arise between OECD countries and major emerging economies. Cette et al. (2017) rely on a two-factor Cobb-Douglas constant returns to scale production function to project GDP for 13 advanced countries plus the euro area at the 2100 horizon. Productivity growth is driven by (exogenous) technological change in the US and a catching up of laggard countries determined by education and regulation.

This paper differs from a related strand of literature aiming to transform into economic projections the Shared

Figure 1: Country GDP



Notes: Map of countries' GDP in levels, expressed in constant 2011 USD.

Socioeconomic Pathways (SSP) scenarios that structures the field of climate change research. A prominent illustration of such scenarios are the projections proposed by the International Institute for Applied Systems Analysis (IIASA).[2] Dellink et al. (2017) build on Duval and de la Maisonneuve (2010) and Fouré et al. (2013) in order to add energy as a production factor and source of income for oil exporting countries and to enlarge the sample of countries for which GDP is projected to developing economies. They also adapt the rather qualitative story telling of the SSPs to the quantification capabilities of a macroeconomic growth model. Differently, Central Banks have initiated in 2017 a network (Network for Greening the Financial System) constructing their own scenarios, different from the SSPs, combining climate and economic impacts at the 2060 horizon. The purpose is to combine the outcomes of integrated assessment models, climate models and natural catastrophe models in order to assess the macroeconomic and financial impact of alternative trajectories on the financial system and the economy. Assumptions are made about policy ambition, policy response, technological change, emission reduction policies and the degree of international coordination to construct six scenarios. Outcomes range from a generalized net zero emissions in 2050, associated with a 1.5 degree increase in global temperature, to laissez-faire leading into the catastrophic territory of warming beyond 3 degrees. Unlike this literature, this paper does not aim to propose alternative scenarios: we describe in the following how to build and estimate a long-term growth model of the world economy, which we use to construct a reference path.

To wrap up, the contribution of this paper is twofold. First, based on the re-estimation of the MaGE model with updated data and methods we provide new economic projections for the world economy that can be mobilized to develop dynamic baselines for global modelling. Second, we illustrate the expected big shifts of the world economy at the 2050 horizon.[3]

The remaining of the paper is organized as follows. Section 1 describes the growth model used in this exercise, the data used, the estimations and how projections were performed. Results of these projection till 2050 are presented in Section 2 and discussed in Section 3. The last section concludes.

[2] See the SSP database developed by IIASA: `https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about`

[3] The projections extend to 2100, as does the database published online. We limit ourselves here to the year 2050, in keeping with the idea of looking ahead one generation.

1 Model

This section introduces to MaGE (Macroeconometrics model for the Global Economy). It presents the general set up before detailing sequentially how the functional relations are derived, estimated and projected for the different components: labour, capital, TFP, energy and energy efficiency, and lastly considering valuation effects.

1.1 Setup

MaGE is a structural long-term model relying on the conditional convergence assumption (Barro and Sala-i Martin, 2004) based on a theoretical three-factors production function and on the estimation of the economic relationships determining the evolution of each of its components.

In detail, MaGE is based on a Constant Elasticity of Substitution (CES) production function aggregating energy (E) with a Cobb-Douglas bundle of two factors – capital (K) and labour (L). The use of this nested CES production function was proposed by David and van de Klundert (1965) in order to encompass different kinds of input-augmenting technical change. This specification implies an elasticity of substitution between labour and capital that is standard, but a (relatively) low elasticity of substitution between energy and the composite factor. This nested CES has been used for climate policy modelling (see for instance van der Werf (2008)). The functional form reads:

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

In Equ. 1, $Y_{i,t}$ denotes GDP of country i at period t; A denotes TFP of the capital-labour bundle and B is energy productivity – thereafter "energy efficiency".

The parameter α is set to 0.3 according to the literature (see for instance Mankiw et al. (1992)). σ is set to 0.15 based on the value of the simulated elasticity of substitution between energy and the composite factor recovered from the model MIRAGE (Decreux and Valin, 2007).[4]

We project GDP for 170 countries over the period 2018-2050 using the following expression:

$$Y_{i,t} = \left[1 - \left(\frac{B_{i,t}}{p_{E,t}} \right)^{\sigma-1} \right]^{\frac{\sigma}{1-\sigma}} A_{i,t} K_{i,t}^{\alpha} L_{i,t}^{1-\alpha} \tag{2}$$

which is obtained from Equ. 1 by substituting the optimality condition for energy, E, as explained in Appendix A. Different from other countries, the GDP of oil-producing countries is projected net of oil rents in order to avoid biased measures of productivity.[5]

With the exception of oil prices and demography, the different components of the GDP are projected relying on the econometrically estimated long-term relationships. Oil price data, $p_{E,t}$, is taken from the US Energy Information Administration (EIA) projections.[6] Demography is taken from the United Nations (UN) central

[4] In section 3.4 we provide a sensitivity to this parameter.

[5] For more details look at appendix A.

[6] EIA data on Real Petroleum prices, Crude oil, Brent Spot, Reference price AEO 2020-2019 $/b from 2019 to 2050. From 2050 until 2100 we set the price of energy to increase at a constant rate equal to its average growth rate over the projection period. For a detailed description of the methodology see appendix B.

scenario (how demography is translated into the labour force by cohort is detailed below). In the next sections we explain in detail the data coverage and sources, the regressions' specifications and the methodology used for the projection of each variable.[7]

1.2 Labour

We consider the labour market as composed by active and non-active workers. The labour force is made up of cohorts at five-year intervals, and is defined as the active fraction of the population in each cohort. We distinguish between male and female labour force participation because male labour force participation is stable, while female labour force participation is still very uneven across countries and subject to significant changes as countries develop. Therefore, following the literature, we characterize the female participation rate as a function of education (Bloom et al., 2009) using secondary and tertiary school attainment data.

1.2.1 Data

Historical labour force data are constructed from UN population data by gender and by five-year cohort using average fertility variant data over the period 1950 to 2100. These total population projections are then coupled with International Labour Organisation (ILO) labour force participation rates by gender and age group over the period 1950 to 2019 (and then their estimates until 2030). The human capital data, necessary for the estimation of our econometric relationship, are proxied by the share of the working age population with secondary and tertiary education. Data are from the Barro & Lee dataset (2018 revision, data from 1950 to 2010) of education attainment for each cohort. The regional aggregation is based on the World Bank Country groups classification of year 2014.

1.2.2 Estimation

Based on the total population data by country, cohort and gender, our first task is to estimate the female participation rate to the labour market in order to construct the labour force. Female activity rate projections are based on the estimation of the following relationship between female participation to the labour force and education attainment:

$$ActFemale_{a,i,t} = fe + \beta^F_{sec} \ln Sec_{a,i,t} + \beta^F_{tert} \ln Tert_{a,i,t} + \epsilon_{a,i,t} \tag{3}$$

where $Sec_{a,i,t}$ and $Tert_{a,i,t}$ are respectively the proportion of age-group a in country i and year t that has at least a secondary and tertiary diploma. Estimation are conducted at the country-age group level, and at the five-year frequency, controlling for unobserved time-invariant country determinants of female activity rate with country fixed effects fe.[8]

Table 1 reports the estimated coefficients, obtained from an OLS regression of the female activity rate on the log of tertiary and secondary education rates[9] for 182 countries over the period 1960-2017. We find a positive

[7]For data constructions and a detailed list of data sources see appendix B.
[8]Activity rates, in this estimation, are at the five-year frequency coherently with the education data frequency.
[9]The dependent variable has been logit transformed $log[(y/(1-y)]$ before running the OLS.

effect of both levels of schooling on activity rates for all the age groups above 25 years old. The negative coefficient for the age groups 15-19 and 20-24 can be instead explained by the length of the studies as people in these age groups could be still attaining the secondary and tertiary education.

The previous relation between female participation and education relies on education attainment. In turn, education attainment must also be estimated. We estimate a catch-up model with respect to the leader country's level of education ($h^{l,*}$). The estimations are performed for age-groups 15-19 and 20-24, for each country, and taking into account the specificities of each region r of the world economy:

$$\ln\left(\frac{h^l_{a,i,t}}{h^l_{a,i,t-1}}\right) = \lambda^l_r \ln\left(\frac{h^{l,*}_{a,i,t-1}}{h^l_{a,i,t-1}}\right) + \epsilon_{i,t} \tag{4}$$

where $l = \{sec, tert\}$ and λ^l_r is the coefficient capturing the speed of convergence with respect to the distance from the leader ($* = US$) frontier at the regional level (r).

Table 2 shows the resulting coefficients. There is a stronger catch-up in developed regions like Western and Eastern Europe, North America and Pacific. The slowest speed of education convergence is instead in Sub-Saharan Africa and in India.

Table 1: Female participation rates estimation by age group, five-year intervals

Dep var:	Female Activity Rate, $ActFemale^a_{i,t}$										
Age group:	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
log(tertiary$_{i,t}$)	-0.028***	-0.015*	0.129***	0.162***	0.129***	0.162***	0.232***	0.195***	0.172***	0.135***	0.087***
	(0.005)	(0.009)	(0.011)	(0.013)	(0.014)	(0.016)	(0.016)	(0.017)	(0.017)	(0.015)	(0.016)
log(secondary$_{i,t}$)	-0.368***	0.035*	0.485***	0.606***	0.423***	0.285***	0.234***	0.273***	0.208***	0.098***	-0.119***
	(0.016)	(0.019)	(0.021)	(0.022)	(0.021)	(0.020)	(0.019)	(0.019)	(0.019)	(0.018)	(0.018)
N	5522	5578	5568	5564	5399	5412	5509	5554	5530	5544	5555
FEs	i	i	i	i	i	i	i	i	i	i	i

Notes: The estimation sample covers 182 countries over the period 1960-2017. Standard errors in parentheses * p<0.1, ** p<0.05, *** p<0.01. The dependent variable is the, logit transformed, activity rate estimated using an OLS by age group. Projections rely on age-group coefficients from column 1 to column 11.

Table 2: Education catch-up process, by education level, age group and region

Dep Var:	Education, $\ln(h^l_{i,t}/h^l_{i,t-1})$					
	Primary		Secondary		Tertiary	
	(1)	(2)	(3)	(4)	(5)	(6)
Age group:	15-19	20-24	15-19	20-24	15-19	20-24
Western Europe	0.134***	0.275***	0.266***	0.201***	0.0735***	0.197***
	(0.042)	(0.085)	(0.055)	(0.013)	(0.020)	(0.031)
Eastern Europe and former USSR	0.247***	0.321***	0.216***	0.343***	0.165***	0.234***
	(0.022)	(0.067)	(0.037)	(0.075)	(0.031)	(0.018)
North America, Oceania and Japan	0.260***	0.166***	0.383***	0.266***	0.169***	0.312***
	(0.038)	(0.027)	(0.113)	(0.017)	(0.014)	(0.029)
Latin America	0.191***	0.202***	0.134***	0.148***	0.122***	0.116***
	(0.006)	(0.019)	(0.016)	(0.008)	(0.025)	(0.013)
Mediterranean region	0.183***	0.148***	0.136***	0.131***	0.113***	0.138***
	(0.016)	(0.017)	(0.018)	(0.022)	(0.024)	(0.013)
Chinese region	0.143***	0.233***	0.140***	0.176***	0.103***	0.0736***
	(0.031)	(0.043)	(0.014)	(0.017)	(0.037)	(0.007)
Sub-Saharan Africa	0.141***	0.112***	0.0722***	0.101***	0.0263***	0.0544***
	(0.024)	(0.010)	(0.012)	(0.007)	(0.007)	(0.007)
India region	0.120***	0.113***	0.179***	0.135***	0.0814***	0.102***
	(0.007)	(0.009)	(0.017)	(0.004)	(0.014)	(0.005)
R-sq	0.529	0.430	0.344	0.483	0.118	0.165
N	1705	1704	1702	1702	1441	1688
Clusters	143	143	143	143	143	143

Notes: The estimation sample covers 143 countries on 5-year intervals from 1955 to 2010. Robust standard errors in parenthesis. * $p<0.1$, ** $p<0.05$, *** $p<0.01$. “Easter Europe” includes the former USSR; “Pacific” includes Oceania and Japan. Projections rely on coefficients from column 1 to column 6.

1.2.3 Projection

Activity rates are projected as the sum of female and male projections by age group. Participation to the labour force is gender specific and we firstly need to project educational attainment. The different levels of education (h^l) are projected as:

$$\ln h^l_{i,t} = (1 - \lambda^l_r)\ln(h^l_{i,t-1}) + \lambda^l_r \ln(h^{l,*}_{i,t-1}) \tag{5}$$

where $l = \{sec, tert\}$ and λ^l_r is the coefficient capturing the speed of regional convergence with respect to the distance from the leader ($*$) frontier at the regional level (r). The leader country is assumed to be the US, consistently with data.[10]

Female activity rate projections depart from ILO projections, as they are augmented by the explicative power of women education attainment informed by the previous catch up dynamics. Female activity rates are projected as:

$$\begin{aligned} ActFemale_{i,t} =& ActFemale_{i,t-1} + \beta^F_{trend}\Delta_{log}\text{Trend}_t \\ &+ \beta^F_{sec}\Delta_{log}Sec_t + \beta^F_{tert}\Delta_{log}Tert_t \end{aligned} \tag{6}$$

where β^F_{trend} is the estimated slope coefficient of the log-trend ($\Delta_{log}\text{Trend}_t$) calculated over the period of ILO projections (2019-2030).

β^F_{sec} and β^F_{tert} are the coefficients resulting from our estimation of Equ. 3 regressing female participation to the labour force on educational attainment.

Male projections are based on the log-trend extension of male activity rate projections by the ILO which are available until 2030. Beyond 2030, we further project male activity rates as:

$$ActMale_{i,t} = ActMale_{i,t-1} + \beta^M_{trend}\Delta_{log}\text{Trend}_t \tag{7}$$

where β^M_{trend} is the estimated slope coefficient of the log-trend ($\Delta_{log}\text{Trend}_t$) calculated over the period of ILO projections (2019-2030).

Then, for each country i and year t, the labour force is projected on the basis of active population, by combining population data with participation rates:

$$L_{i,t} = \left(ActFemale_{i,t} * Population^{Female,UN}_{i,t}\right) + \left(ActMale_{i,t} * Population^{Male,UN}_{i,t}\right) \tag{8}$$

This labour force will be combined with capital in a Cobb Douglas. Then, this bundle – having its own TFP – will be combined with energy using a CES aggregator. We now present how the series of capital are constructed for each country and date.

[10] The US have been the leader for 64% of times over the historical dataset. To project the leader frontier it is assumed that for primary and secondary education, the leader level is fixed at 100%; for tertiary education we estimate a logistic function for age-group 20-24 that grows over time attaining but never exceeding 100%. Education data and projections are at the five-year frequency; to be used at an annual frequency in the projections of activity rates they are interpolated linearly.

1.3 Capital

We consider homogeneous capital K in the model, which is accumulated through the usual permanent inventory process combining capital depletion δ and gross investment, with i being the gross investment rate as a proportion of GDP: $K_{i,t} = (1-\delta)\, K_{i,t-1} + i_{i,t}\, Y_{i,t}$. What differentiates us from the usual approach is that we do not consider closed economies: as a consequence, savings and investment can diverge at any date in a given country, which is the counterpart of capital mobility. In every country, we project domestic investments depending on domestic savings in the spirit of the Feldstein-Horioka relationship (Feldstein and Horioka (1980), FH hereafter): the greater the international capital mobility, the weaker this relationship. The next question is how to project the savings series for each country. Savings are projected here on the basis of a life-cycle assumption (Masson et al., 1998) in which gross savings depend on the age-structure of the population and on the GDP-per-capita gap with respect to the leader country. Finally, we define each country's current account balance in a given year as the difference between savings and investments and impose that at the global level the sum of all countries' current account balances has to be equal to zero at all times.

1.3.1 Data

For the FH relationship we use the World Bank series of Gross Domestic Savings (as a % of GDP) and Gross Fixed Capital Formation (GFCF as a % of GDP) data from 1960 to 2018. The age structure of the population used in the estimations of savings rate comes from the United Nations population data by five-year cohort and gender group (medium fertility variant data from 1950-2100).

1.3.2 Estimation

The first task is to determine savings. Savings rate are projected based on the estimation of a life-cycle model of the gross savings' rate in which savings rates depend on the age structure of the population and on the distance from the leader country ($\star$) in terms of GDP-per-capita. In order to summarise the information contained in the entire cohort distribution—while maintaining a parsimonious parametrisation—we follow Higgins (1998) and Fouré et al. (2012) and construct a vector of demographic variables based on a low-order polynomial. The constructed variables are geometric means of the shares of each cohort in the population. We then estimate the following model at five-year frequency over the period 1960-2017, using the five-year average values of saving rates and GDP:

$$s_{i,t} = fe + \gamma_y \frac{y_{i,t-1}}{y^*_{t-1}} + \gamma_{gy}\, gy_{i,t-1} + \sum_{k=1}^{3} \psi_k d^k_{i,t} + \sum_{k=1}^{3} \gamma_{gyd^k} d^k_{i,t}\, gy_{i,t-1} + \epsilon_{i,t} \tag{9}$$

where fe are country(-time) fixed effects, y is GDP-per-capita, gy its growth rate, and d^k, are the demographic variables summarizing the distribution of five-year cohorts in the population.

Table 3 reports the estimated coefficients. Both an increase in per capita GDP with respect to the leader and a higher GDP per capita growth rate increase savings. The interaction between demographic factors and GDP per capita growth is always statistically significant. Our preferred specification in column 3 is used for

Table 3: Determinants of the savings rate, five-year-averages

Dep Var:	Savings rate, $S_{i,t}$		
	(1)	(2)	(3)
GDPpc$_{i,t-1}/GDPpc^*_{t-1}$	0.116*	0.116*	0.053
	(0.063)	(0.063)	(0.034)
$\Delta GDPpc_{i,t-1}$	0.575***	0.575***	0.479***
	(0.192)	(0.212)	(0.125)
d^1 x $\Delta GDPpc_{i,t-1}$	-14.711***	-14.711***	-12.412***
	(3.334)	(3.562)	(2.062)
d^2 x $\Delta GDPpc_{i,t-1}$	2.460***	2.460***	2.035***
	(0.534)	(0.571)	(0.334)
d^3 x $\Delta GDPpc_{i,t-1}$	-0.110***	-0.110***	-0.090***
	(0.023)	(0.025)	(0.015)
d^1	0.520	0.520	0.442***
	(0.367)	(0.366)	(0.114)
d^2	-0.066	-0.066	-0.044**
	(0.056)	(0.056)	(0.018)
d^3	0.002	0.002	0.001
	(0.002)	(0.002)	(0.001)
R-sq	0.858	0.858	0.364
N	1351	1351	1354
FEs	i t	i t	i
Cluster SEs	i	i t	

Notes: GDP_{pc} is the GDP per capita. The estimation sample covers 171 countries on 5-year intervals over the period 1960-2015. Standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01. Regressions are weighted using country population. Country-year observations with interpolated or extrapolated savings rates are not included in the regression. Projections rely on coefficients from column 3.

projections.[11]

Next, we estimate in panel the long-run relationship introduced by FH between the saving rate ($s_{i,t} = S_{it}/GDP_{i,t}$) and the investment rate ($i_{i,t} = I_{it}/GDP_{i,t}$), which simply reads $i_{i,t} = \alpha_i + \beta_i s_{i,t} + \mu_{it}$. We also take into account the degree of financial openness (fo), as domestic investment in less open economies should depend more on domestic savings. We simply differentiate between OECD and non-OECD countries. In a second step, in order to account for this long-run relationship we estimate an FH-type error-correction regression between savings and investment rates over the sample 1960–2017.[12] Therefore we estimate the error correction model (10) twice for OECD and non-OECD countries.[13]

$$\Delta i_{i,t} = fe + \theta^{fo} \left(i_{i,t-1} - \hat{\alpha_i}^{fo} - \hat{\beta}^{fo}\, s_{i,t} \right) + b^{fo}\, \Delta s_{i,t} + \epsilon_{i,t} \tag{10}$$

where $\Delta i_{i,t}$ and $\Delta s_{i,t}$ are respectively the first difference of investments rates in gross capital formation[14] and savings rates; fe denotes country-by-period fixed effects, where a period span over 20 years. θ^{fo} is the long-run error-correction term; and b^{fo} is the coefficient of the FH relationship by financial openness (fo) sample.

Tables 4 and 5 report the estimated coefficients. In Table 4 the coefficient for non-OECD countries is lower than the one for OECD countries, which reveals that non-OECD country are more financially-open with a higher capital mobility (Coakley et al., 1999; Chakrabarti, 2006; Apergis and Tsoumas, 2009). The coefficient for OECD countries is in line with the most recent values in the literature (0.3 in Kumar and Rao (2011)). Projections rely on our preferred specification in column 1 and column 3 of Table 5 which control for country-by-period (20 years) fixed effects ($fe_{i,T}$).

[11] Coefficients on d^k have no structural interpretation, although these variables summarize the distribution of cohorts in the population. Given that the direct demographic terms is not significant, it is not included in the projections.

[12] Before proceeding to the error correction model estimation, we checked for panel-cointegration using different tests from the Stata *unitroot* package. We consistently reject the null of no unit-root or no co-integration hypothesis.

[13] In a series of robustness we have tested a different country division based on the Chinn and Ito (2006) *de jure* measure of financial openness. For a 3 tertiles division (Open; middle; closed) coefficients for middle and open are very close to the non-OECD coefficient.

[14] Note that for the Feldstein-Horioka estimation we use gross capital formation series for investments, as savings are used to both buy fixed assets and accumulate inventories. The projections of investments are instead based on gross fixed capital formation as the production function and the permanent inventory accumulation method only include fixed assets.

Table 4: The long-term Feldstein-Horioka relation

Dep Var:	Investment Rate, $I_{i,t}$	
	OECD (1)	Non-OECD (2)
Savings rate$_{i,t}$	0.397***	0.116***
	(0.026)	(0.009)
R-sq	0.691	0.602
N	1438	5882
Countries	30	158
FEs	iT	iT

Notes: The estimation sample covers 188 countries in total over the period 1960-2017. *iT* denotes a country-by-period fixed effects, where a period span over 20 years. Robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01. Country-year observations with interpolated or extrapolated savings or investment rates are not included in the regression. Projections rely on coefficients from both column 1 and column 2.

Table 5: The Feldstein-Horioka relation, cointegration vector

Dep Var:	Δ Investment rate, $i_{i,t}$			
	OECD (1)	OCDE (2)	Non-OECD (3)	Non-OCDE (4)
Δ Savings rate$_{i,t}$	0.281***	0.288***	0.072***	0.075***
	(0.030)	(0.029)	(0.009)	(0.009)
Lag Error correction$_{i,t}$	-0.289***	-0.293***	-0.354***	-0.359***
	(0.018)	(0.018)	(0.010)	(0.010)
R-sq	0.242	0.224	0.215	0.197
N	1408	1408	5727	5727
FEs	iT	None	iT	None

Notes: The estimation sample covers 188 countries in total over the period 1960-2017. *iT* denotes a country-by-period fixed effects, where a period span over 20 years. Robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01. Country-year observations with interpolated or extrapolated savings or investment rates are not included in the regression. Projections rely on coefficients from column 1 and column 3.

1.3.3 Projection

Capital-stock series are projected using the permanent inventory method with a depreciation rate set to 0.06.[15] Due to data availability, projections start in 2018 based on the value of capital of the year 2017 and make use of the projected investment rate ($i_{i,t}$) and GDP ($Y_{i,t}$).

As previously discussed, we have to take into account an FH relationship as we do not assume closed economies: domestic investment is not directly deduced from national savings. The first step is to project the savings rates, following the estimated life-cycle equation according to which saving rates depend on the age-structure of the population and on a catch-up model of GDP-per-capita:

$$s_{i,t} = \bar{s} + \gamma_y \left(\frac{y_{i,t-1}}{y^*_{t-1}} - \frac{\overline{y_i}}{\overline{y^*}} \right) + \gamma_{gy} \left(gYgPop_{i,t-1} - \overline{gYgPop} \right) + \sum_{k=1}^{K} \gamma_{gyd^k} \left(d^k_{i,t} \left(gYgPop_{i,t-1} \right) - \overline{gYgPopd^k} \right) \tag{11}$$

where y is GDP-per-capita considered in deviation from the leader ($*$ = US), $gYgPop$ is the growth rate of GDP-per-capita constructed as the difference between the GDP growth rate, gY, and the population growth rate, $gPop$. "Upper bar" variables refer to the average values of the targeted variable over the last five-year period of the observed series, i.e. 2012-2017. The variables d^k are the demographic factors of Equ. 9, and the coefficients (γ_y, γ_{gy} and $\sum_{k=1}^{K} \gamma_{gyd^k}$) are those estimated with this equation.

Then, investment rates are projected on the basis of the previously estimated FH relationship between savings and investments:

$$i_{i,t} = i_{i,t-1} + \theta^{fo} \left(i_{i,t-1} - \alpha^{fo}_i - \beta^{fo} s_{i,t-1} \right) + b^{fo} \left(s_{i,t} - s_{i,t-1} \right) \tag{12}$$

where $s_{i,t}$ is the gross domestic saving rate. The coefficients (θ^{fo}, β^{fo}, b^{fo}) and the constant (α^{fo}_i) are taken from the estimation for the relationship between saving and investment rates.

Finally, we adjust the projections to achieve global consistency for savings and investment. As the sum of current account balances must be equal to zero at the global level, we rescale the investment projections by distributing any deviation to all countries in the model in proportion to each country's share in global investment:

$$\tilde{I}_{i,t} = \frac{I_{i,t}}{\sum_j I_{j,t}} \sum_j S_{j,t}. \tag{13}$$

where $\tilde{I}_{i,t}$ is the country i time t projected world-consistent volume of investment $I_{i,t}$; $\sum_j I_{j,t}$ and $\sum_j S_{j,t}$ are respectively the sum of world investments and savings' volumes.

[15]This value is based on the weighted average of the different fixed capital assets' categories in the Penn World Table, version 9.1. This value is also consistent with the one used in the MIRAGE model that relies on MaGE projections for its dynamic baseline.

1.4 Energy efficiency and energy consumption

Energy is conceived as a function of energy efficiency, GDP and the oil price whose functional form is the result of the firm profit maximization optimality condition obtained as explained in Appendix A. We consider that energy efficiency depends on two main determinants: the distance to the energy productivity frontier and the distance to the income frontier. The distance to the income frontier is often assumed in the empirical literature to follow a U-shaped relationship between economic development and energy efficiency: low-income countries would be more energy efficient because their economies are mainly based on the primary sector; developing countries would use energy intensively during their industrialisation phase, and thus have lower energy efficiency; lastly, the servitization of developed economies would result in an increase in energy efficiency. As we show below, this non-linearity is however not present in our data: energy efficiency accelerates when catching-up countries converge to the income frontier (Stern, 2012).

1.4.1 Data

Energy efficiency data is constructed based on the first order condition of a firm maximization problem as explained in Appendix A:

$$B_{i,t} = \left[\frac{E_{i,t}}{Y_{i,t}} (p_{E,t}^{EIA})^{\sigma} \right]^{\frac{1}{\sigma-1}} \tag{14}$$

Energy consumption data, $E_{i,t}$, are World Bank Energy use (kg of oil equivalent) per \$1000 GDP (at constant 2011 Purchasing Power Parity — PPP) data from 1990 to 2015; GDP data, $Y_{i,t}$, is World Bank GDP series at current USD; oil price data, $p_{E,t}^{EIA}$, are World crude oil, average, \$/bbl series from the World Bank over the period 1960–2030. For estimations, economic development is captured by the income level using GDP per capita constructed as the ratio between the GDP series and Population (UN data series by sex and age, medium variant, 1950-2100). Oil price projections are EIA data on Real Petroleum prices, Crude oil, Brent Spot, Reference price AEO 2020-2019 \$/b from 2019 to 2050.

For estimations, energy efficiency data are corrected for the oil rent of oil producing countries by using corrected GDP series in which oil rents are subtracted from GDP. We refer to the series as the corrected energy productivity $\tilde{B}$.[16] See Appendix A for more details. Oil rents (as a % of GDP) are World Bank data from 1970 to 2017.

1.4.2 Estimation

We estimate a double catch-up model (in growth rates) with respect to the energy-efficiency frontier and the income frontier capturing economic development:

$$\Delta_{log}\tilde{B}_{i,t} = fe + \mu_{distB} \ln\left(\frac{\tilde{B}_{i,t-1}}{\tilde{B}^*_{t-1}}\right) + \mu_{distYcap} \ln\left(\frac{y_{i,t-1}}{y^*_{t-1}}\right) + \epsilon_{i,t} \tag{15}$$

[16] In order to reduce the treat of extreme observations and measurement error in the estimation we use average values of $\tilde{B}$ by region and income for the following economies (iso3 UN codes): ETH, TKM, UZB, ZAR, ZWE, VUT, AFG, GNQ, IRN, KAZ, TTO, BTN, KWT, LBY, OMN, SAU.

where fe are country-year fixed effects; $\frac{B_{i,t-1}}{B^*_{t-1}}$ is the distance to the energy-efficiency frontier ($*$) which is the average of the five most productive countries in each period; and $\frac{y_{i,t-1}}{y^*_{t-1}}$ represents the distance to the income frontier which is defined as the average value of the 5 richest countries in each period.

Table 6 shows the results. As the interaction with low-income countries is not significant, for the projection we use the specification of column 2. The beta coefficients in column 3 show that the two catch up processes are of similar strength.

Table 6: Energy efficiency growth estimation, five-year frequency

Dep Var:	Energy Efficiency, $\Delta_{log}\tilde{B}_{i,t}$		
	(1)	(2)	(3)
$\tilde{B}_{i,t-1}/\tilde{B}^*_{t-1}$	-0.074***	-0.074***	-1.65
	(0.016)	(0.016)	
$GDPpc_{i,t-1}/GDPpc^*_{t-1}$	-0.007	-0.028*	-1.00
	(0.027)	(0.014)	
$GDPpc_{i,t-1}/GDPpc^*_{t-1}$x Low Income	-0.025		
	(0.029)		
N	621	621	
FEs	i t	i t	
Estimator	OLS	OLS	Beta Coeff
Cluster SEs	Region-Income-Year and Country		for Column 2

Notes: The estimation sample covers 129 countries on 5-year intervals over the period 1995-2015. Standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01. Country-year observations with interpolated or extrapolated investment rates are not included in the regression. Projections rely on coefficients from column 2.

1.4.3 Energy efficiency projection

The energy efficiency projections are based on the previously estimated double catch-up model (in growth rates) with respect to the energy efficiency frontier and the income frontier, now modified to account for the average energy efficiency observed over the last five-year period in order to get a sense of the dynamics of the adoption of new − energy efficient − technologies :

$$\Delta_{log}\tilde{B}_{i,t} = \overline{\Delta_{log}\tilde{B}} + \mu_{distB}\Delta \ln\left(\frac{\tilde{B}_{i,t-1}}{\tilde{B}^*_{t-1}}\right) + \mu_{distYcap}\Delta \ln\left(\frac{y_{i,t-1}}{y^*_{t-1}}\right) \tag{16}$$

where $\overline{\Delta_{log}\tilde{B}}$ is the average energy-efficiency observed in the last five-year period of the data; $\frac{B_{i,t-1}}{B^*_{t-1}}$ is the distance to the energy-efficiency frontier ($*$) which is based on the five best performing economies in the last fifteen-year period of the observed data.[17] Consistently, $\frac{y_{i,t-1}}{y^*_{t-1}}$ represents the distance to the income frontier, which is also based on the five best performing economies in the last fifteen-year period of the observed data.[18]. The parameters used in the projections are those of column 2 of Table 6.[19] The energy efficiency level is

[17]The frontier for the last period includes: Denmark, Hong Kong, Ireland, Norway and Switzerland. This is the sample of countries defining the energy-efficiency frontier in the projections.

[18]The frontier for the last period includes: Australia, Denmark, Luxembourg, Sweden and Switzerland. This is the sample of countries defining the income frontier in the projections.

[19]Consistently with the frontiers definition used in the regression, we exclude from the energy frontier sample the small countries

calculated by recursively adding the projected (exponentially transformed) energy efficiency growth rate to the last observed value.

(i.e. below the 25th percentile of workforce distribution); and we exclude from the income frontier the oil-producing countries (i.e. countries whose GDP relies heavily on oil rents, as the 75th percentile of the oil rent variable distribution).

1.4.4 Energy consumption projection

Energy consumption projections are then constructed based on the following firm profit maximization optimality condition:

$$E_{i,t} = Y_{i,t} \frac{B_{i,t}^{\sigma-1}}{p_{E,t}} \tag{17}$$

For oil prices, $p_{E,t}$, we use projections from the Energy Information Administration (EIA) until 2050. From 2050 until 2100 we set the price of energy to increase at a constant rate equal to the average growth rate over the projection period of EIA data. Finally, for energy productivity, $B_{i,t}$, we use the series projected as explained in section 1.4 and for GDP, $Y_{i,t}$, the series projected as explained in Section 1.

1.5 TFP

TFP projections are based on the estimation of a Nelson-Phelps catch-up model to the leader's TFP frontier in which the speed of catch-up is based on secondary and tertiary education. Secondary education is a good indicator of technology diffusion (Benhabib and Spiegel, 1994) and favors imitation-type catch-up, while tertiary education favors innovation (Aghion and Howitt, 1992).[20]

1.5.1 Data

TFP data are constructed as the residual of the CES production function of Equ. 1 expressed by using the definition of energy consumption derived in Section **??**:

$$A_{i,t} = \frac{Y_{i,t}}{K_{i,t}^{\alpha} L_{i,t}^{1-\alpha}} \left[1 - \left(\frac{B_{i,t}}{p_{E,t}^{EIA}} \right)^{\sigma-1} \right]^{\frac{\sigma}{\sigma-1}}. \tag{18}$$

Capital series, $K_{i,t}$, are created as explained in Section 1.3; labour series, $L_{i,t}$, as explained in Section 1.2 and energy productivity, $B_{i,t}$, as explained in Section 1.4. Oil price data are World crude oil, average, \$/bbl series from the World Bank over the period 1960–2030. For the estimations, TFP data are corrected for the oil rent of oil producing countries by using corrected GDP series (in which oil rents are subtracted from GDP) and corrected energy productivity $\tilde{B}$ series. We refer to the series as the corrected TFP $\tilde{A}$. See Appendix A for more details. Oil rents (as a % of GDP) are World Bank data from 1970 to 2017.

For the estimations, human capital variables are the share of the working-age population having a secondary and tertiary diploma. Data are from the Barro & Lee dataset (2018 revision, data from 1950 to 2010) of education attainment for each five-year-age-group. The regional and income division is based on the World Bank Country groups classification of year 2014.

1.5.2 Estimation

TFP estimations are based on the estimation of a Nelson-Phelps catch-up model (in growth rates) with respect to the leader TFP frontier in which the speed of catch-up is based on human capital:

$$\Delta_{log}\tilde{A}_{i,t} = fe + \alpha_{dist} \ln \left(\frac{\tilde{A}_{i,t-1}}{\tilde{A}^*_{t-1}} \right) + \alpha_{tert} h^3_{i,t-1} + \alpha_{dist^2} \ln \left(\frac{\tilde{A}_{i,t-1}}{\tilde{A}^*_{t-1}} \right) \left(h^2_{i,t-1} - h^3_{i,t-1} \right) + \epsilon_{i,t} \tag{19}$$

where $\Delta_{log}\tilde{A}_{i,t}$ is the growth rate of the corrected TFP of country i at period t; fe are income (or region-income) fixed effects; $\ln \left(\frac{\tilde{A}_{i,t-1}}{\tilde{A}^*_{t-1}} \right)$ is the ratio between country i TFP and the leader TFP ($*$); h^3 is the proportion of the working-age population with a tertiary diploma and $\left(h^2_{i,t-1} - h^3_{i,t-1} \right)$ the fraction that has a secondary diploma but not a tertiary diploma. $\tilde{A}^*$ is the leader productivity frontier which is defined as the average value of the five most productive countries in each period.[21] Table 7 shows the results. The signs are as one would have expected: the catch-up effect is being observed, higher education is enhancing productivity, while

[20] Recall that we refer to TFP as the productivity of the capital-labour factor in Equ. 1.

[21] We exclude from the frontier sample the small countries (i.e. below the 25th percentile of workforce distribution) and oil-producing countries (i.e. countries whose GDP relies heavily on Oil rents, as the 75th percentile of the oil rent variable distribution).

secondary education is mitigating the adverse effect of closeness to the frontier. For the projections we retain the specification of column 4 in which all coefficients are significant.

Table 7: TFP estimation results, 5-year intervals

Dep Var:	Total Factor Productivity, $\Delta_{log}\tilde{A}_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
$\frac{\tilde{A}_{i,t-1}}{\tilde{A}^*_{t-1}}$	-0.0223***	-0.0189***	-0.0150***	-0.0146***	-0.571
	(0.005)	(0.005)	(0.004)	(0.004)	
$h^3_{i,t-1}$	0.00680	0.0102	0.0173	0.0323***	0.138
	(0.012)	(0.011)	(0.012)	(0.012)	
$\frac{\tilde{A}_{i,t-1}}{\tilde{A}^*_{t-1}}(h^2_{i,t-1} - h^3_{i,t-1})$	-0.00265	-0.00568	-0.00908*	-0.0135***	-0.258
	(0.004)	(0.005)	(0.005)	(0.004)	
F-stat	258.07	309.74	169.66	456.47	
Hansen P-value	0.82	0.34	0.88	0.82	
N	521	521	519	521	
FEs	Regio-Income	Regio-Income	Regio-Income-Year	Income	Income
Estimator	2SLS	GMM	GMM	GMM	Beta Coeff
Cluster SEs	Region-Income-Year and Country				for column 4

Notes: The estimation sample covers 143 countries on 5-year intervals over the period 1990-2015. Standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01. Country-year observations with interpolated or extrapolated investment rates are not included in the regression. Projections rely on coefficients from column 4.

1.5.3 Projection

TFP projections are based on the estimated catch-up model (in growth rates) with respect to the leader TFP frontier in which the speed of catch-up is based on human capital:

$$\Delta_{log}\tilde{A}_{i,t} = \overline{\nu_i} + \alpha_{dist} \ln\left(\frac{\tilde{A}_{i,t-1}}{\tilde{A}^*_{t-1}}\right) + \alpha_{tert}\left(h^3_{i,t-1}\right) + \alpha_{dist^2} \ln\left(\frac{\tilde{A}_{i,t-1}}{\tilde{A}^*_{t-1}}\right)\left(h^2_{i,t-1} - h^3_{i,t-1}\right) \tag{20}$$

where $\overline{\nu_i}$ is the average TFP growth of country i.[22] Average values of the targeted variable are calculated over the last five-year period of the observed series, i.e. 2012–2017. $\tilde{A}^*$ is the leader TFP frontier which is composed by the average of the 5 most productive countries in the last five-year period of the data.[23]. The coefficients (α_{dist}, α_{dist^2}, α_{tert}) are the results of the estimation of Equ. 19 as reported in column 4 of Table 7. The level of TFP is finally obtained by recursively adding the (exponentially transformed) projected TFP growth rates to the last observed value of TFP.

[22]The $\overline{\nu_i}$ is adjusted as to avoid the risk of a snowball effect of the catching up process.

[23]The frontiers for the last period includes: Australia, Denmark, Ireland, Switzerland, United States. This is the sample of countries defining the frontier in the projections.

1.6 RER and the Balassa-Samuelson effect

So far, we have detailed the methodology for projecting the evolution of GDP at constant 2011 prices. However, it is important to also study the evolution of GDP taking into account valuation effects, as the relative size of countries in terms of markets and financial power also depends on the relative valuation of their income. Therefore, we study here the evolution of GDP at current prices. To do so, we need to model long-run real exchange rates, for which the reference mechanism is the Balassa-Samuelson effect (Balassa (1964), Samuelson (1964)) which relates the appreciation of a currency in real terms to TFP growth differentials in tradable and non-tradable sectors.

1.6.1 Data

For the GDP, we use GDP-PPP in current international dollar, taken from the World Bank over the period 1990–2018. For the real exchange rate, we use the Penn World Table price level of Output-side real GDP (CGDPo) in terms of the USA series for 2011 (data covering the period 1950–2017). Concerning the estimations of the shares of tradable goods in consumption and production, we use the Global Trade Analysis Project (version GTAP10) data on imports and exports by sector and country at World prices and the production and consumption by sector and country at market prices for the year 2014.

1.6.2 Estimation

For estimations we use a model linking the shares of tradable goods in consumption and production to economic development. In detail we estimate two cross-sections (one for tradable goods in consumption c and one for production p) logistic relationships between the tradable shares and PPP GDP-per capita:

$$\ln \frac{\tau^z_{i,t}}{1-\tau^z_{i,t}} = \kappa + \kappa_y \ln y_{i,t} + \epsilon_{i,t} \tag{21}$$

$\tau^z_{i,t}$ with $z = c, p$ is the share of tradable goods respectively in consumption and production. The definition of the tradable share is based on the median threshold observed in the data, sectors whose exports are above the threshold being considered as tradable. $y_{i,t}$ is GDP per capita in country i at time t; κ is a constant and κ_y is the coefficient assessing the elasticity of tradable shares to changes in income. As we can see in Table 8, an increase in PPP GDP per capita tends to reduce the share of tradable goods both in consumption and in production.

1.6.3 Projection

In projection, the shares of tradable goods in consumption and production depend on GDP-per-capita in the following way:

$$\tau^z_{i,t} = \tau^z_{i,t} + \frac{exp(\tau^z_{i,t} + \kappa_y \ln y_{i,t}) - \tau^z_{i,t}}{Trend_t} \tag{22}$$

with $z = c, p$; $Trend_t$ is a linear trend and κ_y is the coefficient resulting from the estimations of the model linking the shares of tradable goods in consumption and production to economic activity.

Table 8: Share of tradable goods estimation

Dep Var:	Consumption (1)	Production (2)
lnYcapPPP	-0.421***	-0.225**
	(0.078)	(0.099)
Constant	3.713***	2.023*
	(0.733)	(1.050)
Obs	176	176
R-sq	0.476	0.285
Cluster SEs	Robust	Robust

Notes: The estimation sample covers a cross-section of 176 countries. Standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01. Regressions are weighted using country consumption (column 1) or production (column 2).

Real exchange rate projections for country i at time t are then expressed as a catch-up model for the capital-labour factor productivity and energy productivity:

$$gRER_{i,t} = \frac{1-\tau^{c}_{i,t}}{\tau^{p}_{i,t}}\left(\mu_{i,t}\, gB_{i,t} + (1-\mu_{i,t})\, gA_{i,t}\right) - \frac{1-\tau^{c,*}_{i,t}}{\tau^{p,*}_{i,t}}\left(\mu^{*}_{i,t}\, gB^{*}_{i,t} + (1-\mu^{*}_{i,t})\, gA^{*}_{i,t}\right) \tag{23}$$

where $\tau^{c}_{i,t}$ is the share of tradables in consumption; $\tau^{p}_{i,t}$ the share of tradables in production; $\mu_{i,t}$ is the share of energy in total production[24]; $gA_{i,t}$ and $gB_{i,t}$ are respectively the growth rate of TFP and of energy productivity computed over the projection period (for the projections of A and B see, respectively, sections 1.5 and 1.4). Real exchange rate projections are computed in deviations from the leader country ($*$) which is the US.

Finally, we project GDP in PPP at constant prices $Y^{PPP,cst}_{i,t}$ by applying the projected growth rate of $Y_{i,t}$ to the actual series, starting in 2011, and we obtain the evolution of GDP at current prices (Y^{crt}) by multiplying $Y^{PPP,cst}$ by the real exchange rate ($RER_{i,t}$):

$$Y^{crt}_{i,t} = RER_{i,t} * Y^{PPP,cst}_{i,t} \tag{24}$$

[24]In detail: $\mu_{i,t} = p^{EIA}_{E,t}\frac{E_{i,t}}{Y_{i,t}}$. $p^{EIA}_{E,t}$ are the EIA oil price projections; $E_{i,t}$ and $Y_{i,t}$ are respectively energy and GDP projection.

2 The world economy 1990-2050

In this section, we present the results of our GDP projections, taking stock of actual changes since 1990. We identify the underlying driving forces, and focus on the evolution of energy consumption to 2050. All the results are available on the EconMap website.

2.1 GDP in volume

Table 9 presents the ranking of countries in terms of GDP volume in 1990, 2020 and 2050 as projected by MaGE. In 1990, the United States was 9 times China in terms of GDP. In 2020, China's GDP represents 75% of the US GDP, China moving from tenth to second place in the world over the period, taking the place of Japan whose GDP represents only 23% of the US GDP compared to 55% in 1990.

In 1990, Germany and France -taken separately- each weighed the equivalent of "two Chinas". In 2020 China weighs more than four times the economic weight of France and three times that of Germany. In 2050, China will have largely surpassed the United States: its economic size will be the double. As illustrated in Figure 2, the expected date of this overtaking is 2027.

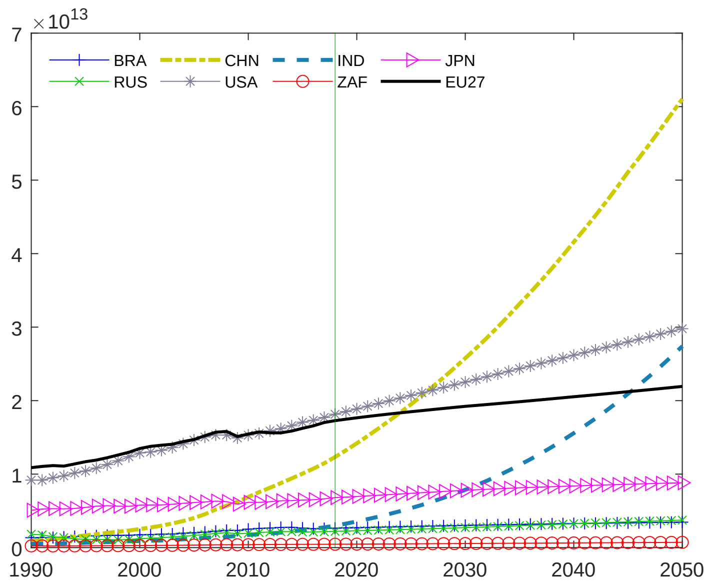
The second major development of the past decade is the emergence of India, which has overtaken its former colonizer in a generation and moved up ten places in international rankings. As it continues to catch up economically, India is expected to become the world's third-largest economy by 2050, with an economic size five times that of the United Kingdom. However, the dynamics of the BRICs (Brazil, Russia, India and China) are heterogeneous. Over the years, Brazil and Russia have lost ground to China and India at a similar pace to that of the European advanced economies.

Table 10 provides a regional picture of these dynamics. Also at the regional level[25] we can clearly see the rise of Asia and in particular of "East Asia & Pacific" over the last generation. This trend is confirmed by the fact that the "East Asia and Pacific" region remains the leading region in terms of GDP volume at the 2050 horizon and by the rise of "South Asia". Another interesting dynamics is given by "Sub-Saharan Africa" which starts to ascend in the ranking. On the side of the regions losing relative importance, "Europe & Central Asia" and "North America" move respectively from first and second rank in 1990 to second and third in 2050.

If we consider the projections not in volumes but including valorization effects (GDP in current USD), the previous results are amplified by the expected appreciation of the Chinese currency in dollar terms. A similar pattern emerges for India (see Appendix C, tables C.4 and C.5). India now overcomes the US and China doubles its size. In terms of PPP per capita income instead, "North America" continues to be the leading region at the 2050 horizon, although—at the country level—China reaches the US in terms of per capita GDP levels in PPP (see Appendix C, tables C.2 and C.3).

[25]The regional grouping is based on the World Bank classification. See Appendix B.

Figure 2: GDP evolution (at constant 2011 USD)



Notes. "BRA" stands for Brazil; "CHN" is China; "IND" is India; "JPN" is Japan; "RUS" is Russia; "USA" is the United States; "ZAF" is South Africa and "EU27" is the European Union with 27 members. *Data source*: Authors' calculations using MaGE 3.1.

Table 9: Long-run projections' ranking of GDP (constant 2011 USD) for the 40 largest economies

	1990		2020			2050		
	Country	10^{12}	Country	10^{12}	Rank	Country	10^{12}	Rank
1	United States	9.19	United States	18.88	=	China	61.03	+1
2	Japan	5.09	China	14.19	+8	United States	29.79	−1
3	Germany	2.73	Japan	6.96	−1	India	27.40	+2
4	France	2.01	Germany	4.36	−1	Japan	8.83	−1
5	Italy	1.87	India	3.56	+10	Germany	5.69	−1
6	Russian Feder.	1.83	U. Kingdom	3.20	+1	U. Kingdom	5.20	=
7	U. Kingdom	1.72	France	3.15	−3	Indonesia	4.95	+9
8	Brazil	1.36	Brazil	2.71	=	France	4.25	−1
9	Canada	1.00	Russian Feder.	2.30	−3	Russian Feder.	3.75	=
10	China	0.94	Italy	2.23	−5	Turkey	3.72	+7
11	Spain	0.92	Canada	2.12	−2	Canada	3.51	=
12	Australia	0.73	Australia	1.76	=	Brazil	3.47	−4
13	Mexico	0.70	Spain	1.62	−2	Nigeria	3.19	+11
14	Netherlands	0.56	Korea, Rep.	1.55	+3	Mexico	3.15	+1
15	India	0.52	Mexico	1.52	−2	Australia	2.99	−3
16	Switzerland	0.51	Indonesia	1.43	+5	Korea, Rep.	2.56	−2
17	Korea, Rep.	0.38	Turkey	1.37	+2	Philippines	1.97	+19
18	Sweden	0.36	Netherlands	1.01	−4	Spain	1.70	−5
19	Turkey	0.35	Saudi Arabia	0.86	+3	Italy	1.70	−9
20	Belgium	0.35	Switzerland	0.81	−4	Thailand	1.43	+8
21	Indonesia	0.35	Iran, Islam. Rep.	0.71	+4	Saudi Arabia	1.40	−2
22	Saudi Arabia	0.34	Poland	0.69	+7	Malaysia	1.31	+10
23	Norway	0.29	Sweden	0.67	−5	Netherlands	1.24	−5
24	Austria	0.28	Nigeria	0.60	+13	Poland	1.18	−2
25	Iran, Islam. Rep.	0.27	Belgium	0.59	−5	Pakistan	1.18	+16
26	Denmark	0.24	Norway	0.59	−3	Egypt, Arab Rep.	1.17	+13
27	Argentina	0.24	Argentina	0.58	=	Vietnam	1.14	+25
28	South Africa	0.24	Thailand	0.52	+10	Switzerland	1.11	−8
29	Poland	0.24	U. Arab Emir.	0.50	+10	Iran, Islam. Rep.	1.08	−8
30	Ukraine	0.23	South Africa	0.48	−2	Sweden	1.00	−7
31	Greece	0.21	Austria	0.48	−9	U. Arab Emir.	1.00	−2
32	Venezuela, RB	0.18	Malaysia	0.46	+19	Kazakhstan	0.99	+14
33	Finland	0.18	Colombia	0.45	+2	Bangladesh	0.99	+21
34	Portugal	0.17	Ireland	0.41	+16	Argentina	0.98	−7
35	Colombia	0.16	Denmark	0.40	−9	Colombia	0.93	−2
36	Czech Republic	0.16	Philippines	0.39	+10	Norway	0.92	−10
37	Nigeria	0.15	Singapore	0.38	+17	Peru	0.86	+11
38	Thailand	0.15	Israel	0.35	+7	Israel	0.84	=
39	U. Arab Emir.	0.14	Egypt, Arab Rep.	0.33	+10	Angola	0.79	+20
40	Romania	0.14	Chile	0.33	+13	Algeria	0.78	+7

Notes. Numbers represent the amount of GDP in trillions (10^{12}) of USD.
Data source: Authors' calculation using MaGE 3.1.

Table 10: Long-run projections' ranking at the regional level: GDP in constant 2011 USD

	1990	2020	2050
1.	Europe & Central Asia	East Asia & Pacific	East Asia & Pacific
2.	North America	Europe & Central Asia	Europe & Central Asia
3.	East Asia & Pacific	North America	North America
4.	Latin America & Caribbean	Latin America & Caribbean	South Asia
5.	Middle East & North Africa	South Asia	Latin America & Caribbean
6.	Sub-Saharan Africa	Middle East & North Africa	Sub-Saharan Africa
7.	South Asia	Sub-Saharan Africa	Middle East & North Africa

Notes: The regions' specification is based on the World Bank region classification.
Data source: Authors' calculation using MaGE 3.1.

2.1.1 Driving forces

Table 11 provides a breakdown of the contribution of each GDP component to growth between 2020 and 2050 for the world's 40 largest economies. The size of India and China increases largely as a result of rapid productivity improvements (+420% and +249% respectively) combined with capital accumulation (+213% and +113% respectively). The economic size of e.g. the United States (+57%), Germany (+30%) and France (+34%) is increasing much less by virtue of catching up, but here too productivity plays an essential role: it explains two-thirds of the growth in France and accounts for all of the growth in Germany, a country in which the accumulation of capital barely offsets the negative contribution of labour. In Japan, the decline in the labour force is too rapid to be offset by capital accumulation, as opposed to Korea or Thailand where capital accumulation remains more dynamic and overcompensate the decline in the labour force.

Beyond BRICs, the spread of technological progress, which increases the efficiency of the combination of capital and labour, thus makes a decisive contribution to the growth of developing countries. Education, which contributes to the efficiency of the labour force, makes it possible to reinforce the gain from strong demographic growth or to limit the consequences of ageing in China. The arrival of Nigeria, Indonesia and Turkey in the world's top 15 in 2050 reminds us that demography is one of the drivers of long-term growth. In the extreme case of Nigeria, labour force growth accounts for a quarter of the growth in the country's economic size over the next generation. Capital accumulation, through investment, also plays an important role, especially if it occurs at a higher rate than labour force growth. A similar relative increase in the ratio of capital per worker is expected in Bangladesh, Indonesia, Iran, Turkey, Malaysia, Philippines, or Vietnam, while capital accumulation does not match the rapid increase in the labour force in Egypt, Pakistan, Angola or Nigeria.

Table 11: Decomposition of the contribution to GDP (constant 2011 USD) growth from 2020 to 2050 of the different components.

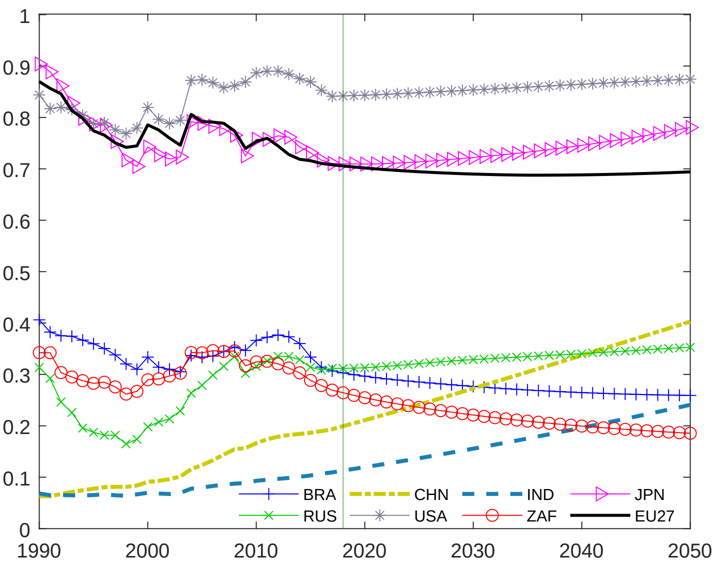
	2020-2050			Contribution to gY			
	Country	gY	Rank	A	K	L	E-fact
1	China	335	+1	+249	+113	−25	−1.5
2	United States	57	−1	+29	+19	+9.1	−0.4
3	India	682	+2	+420	+213	+51	−3.7
4	Japan	26	−1	+38	+8	−20	−0.1
5	Germany	30	−1	+29	+11	−10	−0.2
6	U. Kingdom	62	=	+38	+18	+5.6	−0.1
7	Indonesia	253	+9	+141	+77	+34	−0.8
8	France	34	−1	+24	+11	−0.3	−0.2
9	Russian Feder.	61	=	+66	+12	−16	−1.0
10	Turkey	172	+7	+102	+56	+13	−0.5
11	Canada	65	=	+31	+19	+14	−0.4
12	Brazil	27	−4	+16	+11	+0.1	−0.4
13	Nigeria	525	+11	+222	+144	+159	−1.3
14	Mexico	108	+1	+49	+33	+26	−0.6
15	Australia	69	−3	+24	+23	+21	−0.2
16	Korea, Rep.	65	−2	+57	+25	−16	−0.8
17	Philippines	400	+19	+215	+115	+69	−0.7
18	Spain	5	−5	+19	+7	−21	−0.1
19	Italy	−23	−9	−6.0	−2.1	−15	−0.1
20	Thailand	175	+8	+142	+50	−15	−2.4
21	Saudi Arabia	52	−2	+15	+25	+12	−0.9
22	Malaysia	190	+10	+102	+57	+31	−1.4
23	Netherlands	22	−5	+17	+9.5	−4.4	−0.2
24	Poland	70	−2	+69	+29	−27	−0.3
25	Pakistan	262	+16	+101	+80	+84	−2.1
26	Egypt, Arab Rep.	279	+13	+124	+75	+82	−1.9
27	Vietnam	403	+25	+270	+130	+16	−3.6
28	Switzerland	36	−8	+21	+11	+2.7	−0.08
29	Iran, Islam. Rep.	45	−8	+15	+27	+4.0	−1.4
30	Sweden	49	−7	+24	+15	+9.6	−0.2
31	U. Arab Emir.	109	−2	+80	+41	−11	−1.6
32	Kazakhstan	314	+14	+197	+85	+33	−1.1
33	Bangladesh	333	+21	+192	+104	+37	−1.5
34	Argentina	68	−7	+29	+20	+19	−0.6
35	Colombia	108	−2	+58	+36	+15	−0.3
36	Norway	54	−10	+23	+17	+12	−0.1
37	Peru	230	+11	+123	+69	+38	−0.8
38	Israel	138	=	+45	+43	+49	−0.2
39	Angola	761	+20	+347	+162	+251	−0.7
40	Algeria	238	+7	+134	+63	+43	−2.7

Notes: Numbers represent the amount of GDP in trillions (10^{12}) of USD; the ranking ("Rank") refers to the change in the ranking from 2020 to 2050. The contributions of the different components of GDP to GDP growth (gY) from 2020 to 2050 are expressed in % points. "E-fact" stands for the energy term in brackets in equation 2.
Data source: Authors' calculation using MaGE 3.1.

2.1.2 Capital-Labour productivity

We can now dive into the dynamics of the TFP of the KL bundle. Figure 3 illustrates the expected differences in the productivity of the capital-labour mix for the economies represented in Figure 2. The vertical axis shows the ratio of each country's TFP to the "frontier" corresponding to the five most productive countries at each date (i.e., the frontier shifts over time). We observe that the United States, Japan and the European Union maintain a high level of labour and capital productivity, which may reflect the circulation of technologies and ideas between these economies. However, the dynamics is less favorable for the EU, which is steadily losing ground relative to the technology frontier. The divergence with Japan over the next generation is particularly striking. As for the other countries represented here, China, as expected, and other developing countries like India, are moving closer to the technology frontier, helping to boost their GDP. This catching-up will however not make the frontier reachable for these countries by 2050. This reflects the heterogeneity of China's technological progress across its provinces, and the fact that India is making great progress but from a very low base. This contrasts with Russia, where catching up seems to have been halted by the global financial crisis. Finally, it should be noted that technological catch-up is not systematic, as illustrated by the cases of Brazil and South Africa in this chart.

Figure 3: Total factor productivity , A, relative to the frontier A^*



Notes: "BRA" stands for Brazil; "CHN" is China; "IND" is India; "JPN" is Japan; "RUS" is Russia; "USA" is the United States; "ZAF" is South Africa and "EU27" is the European Union with 27 members.
Data source: Authors' calculations using MaGE 3.1.

2.2 Energy consumption and efficiency

Large economies with dynamic demographics and growing purchasing power will put increasing pressure on the world's resources. This pressure is multidimensional: it concerns the use of raw materials, land for food, energy, emissions of greenhouse gases and pollutants, and waste. Energy consumption, the result of economic activity and energy efficiency, is a good summary of this environmental impact of growth.

Table 12 compares energy consumption growth to GDP growth for the period 2020-2050 (in relative terms to global consumption). It clearly shows that some countries are expected to gradually decouple their GDP growth from energy consumption. For the United States, energy consumption will account for nearly 8% of global energy consumption in 2050, compared to nearly one-quarter in 1990 (the country will account for 13% of global GDP at that time). Japan will follow the same trend of increasing energy efficiency. European and Central Asian countries will also decrease the pressure on resources' consumption over the next generation (see Appendix D Table D.7) while maintaining the same relative position in terms of GDP (see Table 10), therefore increasing their energy efficiency.

For developing countries instead the pressure on resources will increase considerably over the next generation. With China followed by India as the first and second users of resources. China is also increasing its energy efficiency, but the growth of its GDP is such that this country will consume more than a third of the world's energy within a generation. Conversely, Nigeria will only account for 1.4% of world GDP while consuming 1.7% of the world's energy in 2050. At the regional level, the growing pressure on resources will come from Asia ("South Asia" and "East Asia & Pacific"), and the emergence of the "rest of the world" as one of the largest consumers, in this case "Sub-Saharan Africa".

The model takes into account all energy consumed, fossil or renewable, and the doubling of energy consumption at the global level within a generation should not be interpreted as a doubling of greenhouse gas emissions. The projections summarized here will only be sustainable if the energy on which the future growth of the economies is based is largely decarbonized. Given the projected volume of energy consumption, and considering climate imperatives, an intensification of technology sharing at the international level is critical in order to decouple economic growth from energy consumption.

Table 12: Energy consumption's growth and GDP growth as a share of the world

	1990			2020			2050		
	Country	$\frac{E_i}{E_{tot}}$	$\frac{Y_i}{Y_{tot}}$	Country	$\frac{E_i}{E_{tot}}$	$\frac{Y_i}{Y_{tot}}$	Country	$\frac{E_i}{E_{tot}}$	$\frac{Y_i}{Y_{tot}}$
1	United States	23.50	22.73	China	25.80	15.09	China	34.82	27.44
2	Russian Feder.	10.79	4.52	United States	15.96	20.07	India	21.58	12.32
3	China	10.69	2.32	India	8.48	3.79	United States	7.79	13.39
4	Japan	5.38	12.58	Russian Feder.	4.78	2.44	Russian Feder.	2.26	1.69
5	Germany	4.31	6.76	Japan	3.03	7.40	Indonesia	1.87	2.23
6	India	3.75	1.30	Germany	2.18	4.63	Nigeria	1.66	1.43
7	Ukraine	3.09	0.58	Korea, Rep.	2.11	1.64	Japan	1.18	3.97
8	France	2.75	4.96	Brazil	2.08	2.88	Thailand	1.15	0.64
9	Canada	2.59	2.48	Canada	1.97	2.26	Korea, Rep.	1.15	1.15
10	U. Kingdom	2.53	4.25	Indonesia	1.79	1.52	Vietnam	1.06	0.51
11	Italy	1.80	4.62	France	1.69	3.35	Canada	1.00	1.58
12	Brazil	1.72	3.35	Mexico	1.43	1.62	Mexico	0.98	1.42
13	Mexico	1.52	1.74	U. Kingdom	1.22	3.41	Brazil	0.93	1.56
14	Indonesia	1.21	0.85	Iran	1.17	0.75	Turkey	0.91	1.67
15	Korea, Rep.	1.14	0.95	Thailand	1.17	0.56	Germany	0.88	2.56
16	South Africa	1.12	0.59	Turkey	1.04	1.45	Pakistan	0.86	0.53
17	Spain	1.11	2.27	South Africa	1.03	0.51	Uzbekistan	0.74	0.31
18	Australia	1.06	1.80	Italy	0.98	2.37	Cote d'Ivoire	0.73	0.30
19	Kazakhstan	0.90	0.29	Nigeria	0.95	0.63	Egypt	0.73	0.53
20	Iran	0.85	0.67	Australia	0.90	1.88	Malaysia	0.71	0.59
21	Nigeria	0.82	0.38	Spain	0.82	1.73	France	0.71	1.90
22	Netherlands	0.81	1.39	Pakistan	0.74	0.35	Iran	0.59	0.48
23	Romania	0.76	0.33	Malaysia	0.73	0.49	Philippines	0.59	0.89
24	Saudi Arabia	0.71	0.84	Poland	0.68	0.73	Tanzania	0.58	0.23
25	Turkey	0.65	0.88	Saudi Arabia	0.64	0.92	U. Kingdom	0.57	2.34
26	Czech Rep.	0.61	0.39	Argentina	0.64	0.61	Algeria	0.55	0.35
27	Belgium	0.59	0.86	U. Arab Emir.	0.63	0.53	South Africa	0.51	0.32
28	Sweden	0.58	0.89	Vietnam	0.61	0.25	U. Arab Emir.	0.50	0.45
29	Uzbekistan	0.57	0.07	Ukraine	0.59	0.15	Kazakhstan	0.48	0.44
30	Argentina	0.57	0.59	Egypt	0.57	0.35	Australia	0.47	1.34
31	Belarus	0.56	0.08	Netherlands	0.50	1.07	Bangladesh	0.47	0.44
32	Pakistan	0.53	0.23	Algeria	0.43	0.29	Ethiopia	0.44	0.17
33	Thailand	0.51	0.38	Iraq	0.42	0.32	Iraq	0.42	0.32
34	Venezuela	0.49	0.45	Philippines	0.41	0.42	Saudi Arabia	0.36	0.63
35	Egypt	0.40	0.23	Uzbekistan	0.39	0.11	Argentina	0.35	0.44
36	Philippines	0.35	0.25	Kazakhstan	0.39	0.29	Poland	0.33	0.53
37	Finland	0.35	0.44	Belgium	0.37	0.63	Kenya	0.33	0.14
38	Bulgaria	0.35	0.10	Sweden	0.35	0.71	Congo, DR	0.32	0.13
39	Austria	0.31	0.69	Bangladesh	0.33	0.24	Papua NG	0.27	0.12
40	Switzerland	0.30	1.26	Qatar	0.31	0.25	Spain	0.27	0.77

Notes: Energy consumption is measured in kg of oil equivalent per 1000 USD. GDP is in constant USD of 2011. Both series are presented as a share (%) of the world (E_{tot}, Y_{tot}) and countries i are ordered by their use of energy.
Data source: Authors' calculation using MaGE 3.1.

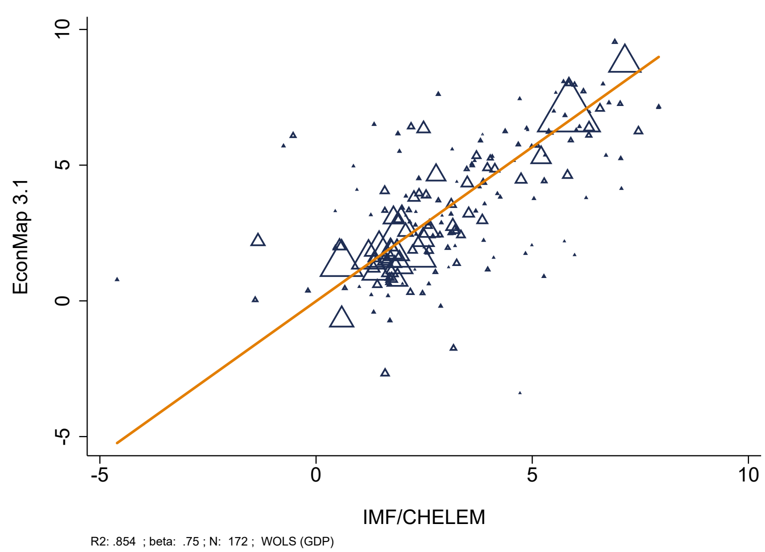
3 Discussion

In this section, we first compare our GDP and energy consumption projections with those of related studies. We then discuss the potential impact of the COVID-19 crisis and of climate change on the projections. Finally, we assess the sensitivity of our results to different assumptions about the elasticity used to calibrate the production function.

3.1 Short-run projections' comparison

We begin by presenting a short-term comparison of our projections with the International Monetary Fund (IMF) *forecasts*, although the two exercises are indeed very different in nature. The question is therefore whether the short-term dynamics of the model, given the information available at the time of the model estimation, can reproduce the short-term developments of the economies. Recall that the last year of data used to estimate all the parameters needed for our projections is before the COVID-19 crisis. Consistently, we rely here on the forecasts made by the IMF before the Pandemic. The time horizon (years 2019–2024) is chosen by the data availability on the IMF projections that are based on the short-run projections of countries' GDP. The size of the triangles in Figure 4 represents the (average) size of countries in terms of GDP. The correlation between our projections and IMF forecasts is of 0.75. This suggests that, although the construction and underlying assumptions of the MaGE model give it a long-term orientation, its results compare fairly well with short-term forecasts, confirming the adequacy of the starting point of MaGE trajectories.

Figure 4: GDP growth rates' comparison between MaGE 3.1 results and IMF forecasts, years 2019–2024



Notes: Authors' calculation using MaGE 3.1 and IMF World Economic Outlook, July 2019 (CEPII CHELEM,). The size of triangles is proportional to the size of countries' annual (average) GDP.

3.2 Long-run projections' comparisons

This section compares our long-term GDP projections with those of four related studies, before benchmarking our projections of energy consumption with those of the International Energy Agency (IEA).

3.2.1 GDP

We compare our long-term GDP projections with the one of the OECD (2018), HSBC (2018), PWC (2017), The Economist Intelligence Unit (2015) and with the previous release of the MaGE model. This is done in Table 13. The top five rows compare the rankings for the year 2050; the next five rows show this comparison for 2030; the last rows give the rankings at the closest date to the start of projections, namely 2020 for our projections with MaGE 3.1. The other dates are 2012 for MaGE 2.4, 2014 for The Economist, 2016 for PWC, 2018 for HSBC and 2020 for the OECD.

As with the 2.4 release of the MaGE model, the United States are expected to be in the second place in 2050 in terms of GDP, followed by India. This is also the case in the projections published by The Economist (see Table 13). In contrast, the OECD and PWC position India ahead of the United States in this time frame. As explained in Table 13, these two sets of studies consider different measures of GDP: GDP in volume (constant USD) as opposed to GDP in Purchasing Power Parity, which can explain the diverging projections. Additionally, we are less optimistic about Indonesia than the OECD, PWC or The Economist, because factors other than demography weigh more heavily on our forecast, such as education and energy efficiency.

Table 13: Long-run GDP projections ranking comparisons with other studies

		MaGE 2.4	MaGE 3.1	OECD	HSBC	PWC	The Economist
	1.	China	China	China		China	China
	2.	US	US	India		India	US
Ranking 2050	3.	India	India	US		US	India
	4.	Japan	Japan	Indonesia		Indonesia	Indonesia
	5.	UK	Germany	Japan		Brazil	Japan
	1.	US	China	China	China	China	
	2.	China	US	US	US	US	
Ranking 2030	3.	Japan	India	India	India	India	
	4.	India	Japan	Japan	Japan	Japan	
	5.	UK	Germany	Indonesia	Germany	Indonesia	
	1.	US	US	China	US	China	US
	2.	Japan	China	US	China	US	China
Ranking at	3.	China	Japan	India	Japan	India	Japan
projection date*	4.	Germany	Germany	Japan	Germany	Japan	Germany
	5.	UK	India	Germany	UK	Germany	UK
Variable		$GDP_{\$2005}$	$GDP_{\$2011}$	$GDP^{PPP}_{\$2010}$	$GDP_{\$2018}$	$GDP^{PPP}_{\$2016}$	$GDP_{\$}$
Year of the study		2012	2021	2018	2018	2017	2015
Horizon projections		2050	2100	2060	2030	2050	2050

Notes: "Ranking at projection date" refers to year 2012 for MaGE 2.4; 2020 for MaGE 3.1 and the OECD; 2018 for HSBC; 2016 for PWC and 2014 for The Economist. *For the OECD the results are reported for 2020, although the study was done in 2018 and reports data every 10 years.
Data source: Econmap 2.4, authors' calculation using MaGE 3.1., OECD (2018), HSBC (2018), PWC (2017) and The Economist Intelligence Unit (2015).

3.2.2 Energy consumption

We now compare the energy consumption in our projections with those of the IEA (IEA, 2020).

These energy consumption projections are consistent, predicting respective shares of 43.3% for Asia-Pacific, 15.4% for North America, 10.2% for Europe and 7.6% for Africa by 2040. These projections invite us to think about climate issues from a broader perspective than Europe, the United States, Japan or even China. The challenge for the next Climate Change Conferences (COPs) will be to find mechanisms for international cooperation to ensure that our energy consumption projections do not result in the use of fossil fuels.

Table 14: Long-run Energy consumption projections ranking comparisons with other studies

MaGE 2.4		MaGE 3.1		IEA	
Regions	%	Regions	%	Regions	%
East Asia & Pacific	45	East Asia & Pacific	44.1	Asian-Pacific	43.3
Europe & Central Asia	15.8	South Asia	23.1	North America	15.4
South Asia	11.2	Europe & Central Asia	9.6	Europe	10.2
North America	9.9	North America	8.7	Africa	7.6
Sub-Saharan Africa	8.4	Sub-Saharan Africa	6.7	Middle-East	6.9
Latin America & Caribbean	5.4	Middle East & North Africa	3.8	Euroasia	5.8
Middle East & North Africa	3.6	Latin America & Caribbean	3.6	Latin America	5.3
Year of the study	2012	2021		2020	
Horizon projections	2050	2100		2040	

Notes: The numbers represent the percentage of energy consumed by a region as a percentage of world energy consumption.
Data source: Authors' calculation using MaGE 3.1 and on the IEA (2020).

3.3 Factors that are not included in the projection

The COVID-19 crisis – both a supply and demand shock – has led to the sharpest contraction of the world economy since the Second World War, and it would be unwise to assume that COVID-19 will not have implications for long-term growth. But beyond the evidence of a fairly strong rebound in the global economy, it is difficult to know at this stage what the long-term impact will be. Firms will have to rethink their value chains to make them more resilient; new technologies (teleworking, robotics, artificial intelligence, connected factory, e-commerce, 3D printing) that companies were reluctant to adopt have become widespread, likely to lead to strong productivity gains. Conversely, a rise in uncertainty could lead economic agents to adopt a wait-and-see attitude, particularly with regard to investment. The change in perception of uncertainty – epidemics are much more likely than previously thought – can be represented as a decline in productivity and rapid obsolescence of installed capital. The cumulative effects on long-term growth would, under this assumption, be a multiple of the effects of the COVID-19 crisis *per se* (Kozlowski et al., 2020). Similarly, hysteresis effects of the crisis cannot be ruled out if the disappearance of companies did not mainly affect the least efficient (Caballero and Hammour, 1994) but favoured the survival of the latter because of accommodating financing (Caballero et al., 2008). The net effect on the long-term path of these different factors is indeed a matter of conjecture. On the other hand, our projections are neither economic forecasts nor expert opinions; they consider a horizon where the effects of temporary shocks will have been absorbed by the economies. For all these reasons, and keeping in mind the exact nature of our exercise, we decide not to include—at this stage—any conjecture on the long-term implications of the current health crisis.

Another clarification to be made is about the economic consequences of climate change at the horizon considered here. Economic activity and energy consumption are tightly linked, although CO_2 emissions may be progressively disconnected from energy consumption in the long run thanks to abatement policies. The feedback effect of climate on growth can be introduced in growth models, and is actually introduced in integrated assessment models using damage functions mapping the response of climate models to greenhouse gas (GHG) emissions into economic impacts. There is however considerable uncertainty about the magnitude of these costs, and the more so that the permanent impact of climate change on economic activity should take into account extreme events with low probability, as evidenced by the occurrence of tropical cyclones (Hsiang and Jina, 2014). According to Auffhammer (2018) the damage functions used in integrated models are "outdated" and based on estimation methods raising identification issues. For example, regressing GDP growth rates across countries on temperature fluctuations to extrapolate the impact of future global warming on global productivity is only valid under the assumption that the intensity of adaptation efforts does not increase with rising temperatures.[26] Against this background, the present projections are based on rather conservative choices. The model we rely on projects GDP, energy use as an aggregate[27] and energy efficiency.[28] In the absence of a damage function,

[26]Burke et al. (2015) conclude that "If future adaptation mimics past adaptation, unmitigated warming is expected to reshape the global economy by reducing average global incomes roughly 23% by 2100"

[27]We use World Bank data on total energy use in kg of oil equivalent originating from International Energy Agency (IEA).

[28]A distinction is to be made between energy intensity of the GDP and energy efficiency. While energy intensity is the ratio of energy consumption to GDP, energy efficiency is a more encompassing concept accounting for country characteristics (Agency, 2014). In IEA words " a small service-based country with a mild climate would certainly have a much lower intensity than a large industry-based country in a very cold climate, even if energy is more efficiently consumed in this country than in the first" (op.cit. p. 19). In MaGE, energy intensity is a function of energy efficiency, the energy price and the elasticity of substitution between

and for a given level of energy efficiency, an increase in the energy price is curbing the perspectives of GDP growth. In turn, projected energy efficiency has its own dynamics driven by the estimated catching up to the energy frontier (the most energy efficient countries) and the income frontier.

3.4 Sensitivity

In this section we finally provide a sensitivity on the elasticity of substitution between the composite capital-labour factor and the energy factor, which is a key parameter of our model. In Table 15 we compare the country rankings and GDP in 2050 obtained in our baseline estimations with an elasticity of 0.15, with two alternative values: 0.10 and 0.20. As the table shows, GDP projections are not very sensitive to such alternative parametrization.

energy and the labour-capital bundle.

Table 15: GDP projections (constant 2011 USD) at horizon 2050 for different σ

	Baseline $\sigma = 0.15$		$\sigma = 0.10$		$\sigma = 0.20$	
	Country	10^{12}	Country	10^{12}	Country	10^{12}
1	China	61.03	China	61.24	China	60.75
2	United States	29.79	United States	29.84	United States	29.71
3	India	27.40	India	27.58	India	27.16
4	Japan	8.83	Japan	8.83	Japan	8.82
5	Germany	5.69	Germany	5.70	Germany	5.68
6	U. Kingdom	5.20	U. Kingdom	5.20	U. Kingdom	5.19
7	Indonesia	4.95	Indonesia	4.96	Indonesia	4.94
8	France	4.25	France	4.25	France	4.24
9	Russian Feder.	3.75	Russian Feder.	3.76	Russian Feder.	3.73
10	Turkey	3.72	Turkey	3.73	Turkey	3.71
11	Canada	3.51	Canada	3.52	Canada	3.50
12	Brazil	3.47	Brazil	3.47	Brazil	3.45
13	Nigeria	3.19	Nigeria	3.19	Nigeria	3.18
14	Mexico	3.15	Mexico	3.16	Mexico	3.14
15	Australia	2.99	Australia	2.99	Australia	2.98
16	Korea, Rep.	2.56	Korea, Rep.	2.57	Korea, Rep.	2.55
17	Philippines	1.97	Philippines	1.97	Philippines	1.97
18	Spain	1.70	Spain	1.71	Spain	1.70
19	Italy	1.70	Italy	1.70	Italy	1.70
20	Thailand	1.43	Thailand	1.45	Thailand	1.42
21	Saudi Arabia	1.40	Saudi Arabia	1.40	Saudi Arabia	1.40
22	Malaysia	1.31	Malaysia	1.31	Malaysia	1.30
23	Netherlands	1.24	Netherlands	1.24	Netherlands	1.24
24	Poland	1.18	Pakistan	1.18	Poland	1.18
25	Pakistan	1.18	Poland	1.18	Pakistan	1.17
26	Egypt, Arab Rep.	1.17	Egypt, Arab Rep.	1.18	Egypt, Arab Rep.	1.17
27	Vietnam	1.14	Vietnam	1.15	Vietnam	1.12
28	Switzerland	1.11	Switzerland	1.11	Switzerland	1.11
29	Iran, Islam. Rep.	1.08	Iran, Islam. Rep.	1.08	Iran, Islam. Rep.	1.07
30	Sweden	1.00	Sweden	1.00	Sweden	1.00
31	U. Arab Emir.	1.00	U. Arab Emir.	1.00	U. Arab Emir.	0.99
32	Kazakhstan	0.99	Bangladesh	0.99	Kazakhstan	0.98
33	Bangladesh	0.99	Kazakhstan	0.99	Bangladesh	0.98
34	Argentina	0.98	Argentina	0.98	Argentina	0.97
35	Colombia	0.93	Colombia	0.93	Colombia	0.93
36	Norway	0.92	Norway	0.92	Norway	0.92
37	Peru	0.86	Peru	0.86	Peru	0.85
38	Israel	0.84	Israel	0.84	Israel	0.84
39	Angola	0.79	Angola	0.79	Angola	0.79
40	Algeria	0.78	Algeria	0.79	Algeria	0.78

Notes: Numbers represent the amount of GDP in trillions (10^{12}) of USD.
Data source: Authors' calculation using MaGE 3.1.

4 Conclusion

In this paper, we have studied the long-term structural relationships that determine the growth of the world economy to 2050. To do so, we have re-estimated the MaGE model with updated database and methods. The projections obtained with the new estimates show a picture of a changing world, in which China and India clearly assert their position as leading economies. China is expected to overtake the US by 2027. By which time other South Asian countries and, for the first time, some sub-Saharan African countries would move up the world rankings to the top. The drivers of these changes are the dynamics of demography, but also the spread of technological progress - which increases the efficiency of the combination of capital and labour - and the dynamism of capital investment.

While Europe, Japan and to a lesser extent the United States will sharply reduce their relative energy consumption over the next generation, the large developing economies with a dynamic demography and a growing purchasing power will instead exert an increasing pressure on global resources. This is particularly true for the fast growing economies of Asia and sub-Saharan Africa, whose energy consumption is set to increase considerably despite progress in energy efficiency. If the growth projected by MaGE is to be compatible with acceptable global warming, a rapid switch to non-fossil fuels is imperative.

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A Firms optimization

In this section we borrow tightly from the calculations in Fouré et al. (2012). Energy consumption projections are based on the optimality condition for energy of a firm maximising its profits (π) given the CES production function of equation 1, that we rewrite considering a combined factor of capital and labour $Q = K^{\alpha}L^{1-\alpha}$. The problem reads:

$$\begin{aligned} \max \quad & \pi = Y - p_E E - p_Q Q \\ \text{s.t.} \quad & Y^{\rho} = (AQ)^{\rho}\,(BE)^{\rho} \end{aligned}$$

where $\rho = \frac{\sigma-1}{\sigma}$, p_E and p_Q, are respectively the real prices of energy and of the combined factor Q and the budget constraint is the cost function the firm is facing. The first order condition[29] for this problem is:

$$\frac{E}{Q} = \left[\frac{p_Q}{p_E}\frac{B}{A}^{\rho}\right]^{\sigma}. \tag{A.1}$$

If we substitute equation A.1 into the budget constraint and in the expression of profits we obtain:

$$\begin{aligned} Y^{\rho} &= \left(\frac{p_E}{B^{\rho}}\right)^{\sigma-1} E^{\rho}\left[(B^{\rho})^{\sigma}p_E^{1-\sigma} + (A^{\rho})^{\sigma}p_Q^{1-\sigma}\right] \\ Y &= \left(\frac{p_E}{B^{\rho}}\right)^{\sigma} E^{\rho}\left[(B^{\rho})^{\sigma}p_E^{1-\sigma} + (A^{\rho})^{\sigma}p_Q^{1-\sigma}\right] \end{aligned}$$

If we divide the second equation by the first we obtain:

$$Y^{1-\rho} = \frac{p_E}{B^{\rho}}E^{1-\rho} \tag{A.2}$$

that re-arranged yields the optimality condition for energy consumption, equation 17 in the text:

$$E = Y\frac{B^{\sigma-1}}{p_E}. \tag{A.3}$$

Re-expressed for energy productivity, B, yields equation 14 and substituted in equation 1 yields equation 2.

[29] The first order conditions of the problem are two:

$$\begin{aligned} \lambda\rho A^{\rho}Q^{\rho-1} &= p_Q \\ \lambda\rho B^{\rho}E^{\rho-1} &= p_E \end{aligned}$$

by removing the Lagrangian multiplier λ the problem boils down to equation A.1.

A.0.1 The case of oil producers

For oil producing countries we consider a measure of GDP that is corrected for oil rents and that we refer to as the corrected-GDP, $\tilde{Y}$:

$$\tilde{Y} = Y - oilrent, \tag{A.4}$$

The corresponding corrected-TFP and the corrected-energy productivity are computed using $\tilde{Y}$:

$$\tilde{B}_{i,t} = \left[\frac{E_{i,t}}{\tilde{Y}_{i,t}} p_{E,t}^{\sigma} \right]^{\frac{1}{\sigma-1}}$$

$$\tilde{A}_{i,t} = \frac{\tilde{Y}_{i,t}}{K_{i,t}^{\alpha} L_{i,t}^{1-\alpha}} \left[1 - \left(\frac{\tilde{B}_{i,t}}{p_{E,t}} \right)^{\sigma-1} \right]^{\frac{\sigma}{\sigma-1}}$$

This variables' specification is used in all the estimations to avoid biases in the productivity measures due to the strength of the oil sector.

Each component is then projected based on these estimations and corrected measures. Only at the end, oil rents are added back to obtain the final projection of GDP and of each of its components for all countries.

B Data sources and database construction

This appendix details all the data used in MaGE 3.1 and their sources. Eventual changes with respect to MaGE 2.4 and the complete database are available on the EconMap website.

B.1 Database construction

In this section we explain the way we transform the raw data to construct a coherent and homogeneous database with reference year 2011 and reference currency the USD. Notice that unless differently stated, we work with an unbalanced panel without filling the missing values.[30] Data treatment is flexibly coded into the replication programs, available online, and can be relaxed or modified from the *Master.do* file.

Series numbers refers to Table B.1.

1. **Oil prices** Historical nominal oil price series (series 1.d) are deflated using the GDP implicit price deflator (series 11) using 2011 as reference year. Oil prices projections (series 1.a in the baseline and 1.b-1.c in the scenarios) are linked to historical series (manipulated as explained in the previous point) by computing and adding the growth rate of the projection period (respectively reference and scenarios) to the last observed values of the historical series. The values from 2050 until 2100 are obtained by prolonging the trend over the projection period constructed as explained before. For MIRAGE, data from 2002 to 2019 is smoothed using a cubic Hermite interpolation.

2. **Oil rents** No transformations.

3. **Energy consumption** When Energy consumption data is missing we interpolate it based on GDP data at the country level if possible, otherwise pooling at the region-income level with country fixed effects, otherwise simply pooling at the country-income level, depending on data availability. Energy consumption data are re-aligned on MaGE 2.4 1995 values, by adding the growth rate of the actual series' growth rates.

4. **GDP** GDP series in the database are constructed by using as reference series GDP at current prices for the year 2011 (series 4.b) and adding backward and forward its growth rate (series 5.a). If the values for the series 5.a are missing we fill it through a simple interpolation using series 4.c in growth rates; if also missing using series 5.b. GDP per capita is constructed by dividing these series of GDP by UN population data (series 6.a). GDP-PPP per capita is constructed by dividing the GDP, PPP in current international $ data (series 4.a) by UN population data (series 6.a).

5. **GDP growth** No transformations for series 5.a-b.

6. **Population** No transformations for series 6.a-b-c-d.

7. **Activity rate** No transformations for series 7.a-b.

8. **Education** No transformations.

[30] Given the incidence of missing and/or extreme observations we calibrate savings and investments of Nigeria on Angola before the year 2008.

9. **Capital, Savings** Investment series are constructed by multiplying the investment rate (the growth rate of the previous series) by World Bank GDP series at current USD (series 9.a).

   To construct the capital stock series we use the Penn World Table capital stock data at constant 2011 prices (series 9.d) and apply the permanent inventory method as explained in section 1.3 using the depreciation rate value explained in the text and the investment series constructed as described before. The starting year depends on the first available year in the data, for most countries it is 1960. Where data on the capital stock is missing, we interpolate it based on GDP data (constructed as explained at point 4.) at the country level if possible, otherwise pooling at the region-income level with country fixed effects, otherwise simply pooling at the country-income level, depending on data availability. For ten countries we are obliged to impute the initial level of their capital stock as 2.6 times their GDP (according to the average capital-output ratio in the database). These countries are flagged in the final database.

10. **Real exchange rates** No transformations.

11. **GDP deflator** No transformations.

12. **Traded sectors** No transformation for series 12.a-b-c-d.

13. **Region and income** No transformations.

B.2 Data sources

All the data sources are detailed in table B.1.

Table B.1: MaGE 3.1 database

Variable needed	Source	Variable name	Time span
1. Oil prices	Energy Information Administration	a) Real Petroleum Prices : Crude Oil : Brent Spot, Reference, AEO2020 - 2019 $/b b) Real Petroleum Prices : Crude Oil : Brent Spot, High price, AEO2020 - 2019 $/b c) Real Petroleum Prices : Crude Oil : Brent Spot, Low price, AEO2020 - 2019 $/b	2019-2050
	World Bank	d) Crude oil, average, nominal, $/bbl - World	1960-2030
2. Oil rents	World Bank (WDI)	Oil rents (% of GDP)	1970-2017
3. Energy consumption	World Bank	Energy use (kg of oil equivalent) per $1,000 GDP (constant 2011 PPP)	1990-2015
4. GDP	World Bank	a) GDP, PPP (current international $) b) GDP (current USD)	1990-2018
	CEPII (chelem)	c) GDP in $ constant prices 2011	1960-2020
5. GDP growth	World Bank	a) GDP growth (annual %)	1961-2018
	IMF (weo)	b) GDP growth, constant prices (annual %)	1980-2024
6. Population	United Nations	a) Population by Age and Sex, Medium variant b) Population by Age and Sex, Other variants	1950-2100
		c) Death by age groups both sexes	1950-2020
	International Labour Organization	d) Population by sex and age -UN estimates and projections	1990-2030
7. Activity rate	International Labour Organization	a) Labour force participation rate by sex and age (%)	1946-2019
		b) Labour force participation rate by sex and age (%) - ILO estimates July 2019	1990-2030
8. Education	Barro & Lee dataset (2018 update)	Education attainment by Five-year Age Group	1950-2010
9. Capital, Savings	World Bank	a) Gross capital formation (% of GDP) b) Gross fixed capital formation (% of GDP) c) Gross domestic savings (% of GDP)	1960-2018
	University of Groningen, PWT table 9.1	d) Capital stock at constant 2011 national prices	1950-2017
10. Real exchange rates	University of Groningen, PWT table 9.1	Price level of CGDPo (PPP/XR), price level of USA CGDPo in 2011=1	1950-2017
11. GDP deflator	FRED, Saint Louis FED	Gross Domestic Product: Implicit Price Deflator	1947-2019
12. Traded sectors	Global Trade Analysis Project (GTAP 10)	a) Imports by sector and country at the World prices b) Exports by sector and country at the World prices c) Production by sector and country at the Agent prices d) Consumption by sector and country at the Market prices	2014
13. Region and income	World Bank	Country and Lending Groups classifications	2018

C Other measures of GDP

C.1 GDP per capita

Table C.2 presents the ranking of economies for GDP per capita in terms of purchasing power parity (PPP). Table C.3 presents the same ranking aggregated at the regional level.

Table C.2: Long-run GDP per capita projections' ranking, in 2011 PPP

	1990		2020			2050		
	Country	10^3	Country	10^3	Rank	Country	10^3	Rank
1	U. Arab Emir.	112	Qatar	123	+1	Qatar	172	=
2	Qatar	86	Macao, China	109	+6	Singapore	138	+2
3	Brunei	85	Luxembourg	102	+1	U. Arab Emir.	138	+2
4	Luxembourg	58	Singapore	92	+6	Luxembourg	128	−1
5	Switzerland	49	U. Arab Emir.	72	−4	Macao, China	126	−3
6	Norway	43	Brunei	72	−3	Turkmenistan	103	+55
7	Saudi Arabia	43	Ireland	71	+27	Ireland	102	=
8	Macao, China	40	Norway	67	−2	Malta	96	+14
9	United States	36	Kuwait	63	+18	Hong Kong	87	+2
10	Singapore	35	Switzerland	60	−5	Norway	86	−2
11	Bahrain	35	Hong Kong	59	+18	China	80	+66
12	Oman	35	United States	57	−3	Lithuania	79	+25
13	Denmark	34	Iceland	53	+10	United States	79	−1
14	Netherlands	32	Netherlands	51	=	Estonia	76	+24
15	Germany	32	Saudi Arabia	51	−8	Iceland	75	−2
16	Austria	31	Denmark	50	−3	Kazakhstan	75	+33
17	Italy	31	Sweden	48	+2	Latvia	75	+30
18	Bahamas	31	Germany	47	−3	Mongolia	72	+64
19	Sweden	31	Australia	46	+6	Switzerland	72	−9
20	Japan	30	Austria	46	−4	Korea, Rep.	71	+10
21	France	30	Bahrain	45	−10	Brunei	70	−15
22	Belgium	30	Malta	45	+21	New Zealand	69	+9
23	Iceland	30	Canada	45	+1	Bahrain	69	−2
24	Canada	29	Belgium	44	−2	Malaysia	68	+17
25	Australia	29	Finland	42	+1	Turkey	66	+20
26	Finland	29	U. Kingdom	42	+4	Panama	65	+26
27	Kuwait	28	France	41	−6	Germany	65	−9
28	Libya	27	Japan	41	−8	Sweden	64	−11
29	Hong Kong	27	Puerto Rico	39	+4	Denmark	64	−13
30	U. Kingdom	27	Korea, Rep.	39	+21	Saudi Arabia	64	−15
31	Spain	24	New Zealand	39	+1	Netherlands	62	−17
32	New Zealand	24	Israel	37	+3	U. Kingdom	62	−6
33	Puerto Rico	23	Oman	36	−21	Japan	62	−5
34	Ireland	22	Spain	35	−3	Canada	61	−11
35	Israel	22	Italy	35	−18	Australia	61	−16
36	Russian Feder.	21	Czech Republic	34	*na*	Israel	60	−4
37	Greece	21	Lithuania	33	*na*	Slovak Republic	59	+3
38	Portugal	20	Estonia	33	+12	Poland	58	+4
39	Gabon	20	Slovenia	33	+1	Belgium	55	−15
40	Slovenia	19	Slovak Republic	32	+8	France	54	−13

Notes: Numbers represent the amount of GDP per capita (in PPP terms) in thousands (10^3) of USD.
Data source: Authors' calculation using MaGE 3.1.

Table C.3: Long-run projections' ranking at the regional level: GDP per capita in 2011 PPP

	1990		2020		2050	
	Country	10^3	Country	10^3	Country	10^3
1.	North America	32	North America	50	North America	69
2.	Middle East & North Africa	25	Europe & Central Asia	31	East Asia & Pacific	49
3.	Europe & Central Asia	19	Middle East & North Africa	31	Europe & Central Asia	48
4.	East Asia & Pacific	14	East Asia & Pacific	26	Middle East & North Africa	45
5.	Latin America & Caribbean	9	Latin America & Caribbean	14	South Asia	28
6.	Sub-Saharan Africa	2	South Asia	8	Latin America & Caribbean	25
7.	South Asia	2	Sub-Saharan Africa	4	Sub-Saharan Africa	10

Notes: The regions' specification is based on the World Bank region classification. Numbers represent the amount of GDP per capita (in PPP terms) in thousands (10^3) of USD.
Data source: Authors' calculation using MaGE 3.1.

C.2 GDP in current dollar

Table C.4 presents the ranking of economies for GDP in terms of current USD. Table C.5 presents the same ranking aggregated at the regional level.

Table C.4: Long-run GDP in current USD

	1990		2020			2050		
	Country	10^{12}	Country	10^{12}	Rank	Country	10^{12}	Rank
1	United States	5.95	United States	20.76	=	China	142.96	+1
2	Japan	3.59	China	19.08	+25	India	79.73	+2
3	Germany	2.24	Japan	4.81	−1	United States	32.77	−2
4	France	1.56	India	3.85	+7	Indonesia	7.11	+10
5	Italy	1.47	Germany	3.54	−2	Japan	6.79	−2
6	U. Kingdom	1.31	U. Kingdom	2.82	=	U. Kingdom	5.12	=
7	Russian Feder.	0.85	France	2.47	−3	Germany	4.20	−2
8	Spain	0.75	Brazil	2.05	+1	Philippines	3.91	+25
9	Brazil	0.75	Russian Feder.	1.87	−2	Turkey	3.68	+8
10	Canada	0.57	Canada	1.67	=	Russian Feder.	3.62	−1
11	India	0.47	Italy	1.61	−6	France	3.00	−4
12	Netherlands	0.41	Korea, Rep.	1.60	+9	Korea, Rep.	2.90	=
13	Mexico	0.36	Australia	1.38	+2	Bangladesh	2.70	+26
14	Iran, Islam. Rep.	0.35	Indonesia	1.34	+12	Canada	2.69	−4
15	Australia	0.34	Spain	1.23	−7	Nigeria	2.69	+10
16	Switzerland	0.33	Mexico	1.21	−3	Mexico	2.34	=
17	Argentina	0.31	Turkey	0.94	+7	Australia	2.15	−4
18	Sweden	0.31	Saudi Arabia	0.91	+1	Vietnam	2.12	+25
19	Saudi Arabia	0.29	Netherlands	0.81	−7	Brazil	1.96	−11
20	Belgium	0.27	Argentina	0.74	−3	Thailand	1.84	+6
21	Korea, Rep.	0.25	Switzerland	0.61	−5	Kazakhstan	1.66	+26
22	China	0.23	Poland	0.58	+14	Poland	1.23	=
23	Nigeria	0.23	Sweden	0.57	−5	Malaysia	1.21	+8
24	Turkey	0.23	Iran, Islam. Rep.	0.57	−10	Spain	1.13	−9
25	Austria	0.22	Nigeria	0.55	−2	Turkmenistan	1.10	+65
26	Indonesia	0.19	Thailand	0.53	+7	Saudi Arabia	1.10	−8
27	Denmark	0.19	Belgium	0.51	−7	Argentina	1.08	−7
28	Norway	0.17	Singapore	0.42	+12	Pakistan	1.07	+12
29	Finland	0.17	Norway	0.42	−1	Peru	0.90	+16
30	South Africa	0.14	U. Arab Emir.	0.42	+22	Cote d'Ivoire	0.88	+52
31	Greece	0.13	Malaysia	0.41	???	Uzbekistan	0.85	+52
32	Portugal	0.11	Hong Kong, China	0.40	+7	Sudan	0.81	+28
33	Thailand	0.11	Philippines	0.40	+15	Colombia	0.81	+4
34	Egypt, Arab Rep.	0.10	Austria	0.39	−9	Angola	0.80	+22
35	Ukraine	0.10	Israel	0.36	+10	Netherlands	0.79	−16
36	Poland	0.09	South Africa	0.35	−6	Tanzania	0.77	+39
37	Venezuela, RB	0.09	Colombia	0.35	+7	Sweden	0.76	−14
38	Algeria	0.08	Denmark	0.34	−11	U. Arab Emir.	0.74	−8
39	Hong Kong, China	0.08	Bangladesh	0.33	+20	Egypt, Arab Rep.	0.73	+14
40	Singapore	0.07	Pakistan	0.32	+3	Hong Kong, China	0.73	−8

Notes: Numbers represent the amount of GDP in billions (10^{12}) of current USD.
Data source: Authors' calculation using MaGE 3.1.

Table C.5: Long-run projections' ranking at the regional level: GDP in current USD

	1990	2020	2050
1.	Europe & Central Asia	East Asia & Pacific	East Asia & Pacific
2.	North America	North America	South Asia
3.	East Asia & Pacific	Europe & Central Asia	North America
4.	Latin America & Caribbean	Latin America & Caribbean	Europe & Central Asia
5.	Middle East & North Africa	South Asia	Latin America & Caribbean
6.	Sub-Saharan Africa	Middle East & North Africa	Sub-Saharan Africa
7.	South Asia	Sub-Saharan Africa	Middle East & North Africa

Notes: The regions' specification is based on the World Bank region classification.
Data source: Authors' calculation using MaGE 3.1.

D Energy

Table D.6 presents the ranking of economies in terms of their energy consumption. Table D.7 presents the same ranking aggregated at the regional level, together with the regional ranking of energy efficiency.

Table D.6: Long-run energy projections' ranking

	1990		2020			2050		
	Country	10^9	Country	10^9	Rank	Country	10^9	Rank
1	United States	13.68	China	26.10	+2	China	95.50	=
2	Russian Feder.	6.28	United States	16.15	−1	India	59.20	+1
3	China	6.22	India	8.58	+3	United States	21.37	−1
4	Japan	3.13	Russian Fed.	4.84	−2	Russian Feder.	6.21	=
5	Germany	2.51	Japan	3.07	−1	Indonesia	5.12	+5
6	India	2.18	Germany	2.20	−1	Nigeria	4.56	+13
7	Ukraine	1.80	Korea, Rep.	2.13	+8	Japan	3.25	−2
8	France	1.60	Brazil	2.11	+4	Thailand	3.16	??
9	Canada	1.51	Canada	2.00	=	Korea, Rep.	3.15	−2
10	U. Kingdom	1.47	Indonesia	1.81	+4	Vietnam	2.90	+18
11	Italy	1.05	France	1.71	−3	Canada	2.76	−2
12	Brazil	1.00	Mexico	1.44	+1	Mexico	2.70	=
13	Mexico	0.88	U. Kingdom	1.24	−3	Brazil	2.54	−5
14	Indonesia	0.70	Iran, Islam. Rep.	1.19	+6	Turkey	2.51	+2
15	Korea, Rep.	0.66	Thailand	1.18	+18	Germany	2.40	−9
16	South Africa	0.65	Turkey	1.05	+9	Pakistan	2.36	+6
17	Spain	0.64	South Africa	1.05	−1	Uzbekistan	2.03	+18
18	Australia	0.62	Italy	0.99	−7	Cote d'Ivoire	2.00	+44
19	Kazakhstan	0.52	Nigeria	0.96	+2	Egypt, Arab Rep.	1.99	+11
20	Iran, Islam. Rep.	0.50	Australia	0.91	−2	Malaysia	1.95	+3
21	Nigeria	0.47	Spain	0.82	−4	France	1.94	−10
22	Netherlands	0.47	Pakistan	0.75	+10	Iran, Islam. Rep.	1.63	−8
23	Romania	0.44	Malaysia	0.74	+22	Philippines	1.62	+11
24	Saudi Arabia	0.41	Poland	0.69	*na*	Tanzania	1.60	+24
25	Turkey	0.38	Saudi Arabia	0.65	−1	U. Kingdom	1.56	−12
26	Czech Republic	0.35	Argentina	0.65	+4	Algeria	1.51	+6
27	Belgium	0.34	U. Arab Emir.	0.64	+21	South Africa	1.41	−10
28	Sweden	0.34	Vietnam	0.62	+22	U. Arab Emir.	1.37	−1
29	Uzbekistan	0.33	Ukraine	0.60	−22	Kazakhstan	1.30	+7
30	Argentina	0.33	Egypt, Arab Rep.	0.58	+5	Australia	1.30	−10
31	Belarus	0.32	Netherlands	0.51	−9	Bangladesh	1.29	+8
32	Pakistan	0.31	Algeria	0.44	+12	Ethiopia	1.20	+14
33	Thailand	0.30	Iraq	0.42	+16	Iraq	1.15	=
34	Venezuela, RB	0.28	Philippines	0.41	+2	Saudi Arabia	0.97	−9
35	Egypt, Arab Rep.	0.23	Uzbekistan	0.40	−6	Argentina	0.96	−9
36	Philippines	0.21	Kazakhstan	0.40	−17	Poland	0.91	−12
37	Finland	0.20	Belgium	0.38	−10	Kenya	0.90	+14
38	Bulgaria	0.20	Sweden	0.35	−10	Congo, Dem. Rep.	0.89	+22
39	Austria	0.18	Bangladesh	0.33	+17	Papua N. Guinea	0.73	+35
40	Switzerland	0.17	Qatar	0.31	*na*	Spain	0.73	−19

Notes: Energy consumption is expressed in terms of kg of oil equivalent per 1000 USD (expressed in billions (10^9) of constant 2011 USD).
Data source: Authors' calculation using MaGE 3.1.

Table D.7: Long-run projections' ranking at the regional level: energy consumption and efficiency

	1990	2020	2050
Energy consumption, E			
1.	Europe & Central Asia	East Asia & Pacific	East Asia & Pacific
2.	North America	Europe & Central Asia	South Asia
3.	East Asia & Pacific	North America	Europe & Central Asia
4.	Latin America & Caribbean	South Asia	North America
5.	South Asia	Latin America & Caribbean	Sub-Saharan Africa
6.	Sub-Saharan Africa	Middle East & North Africa	Middle East & North Africa
7.	Middle East & North Africa	Sub-Saharan Africa	Latin America & Caribbean
Energy Efficiency, $\tilde{B}$			
1.	Europe & Central Asia	Europe & Central Asia	Europe & Central Asia
2.	Latin America & Caribbean	Latin America & Caribbean	Latin America & Caribbean
3.	Sub-Saharan Africa	East Asia & Pacific	East Asia & Pacific
4.	East Asia & Pacific	Sub-Saharan Africa	Middle East & North Africa
5.	Middle East & North Africa	Middle East & North Africa	Sub-Saharan Africa
6.	South Asia	South Asia	South Asia
7.	North America	North America	North America

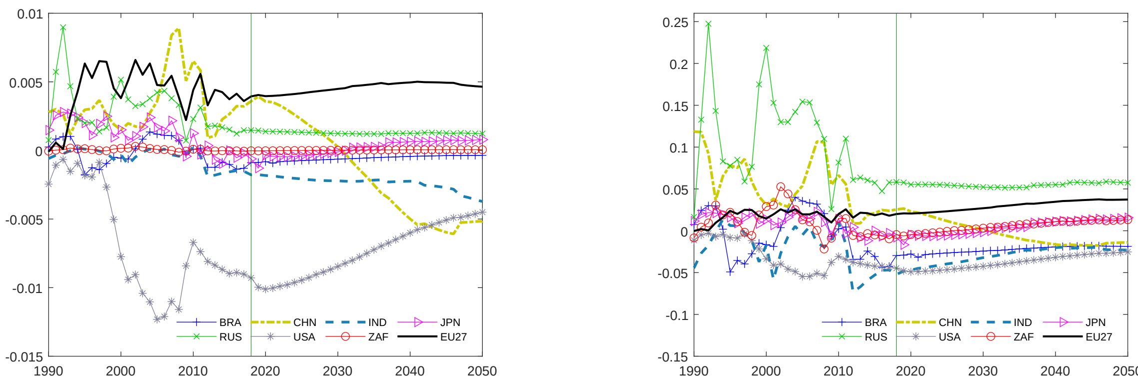
Notes: The regions' specification is based on the World Bank region classification.
Data source: Authors' calculation using MaGE 3.1.

E Other figures

E.1 Current accounts' paths

In this section we show the evolution of the current account for a selection of countries. Over the projection horizon current accounts gradually close, attesting that our projection are obtained under well-behaved dynamics of the savings and investments.

Figure E.1: Current Account



(a) As a share of world GDP

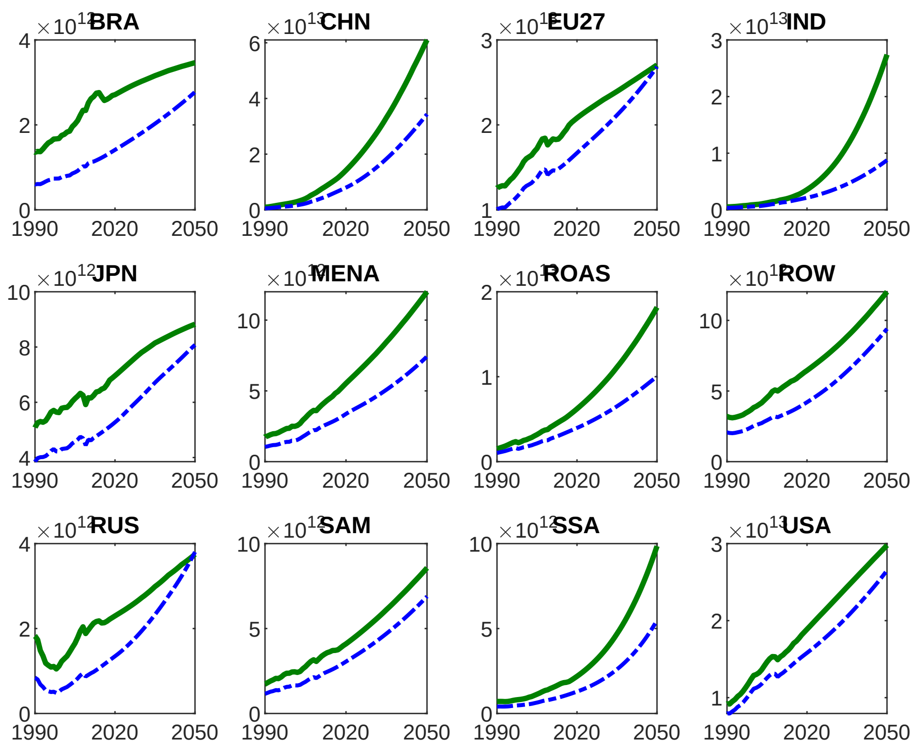
(b) In terms of domestic GDP

Notes: "BRA" stands for Brazil; "CHN" is China; "IND" is India; "JPN" is Japan; "RUS" is Russia; "USA" is the United States; "ZAF" is South Africa and "EU27" is the European Union with 27 members.
Data source: Authors' calculations using MaGE 3.1.

E.2 Comparison with the results of MaGE 2.4

In the section we compare the GDP evolution for a selection of countries and regions for MaGE 3.1 (solid lines) with the previous release of MaGE (dotted lines). The differences in the historical period reflect data revisions and the fact that in the new version only energy consumption data has been filled when the data was missing. In the projections' period, the differences between the two versions depend on both the new starting point from the data and the corresponding new estimation of the structural relationships on which projections are based.

Figure E.2: Comparison of GDP evolution (at constant 2011 USD)



Notes: Solid lines refer to MaGE 3.1 and dotted lines to MaGE 2.4. "BRA" stands for Brazil; "CHN" is China; "IND" is India; "JPN" is Japan; "RUS" is Russia; "USA" is the United States; "ZAF" is South Africa and "EU27" is Europe with 27 members. "MENA" stands for Middle-East and North African; ROAS for Rest of Asia; ROW is the Rest of the World; "SAM" stands for South America; and "SSA" for Sub-Saharan Africa.
Data source: Authors' calculations using MaGE 3.1.