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International Futures (IFs) and integrated, long-term forecasting of global transformations

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ABSTRACT

The International Futures (IFs) long-term global forecasting system, with a development history spanning 40 years, has deep roots in world modeling and integrated assessment modeling. Its highly integrated models span demographics, economics, education, health, governance, agriculture, energy, infrastructure and the environment. The open-source system is available for stand-alone use and on the web with an interactive interface and a large supporting database. IFs users represent education, government (national and international), non-governmental organizations, firms, and policy research organizations. This paper uses IFs to provide Base Case forecasts of global transformations that appear to be unfolding in human development (special attention to education and aging), social development (distribution and power), and the relationship of humans with their environment (advancing mastery and sustainability challenges). It illustrates scenario analysis with alternative forecasts of global poverty, carbon emissions, global patterns of national governance, the human development index, and food and agricultural development. The paper concludes by noting that such modeling and forecasting, while much advanced since the 1970s, still marries craft-like art with advancing science.

1. Introduction

Eradicating poverty, advancing education, improving health, building global infrastructure, strengthening governance, all while protecting sustainable interactions with our environment—these are among the most critical issues challenging humanity this century. Adding to the challenge, each of these issues interacts spatially, causally, and temporally with the rest—they are global, interconnected and long-term in nature.

International organizations, national governments, nongovernmental organizations, firms, and, of course individuals and families all think about these issues and regularly take action to address them. Increasing knowledge and data inform both thinking and action. Yet most analyses and derivative activities do not fully take into account the global, causal, and temporal connections among these issues. Nor can they—attempts to analyze all forward implications of every decision may paralyze policy. At the same time, however, the character and importance of these issues requires us to constantly improve our ability to undertake comprehensive and integrated analyses as basis for action.

There are two primary traditions in global forecasting that help us move in that direction: *integrated assessment modeling* and *world modeling*. Integrated assessment modeling (IAM) tends to focus on sustainability issues, and the models most likely to be found in IAM forecasting systems are energy, agriculture, and the environment, followed by economics and

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demographics. Examples can be found in the work of the International Institute of Applied Systems Analysis (IIASA; see the documentation of several models at http://www.iiasa.ac.at/web/home/research/modelsData/Models–Tools–Data.en.html) and the Netherlands National Institute for Public Health and the Environment (Stehfest et al., 2014). Jaeger and Henrichs (2008) provided one compilation of such models, as has CIESEN at http://sedac.ciesin.columbia.edu/mva/iamcc.tg/TGsec4.html.

The world modeling tradition was especially active in the 1970s and early 1980s and, in part with the impetus of the Club of Rome models, such as the work of Forester (1971) and the Meadows team (Meadows et al., 1974), cut across socio-political and sustainability issues (Cole, 1977; Meadows, Richardson, & Bruckman 1984; Hughes, 1984). See the useful 2015 on-line review by Castro and Jacovkis at http://jasss.soc.surrey.ac.uk/18/1/13.html. Not surprisingly, the IAM tradition then drew on the early work of world modeling, not least via the conferences that IIASA organized in Laxenburg, Austria, during the mid-1970s to present and analyze world models. Hughes (1980) reviewed and compared the world models that emerged during the 1970s with special attention to the work of the Mesarovic-Pestel team. The foci points of the tradition are less sharply and consistently defined than those of IAM (Hughes, 1984b, 1985). For instance, the GLOBUS model developed in the 1980s at the Wissenschaftszentrum Berlin (see Bremer, 1987) placed much focus on domestic and international political economy forecasting.

The International Futures (IFs) project, with early roots in world modeling, has always recognized the close interaction of three dimensions of human activity, positioning it to a considerable degree within and across both the IAM and world modeling traditions (Hughes, 1993, 1999, 2001, 2002):

- *the development of individual human capabilities*, including the achievement of improved health, extended education, and adequate material well-being;
- *the evolution of social systems*, including the advance of transparent, inclusive democracy and capable governance, as well as improvement of distribution;
- *the interaction of human systems with the broader biological and physical environment*, including the achievement of sustainability of physical inputs and the protection of natural systems from human outputs.

This paper will present forecasts from IFs in each of these three areas, using key global transitions as a lens through which to view them. We will begin with forecasts from the Base Case of IFs and indicate how that scenario compares with other forecasts of important variables. We will then proceed to alternative scenarios in part so as to demonstrate the capability of the IFs system to create and explore very different possible futures. Before turning to forecasts, however, it is important to provide basic information on the IFs system.

2. International Futures (IFs)

International Futures (IFs) is a large-scale, long-term, integrated global modeling system (Hughes & Hillebrand 2006). The broad purpose of the IFs forecasting system is to serve as a thinking tool for the analysis of near through long-term country-specific, regional, and global futures across multiple issue areas. Those interacting issue areas include population, economics, education, health, energy, agriculture, infrastructure, the environment, and socio-political systems. IFs represents 186 countries and their interactions as well. It incorporates a database of more than 3,000 series across the issue areas, with data from 1960, when available, to most recent values.

The user interface of IFs is designed to facilitate interaction with the data analysis, forecasting, and scenario building functionalities of the system, making it quite easy to use. The system has always been freely available to others (find and use it at http://pardee.du.edu) and the code of the model proper has been available under public license. These characteristics probably make the IFs system the most widely used global model; it is certainly one of the most advanced currently available as an aide to thinking, analysis, and action related to global futures.

2.1. Overview of current IFs structure

Fig. 1 identifies the major models within the International Futures (IFs) system. It cannot begin to identify all the linkages within or across these models. Technical documentation on each model is available in the working papers on the Pardee Center web site (http://pardee.du.edu/model-documentation).

IFs is a hybrid system that does not fall neatly into econometric, systems dynamics or other model categories. It is a structure-based, agent-class driven, dynamic modeling system. Households, governments and firms are major agent-classes. Still, the system draws upon standard approaches to modeling specific issue areas whenever possible, extending those as necessary and integrating them across issue areas. Among the important reasons for a hybrid approach is that it allows the combination of close attention to stocks and flows (and differentiation among them as in systems dynamics) and to data and estimation of relationships. IFs further combines these traditions with a heavy use of algorithmic or rule-based elements and even, when it comes to equilibration, with some elements of control theory. Maintenance of accounting structures is very important in the overall system, including the use of them to track aging populations (cohort component structure), financial flows among agent classes (social accounting), energy resources and production/demand, land use, and carbon stocks and flows. The overall system is recursive with single-year time steps.

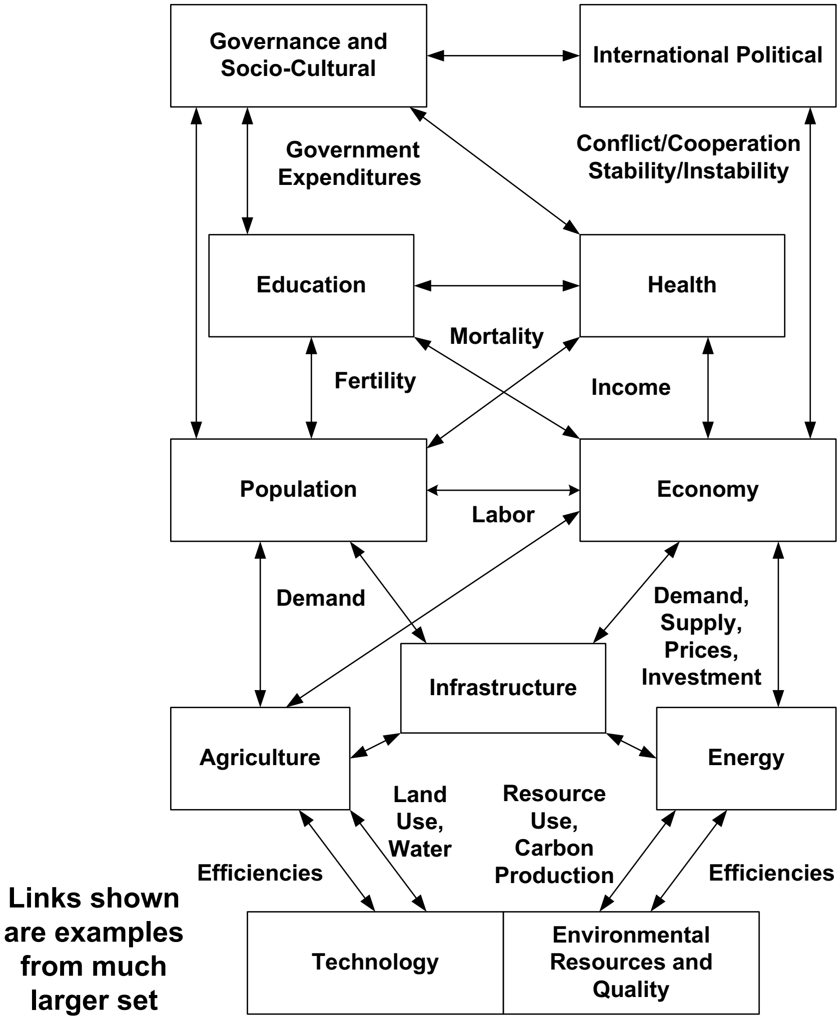

Fig. 1. The models of the International Futures (IFs) forecasting system.

The demographic model uses a standard cohort-component representation, portraying demographics in 5-year categories (adequate for most users), but building on underlying 1-year categories to be consistent with its computational time steps. Unlike most demographic forecasting systems, both fertility and mortality are computed endogenously (migration is specified exogenously, currently using forecasts from IIASA[1]). The availability in the IFs system of both education and health models greatly facilitates such endogenous treatment. Data come from the United Nations Population Division's latest revision updates every two years.

The 6-sector economic model structure is general equilibrium-seeking, in which a Cobb–Douglas formulation drives production and in which multifactor productivity is substantially an endogenous function of human capital, social capital/ governance, physical capital (infrastructure and energy) and knowledge capital (Hughes, 2005). Although capital and labor accumulations are very important, in long-term forecasting the formulations around productivity heavily shape dynamics within the economic model and its interaction with other models. There is also a foundational representation of global technology development and diffusion that facilitates further representation of productivity dynamics and inter-country convergence or lack thereof. A linear expenditure system determines household demand. A social accounting matrix structures flows across sectors and agent categories, assuring full financial flow consistency (Hughes & Hossain, 2003). Data come heavily from the World Bank and the Global Trade Analysis Project. The project has also built a treatment of the informal economy.

[1] As a result of project work connected to the Shared Socio-economic Pathways initiative discussed later, the IFs system includes in its database IIASA forecasts on migration and education, Organization for Cooperation and Development and Potsdam Institute for Climate Impact Research forecasts of GDP, and National Center for Atmospheric Research forecasts of urbanization. The system also includes forecasts on its key variables from many other sources, allowing systematic comparison of those with each other and with the forecasts of IFs.

The education model represents the progression of students, year-by-year, through primary, lower secondary, upper secondary and tertiary education, with some representation also of vocational education and the portion of tertiary students in science and engineering. Key dynamic elements include the entry (or transition) rates to the various levels and the persistence or survival of students year-by-year. Government spending on education per student and overall is also important. Data are heavily from the UNESCO Institute of Statistics.

The IFs global health model represents a hybrid and integrated approach to forecasting health outcomes. It is hybrid because it uses drivers at both distal (i.e. income, education, and technology) and proximate (e.g. risk factors such as smoking rates and undernutrition levels) levels to produce outcomes and integrated because both drivers and outcomes are situated within the greater IFs system, allowing for the incorporation of forward linkages and feedback loops. (The Mathers and Loncar (2006) model of the World Health Organization, upon which IFs built with the support of Mathers, treats only distal drivers.) Together, this approach enables users to explore dynamic age, sex, and country-specific health outcomes related to 15 individual and clustered causes of mortality out to the year 2100 (see Hughes et al., 2011b).

Energy and agricultural models are partial equilibrium with a physical basis that is translated to monetary terms for interface with the economic model. The energy model represents resources and reserves on the production side, which differentiates oil, gas, coal, hydroelectric, nuclear, and other renewable sources. The dynamics around the stocks of fossil resources and their use and those around the development of renewable forms are critical. The agricultural model represents land usage on the production side, which differentiates crops, meat and fish. As in the economic model, production-side representations are key to long-term dynamics. Trade in the energy, agricultural, and broader economic models uses a pooled approach rather than bilateral flows.

The energy model is driven on the demand side by the size of economies and populations, representing also the continued reduction of energy intensities in most countries. On the supply side, production requires not only resource bases, but also the accumulation of capital stock via investment in competition with other sectors. Trade is responsive to differential cost and price structures across countries. Interventions by the user can represent geopolitically based constraint in the growth of production, as well as decisions to restrain exports. Global prices are normally calculated so as to clear the market, but user interventions can override market prices. Most data are from the International Energy Agency. A recent update of the model added data on and forecasting of contributions from unconventional fossil resources (aggregating shale oil and gas, tight oil, coal-bed methane, etc.).

The agricultural model is similar to the energy model in general structure. Demand is very responsive to population and income levels; assumptions about future meat demand of emerging countries are important to long-term dynamics. On the supply side, crop yield per hectare is critical. Trade and price equilibration are similar to those in energy. Most data are from the UN Food and Agriculture Organization. The project is now substantially extending its treatment of aquaculture and wild fisheries.

The infrastructure model addresses selected forms for transportation (roads and paved percentage of them), electricity generation and access, water and sanitation, and information and communications technology (land-lines, mobile telephones and broadband connectivity by mobile phone or line). Demand and supply are related through the interaction of financial requirements and availability of private and public funds. Many parameters for setting and pursuing targets of access are available, and data are drawn from many sources.

The environmental model is closely tied to energy and agriculture, because both demands from those systems (for fossil fuels, land, fish, and water) and outputs from them (especially carbon dioxide) are key drivers of the model. The model represents atmospheric carbon as a stock and feeds its level forward to temperature and precipitation changes that, in turn, affect agriculture.

Technology is not actually a separate model. Rather, technology is represented across and within all the other models, for instance in changing cost structures for energy forms and rates of progress in raising agricultural yields.

The domestic governance model represents governance in terms of three dimensions (security, capacity, and inclusion), each of which involves two or more elaborating variables. Variables connected to the dimensions include risk of domestic conflict, corruption, government effectiveness, democracy, and gender empowerment. Change in these variables is driven by variables across the other models, especially by income and educational levels. Change in the three governance dimensions, in turn, drives other aspects of the integrated system, including economic productivity growth.

Revenues and expenditures are another critical element of governance represented in the model. Revenues involve streams from firms, households, and in the case of foreign aid from other governments. Expenditures involve streams to transfer payments and to direct expenditure on the military, education, health, infrastructure, R&D and a residual other category. Government revenues and expenditures are fully integrated within the larger social accounting matrix system.

There are some additional important socio-political elements integrated with the governance and other models. These include components of the human development index (income, life expectancy, and literacy) and the basic dimensions of the World Value Survey (traditional/secular rational and material/self-expression).

The international political model calculates national material power (from inputs such as economic output, population, military spending, and a proxy for technological advance), but also allows the user flexibility around including and weighting these and other elements. Whether countries pose a threat to each other is a complex function of such power and of a number of other variables including level of democratization and trade relationships. The variables of the international political model are primarily satellites to the rest of the IFs system, but power dynamics do affect military spending levels directly and therefore all government finance indirectly. The IFs project has a major data making project underway to enhance existing and build new series on international relationships, including those often considered to represent soft power.

The integration with a large database including series for all key model variables since 1960 allows comparison of model performance with historical series, one aspect of verification, validation, and accreditation efforts (Sargent, 1998). The database also allows analysis of forecasts as an extension of historic patterns. The interface further facilitates the structuring of interventions, singly and in combination, for the purpose of scenario development.

The strengths of the model include (1) its representation of a wide range of fundamental structures in global issue systems, as well as of the agent-driven flows that change those structures over time, (2) the extensive data foundations of the system, (3) its integration of important global subsystems, and (4) its usability and transparency. Weaknesses include those common to most such models, including the substantial uncertainties around (1) important data (such as ultimately recoverable energy resources), (2) fundamentally important relationships (including drivers of economic productivity) and (3) even some fundamentally important key dynamic forces (such as technological advance).

2.2. Users and uses of IFs

The first versions of IFs emerged in the late 1970s when Barry Hughes built them by drawing on his experience at Case Western Reserve University with early Club of Rome and other world models (Hughes, 1980). IFs was publically available through a provider of educational software named CONDUIT at the University of Iowa. Hence the system began as an educational tool and, as indicated, remains a thinking tool—members of the IFs project do not write about long-term predictions, but rather about exploring and thinking about long-term futures through alternative forecasts and scenarios.

IFs evolved gradually into a larger analysis and decision-support system, influenced in early years by the association of Hughes with the GLOBUS modeling project at the Science Center in Berlin (Bremer, 1987; Bremer & Hughes, 1990). Over the last decade, the Frederick S. Pardee Center for International Futures of the University of Denver has housed the IFs system. The Center continues to make the system freely available for the use of others in both downloadable and online versions (at Pardee.du.edu, where there is also system documentation). Access to selected IFs forecasts is also available online through Google's Public Data Explorer and full access to the model exists through the African Futures Project and country and issue-specific pages of Wikipedia.[2] The constant and open use of IFs over many years, resulting in much feedback and generating many enhancements, has been essential to its ongoing improvement.

IFs has supported a wide range of scientific analyses and policy-oriented projects. For instance, it was a core component of two projects exploring the New Economy sponsored by the European Commission (Johnston & Hughes, 2004; Moyer & Hughes, 2012). Forecasts from IFs heavily supported the Global Trends 2020, 2025, and 2030 reports to the President by the U.S. National Intelligence Council (US NIC, 2004, 2008, 2012). IFs provided forecasts for the fourth Global Environment Outlook of the United Nations Environment Program (UNEP, 2007). It was also used in support of two United Nations Development Programme Reports (UNDP HDR 2011, 2013; see, Hughes et al., 2011a; Hughes, Irfan, Moyer, Rothman, & Solórzano, 2012; Hughes, 2013 for supporting policy research papers). IFs supported a study of the future of education in the southern Africa region (Irfan & Margolese-Malin, 2012). The United States Institute of Peace commissioned a study of work with IFs and other projects on fragile or vulnerable states (Hughes, Moyer, & Sisk, 2011). The World Bank supported a study of the prospects for eradicating poverty by 2010 in fragile and conflict-afflicted states (Burt, Hughes, & Milante, 2014).

The Overseas Development Institute has used IFs forecasts and scenarios on global poverty in two major reports (Shepherd et al., 2013, 2014) as well as in other work, including a project for Save the Children.[3] In partnership with a pan-African think tank, the Institute for Security Studies (ISS) in South Africa, the project has produced a series of more than nine publically released policy briefs on African Issues (available at http://pardee.du.edu/african-futures and on the ISS website), covering topics ranging from the future of water and sanitation (Eshbaugh, Firnhaber, McLennan, Moyer, & Torkelson, 2011) through attaining food security (Moyer Jonathan & Firnhaber, 2012) to eradicating malaria and gas fracking in South Africa (Hedden, Moyer, & Rettig, 2013). IFs serves as the primary tool for the African Futures 2050 project based at the ISS (Cilliers, Hughes, & Moyer, 2011). The Pardee Center has also worked with the government of the Western Cape province of South Africa on a series of policy briefs and to embed use of the IFs system in the government's policy-making processes, and the Center has similarly collaborated with the National Center for Strategic Planning or CEPLAN in the government of Peru (see CEPLAN, 2014, for its own description of the IFs model and its use in their work). With respect to non-governmental organizations, the Pardee Center supported Population Services International on a study of the health impact of moving from solid-fuel to modern cookstoves in households (Kuhn, Rothman, Turner, Solórzano, & Hughes, 2014) and is similarly working with Water for People to explore the impact of providing safe water and sanitation and with Action Contre la Faim on nutrition and other issues.

On the environmental side, the IFs project has begun to connect (Rothman, Siraj, & Hughes, 2014) with the Shared Socio-economic Pathways (SSP) initiative (Nakicenovic, Lempert, & Janetos, 2014; O'Neill et al., 2014) that in turn connects to the work of the Intergovernmental Panel on Climate Change. The IFs project work is focused on analyzing the internal coherence

[2] IFs forecasts on Google Public Data Explorer are at http://www.google.com/publicdata/explore?ds=n4ff2muj8bh2a_. On the African Futures website IFs is at http://www.issafrica.org/futures/explore-the-future. At the bottom of Wikipedia country pages links to forecasts for the country in IFs can be found under the External Links section.

[3] Private correspondence with Amanda Lenhardt.

of the five SSP scenarios given that issue-specific forecasts for them have come from different modeling groups with largely unconnected models and on extended consequences of the scenarios.

The Center has not kept track of the numbers of students, scholars, policy analysts and others who have, over the years, used or at least perused the IFs system, but there is little question that many thousands have. Some of that use has led to published third-party research and analysis that relied heavily on the system. See, for example, Casetti (2003), Chadwick (2006), Hillebrand (2008), Cave et al. (2009), Hillebrand (2010), Cantore (2011), Cantore (2012), Pearson (2011), Birkmann et al. (2013), USAID (2013), Cilliers and Schúnemann (2013), Cilliers and Sisk (2013), Cantore (2014), McCauley (2014), Hillebrand and Closson (2015), and West et al. (2013).

The most substantial use of the International Futures (IFs) system in recent years, however, has been the publication by the Pardee Center of its five-volume flagship series called Patterns of Potential Human Progress, on the global issues of poverty, education, health, infrastructure, and governance. Paradigm Publishers in Boulder, Colorado, and Oxford University Press in New Delhi, India, co-published the volumes. (In sequence those are Hughes et al., 2009; Dickson, Hughes, & Irfan, 2010; Hughes et al., 2011c; Rothman, Irfan, Margolese-Malin, Hughes, & Moyer, 2013; Hughes, Joshi, Moyer, Sisk, & Solórzano, 2014). The production of this series served two major purposes: (1) motivating the development of entirely new models within the forecasting system, several of them (like health, infrastructure, and governance) fundamentally unique; and (2) generating substantial exposure of the system to other users for their own analyses (as indicated above).

3. Forecasting with IFs: Base Case

Major interacting global transitions are underway in the twenty-first century with respect to each of the three human spheres identified earlier, namely *the development of individual human capabilities*, *the evolution of social systems*, and *the interaction of human systems with the broader biological and physical environment.* (See also Hughes, 1997, 2001b, 2004, 2004b). Although it is oversimplification, it will be useful here to consider IFs forecasts with respect to two transitions in each of these three spheres:

1. Human development: capacity of selves
   - A. Education
   - B. Fertility in interaction with longevity/aging
2. Social development: relationship with each other
   - C. Distribution and power
   - D. Governance character and quality
3. Bio-physical development: relationship with technology and the environment
   - E. Mastery
   - F. Sustainability

3.1. Human development

Two core transitions of human development consist of the movement of society from low to extended education and from high to low fertility (see also Hughes & Irfan, 2007). Fig. 2 shows both of these interacting transitions globally across a half century of historical data and across another half century of forecast horizon, focusing on adult female educational attainment (historically about a year less than males, but converging in our forecasts). In 1960 the average woman in the world had fewer than 3 years of formal education and gave birth to 5 children. We are on track to a world in 2060 in which the average woman will have more than 10 years of formal education and give birth to 2 or fewer children, a truly dramatic and fundamentally important transformation over a century.

Although the specifics vary by country, the general pattern of these core human development transformations is occurring around the world. In Latin America, the cross-over of fertility and education occurred in 1960 for Cuba, in 1962 for Chile, but only in 2008 for Guatemala. For Turkey it happened in 1986, for Iran it was 1992, and for India 2000. For Africa as a continent it occurred in 2010. The cross-over point seems invariably to be numerically very near values of 4 for both fertility and years of adult education (although sometimes as high as 5), what this author calls "the global law of female role transformation." When examining these cross-overs with IFs it is remarkable to see the extent to which major social transitions including democratization tend to occur 1–2 generations behind the human development cross-over point.

The ongoing transitions of Fig. 2 are not simple extrapolations in IFs, but are instead the dynamic results of large-scale demographic and educational models representing each of 186 countries. Fig. 3 shows the detail in 2010 and 2060 of the global transitions by age, sex, and level of educational attainment.

The human developmental transitions have, of course, major impacts in the world (and the IFs system) for all other human systems. Most of those are beneficial. But some will also be very challenging. For instance, the aging of populations will put increasing burdens on governmental financial systems. Extension of life expectancy, about 2.4 years per decade over the last century for the longest-lived national female population globally (Oeppen & Vaupel, 2002), will most likely continue,

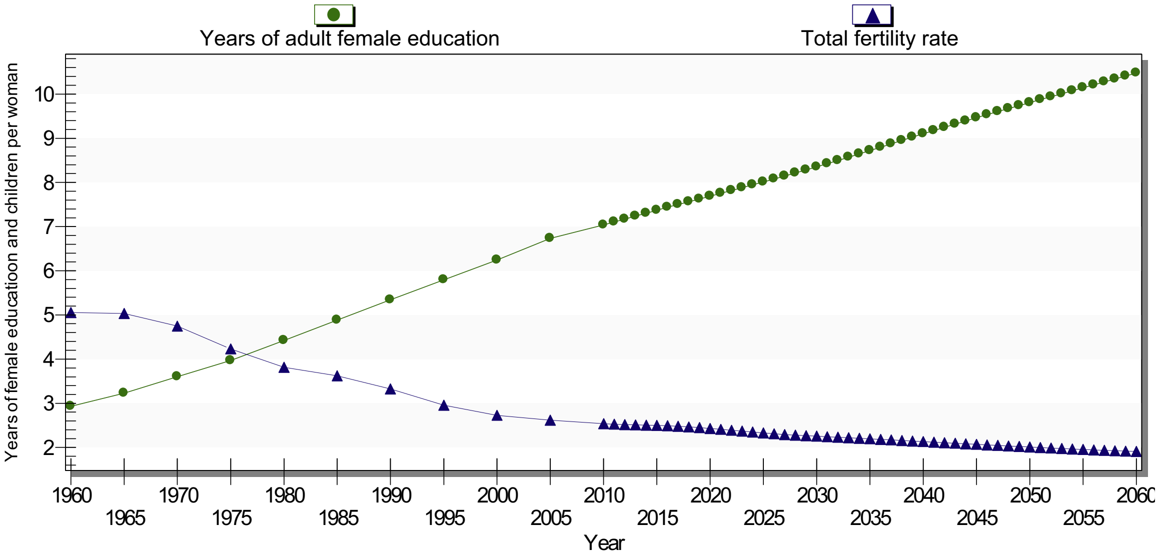

Fig. 2. The core global human development transformations: replacing high fertility and low female education with their inverse.
Source: International Futures, version 7.11.

although the IFs Base Case anticipates a slowing rate of extension as the rapid global reduction in infant and child mortality reach natural limits. The Base Case scenario of IFs rather conservatively anticipates adding only another 15 years of average global life expectancy between 2010 and 2100 (from just over 70 to nearly 85, with Japanese women going only from 87 to 94).[4] Even with that conservatism Fig. 4 indicates that for populations in the Organization for Economic Cooperation and Development (OECD) the ratio of those of working age—assuming that to be roughly 15–65—to those above that age has already fallen in 2015 nearly to 4 and will be half that by 2060. Pension systems in those countries creak now, and many will break before then, requiring both painful movements from defined benefits (as in the US social security system) to defined contributions and requiring substantial postponements in retirement age. This is not just a challenge for high-income countries; in non-OECD countries, where fertility rates have fallen much faster in the last half century, the issue will transform societies even more rapidly.

3.2. Social development

Turning to social development, the focus is usually placed on GDP per capita, growth of the middle class, and other income level measures such as poverty reduction.[5] Although IFs forecasts those, we focus here on distributional issues and the related one of global power as well as the issue of transformation in governance.

Gini indices are the most common measure of distribution and the IFs project has collected them from a wide variety of sources over time to construct a large database historically for most countries of the world. Fig. 5 indicates the pattern of their evolution since 1960 (smoothed because of irregular reporting country sets and a mixture of sources). There has been a small increase in average Ginis (with higher values being more unequal) in recent decades, consistent with the observation of many observers, but actually less increase in the high-income countries on which Piketty (2014) has focused than in other income groupings. The best basis for forecasting income distributions is the use of a large number of population subcategories, ideally done within the kind of social accounting matrix system that IFs uses. Unfortunately, past releases of the Global Trade and Analysis Project database for social categories only included skilled and unskilled workers, and that does not yet provide the basis for confidence in IFs forecasts of national income distributions (hence the figure only shows forecasts through 2020 and our longer-term forecasts remain roughly constant). That story is not unlike that of the longer-term global history, in which there have been periods of increase and decrease in inequality and much variation within and across income categories.

The bigger long-term story concerning inequality has, however, been that across countries and peoples around the world. The major increases in global inequality around the world after the beginning of the industrial revolution took the ratio of

[4] Our work in a project sponsored by the SENS foundation explored the possibility of *much* more dramatic and rapid life extension and its implication for demographics, fiscal balances and retirement, and environmental sustainability (Hughes et al., 2015).

[5] See Hughes, Joshi, et al. (2014: 103–104) for the project's own forecasting of the growth of the global middle class; also Joshi, Hughes and Sisk (2015).

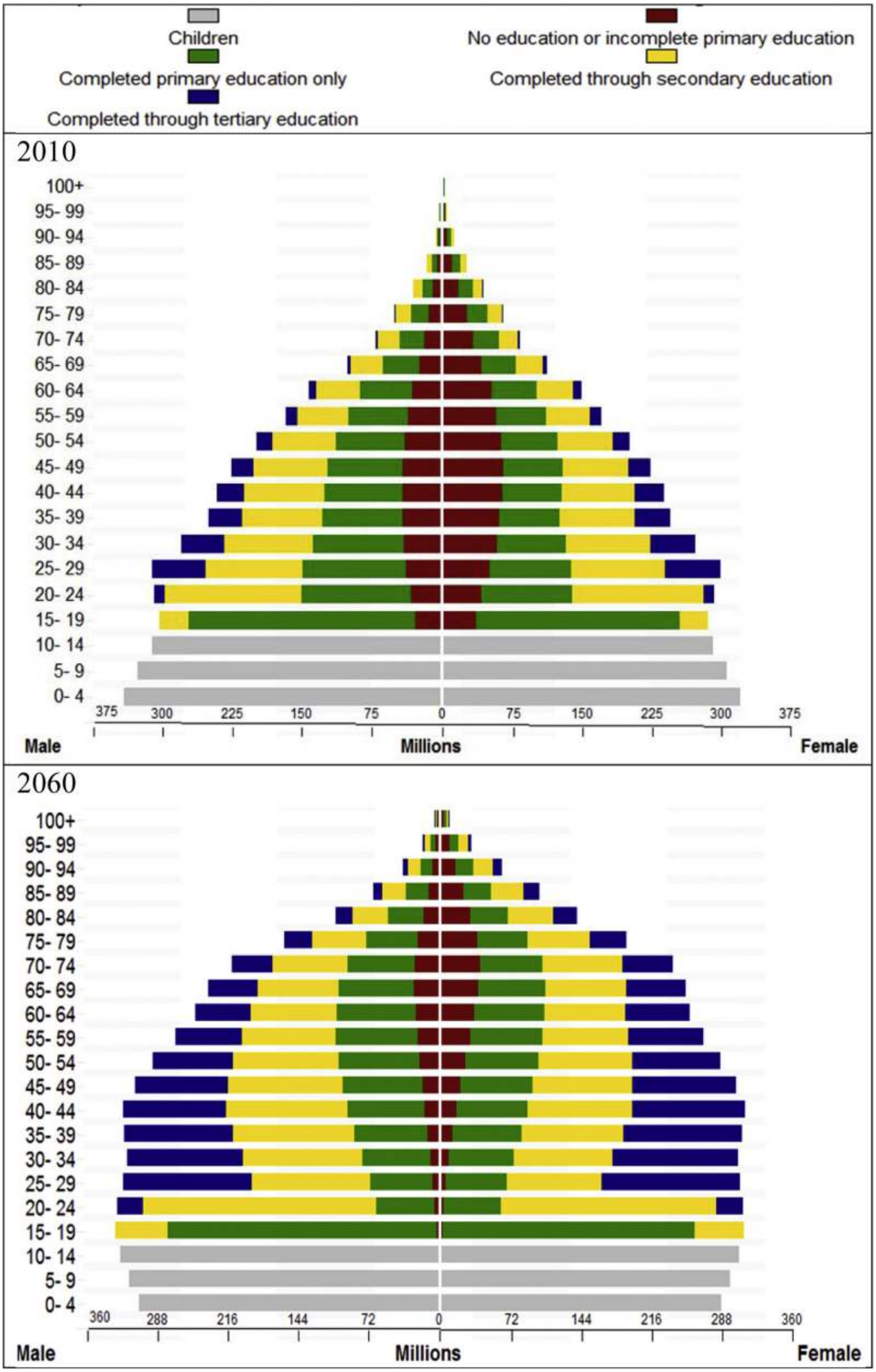

Fig. 3. Core global human development transitions by age, sex, and educational attainment level.
Source: International Futures, version 7.11.

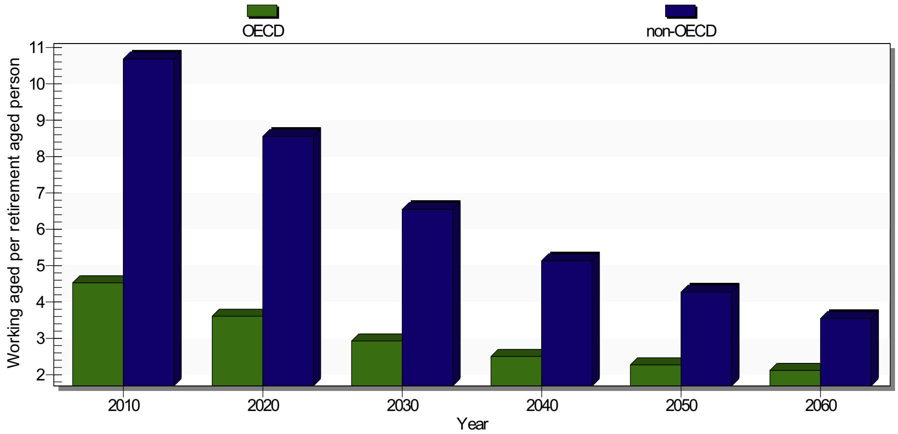

Fig. 4. Working aged (15–65) people per retirement aged (65+) people.
Notes: OECD is the Organization for Economic Cooperation and Development and the current membership is used across the forecast horizon. Not all people between 15 and 65 work, so the labor dependency ratio is even lower than the population ratio shown.
Source: International Futures, version 7.11.

GDP per capita in the current OECD country set to that of the non-OECD countries to a level of about 15 late in the twentieth century. Fig. 6 shows, however, that the story line began to change in the 1990s with the rapid growth in China especially, but the increasingly common pattern of more rapid per-capita growth in the developing world than in the more economically developed world. Again, the IFs forecast of continued decline in the ratio is not an extrapolation of it, but rather the dynamic and interactive result of the functioning of its demographic, education, economic and all other models. Interestingly, the value forecast for 2100 falls to about 1.5, not so different from the relationship that Braudel (1979) estimated for 1800.

Distribution reflects power and reinforces it. And the changing global income distribution reflects the shift in power from the global North to South. It has come to be accepted by nearly all observers that China's power will rise to that of the US and then exceed it by sometime near or even before 2030. See the IFs forecast in Fig. 7, which extends the forecast horizon to 2100 to show the likely challenge of India to China before that time. It may be relatively short "Chinese century."

One of the major concerns of observers of this impending power transition to Chinese global lead is the authoritarian character of China and the implications of that for the nature of systemic leadership that China might provide. Even more concerning is the potential for instability within China as it moves into a superior bipolar position (ignoring the alliance structure of the U.S., which leverages its own power but also its obligations). Fig. 8 shows the IFs forecast of democracy levels

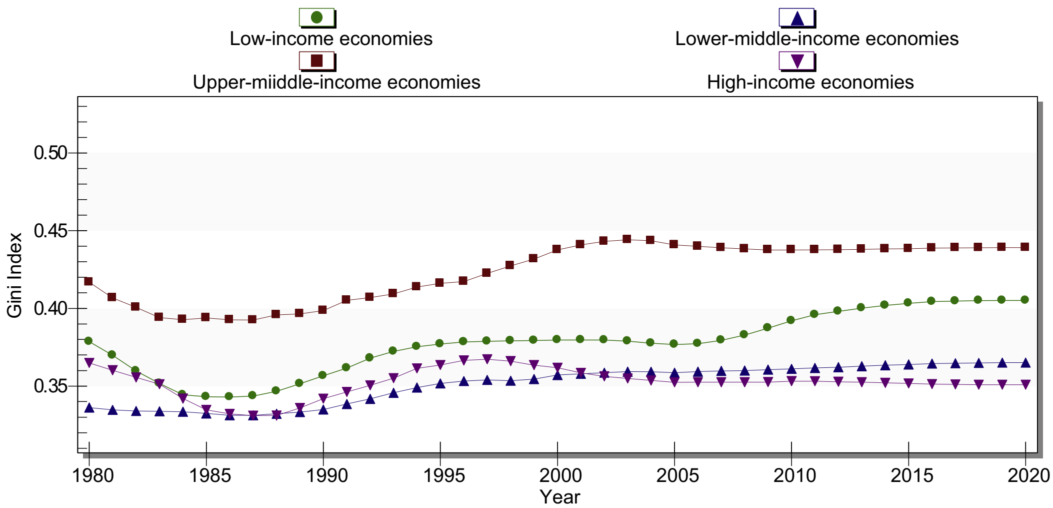

Fig. 5. Gini indices for World Bank income categories of countries.
Notes: Population-weighted averages with 10-year moving average for smoothing.
Source: International Futures, version 7.11.

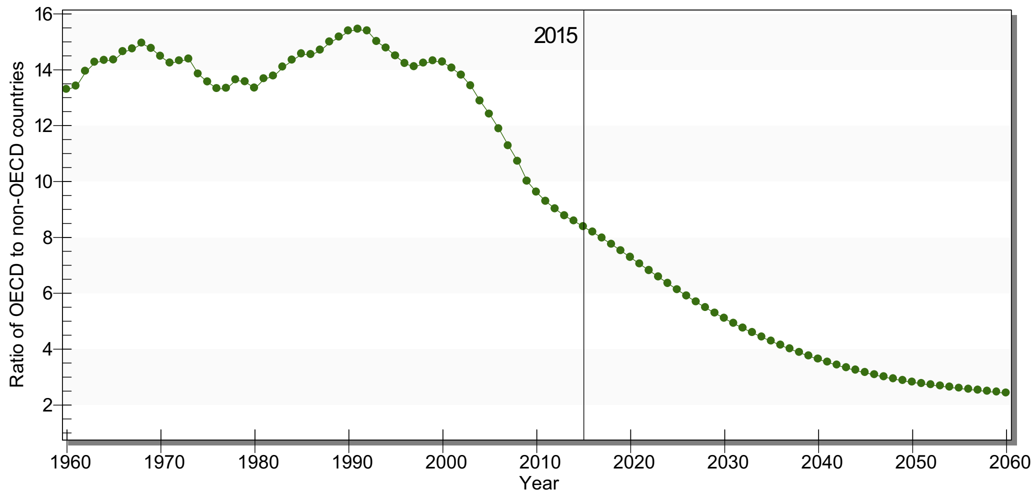

Fig. 6. Ratio of GDP per capita in OECD to non-OECD countries.
Notes: The ratio uses GDP per capita at market exchange rates and excludes the ex-communist or transition countries because of the non-comparability of data before 1990.
Source: International Futures, version 7.11.

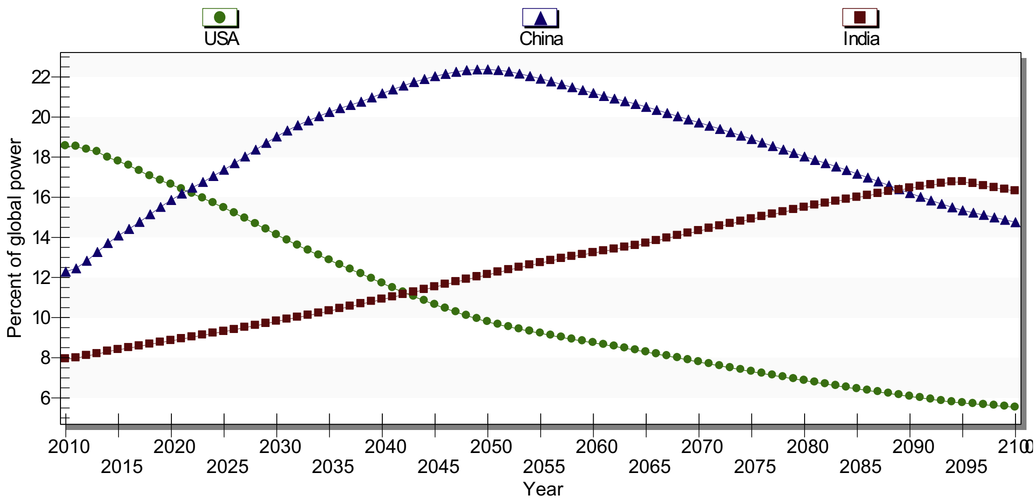

Fig. 7. Global system power share of the United States, China and India.
Notes: Using the Hillebrand-Herman-Moyer power measure (Moyer, 2015). That measure uses a weighted sum of population, GDP, GDP per capita at purchasing power parity (as a proxy for general technological prowess), military spending, nuclear capability, and diplomatic connectivity.
Source: International Futures, version 7.11.

in the three countries.[6] In reality transitions of polities from authoritarian to democratic status are very seldom smooth and that of China, if it occurs as we anticipate, will almost certainly be subject to jumps and possible regressions. It is the range of roughly 5–15 on the Polity scale that typically includes the most unstable political change and domestic and international behavior (Goldstone et al., 2010), and China is poised to enter that range.

3.3. Humans and the bio-physical environment

Forecasting of the relationship of humans to their broader environment commonly focuses most heavily on either advances in our technology with a frequent presumption of environmental mastery (including our ability to move rapidly to

[6] Hughes, Joshi, et al. (2014) present the representation of governance within IFs across three categories: security, capacity, and inclusion (including democratization).

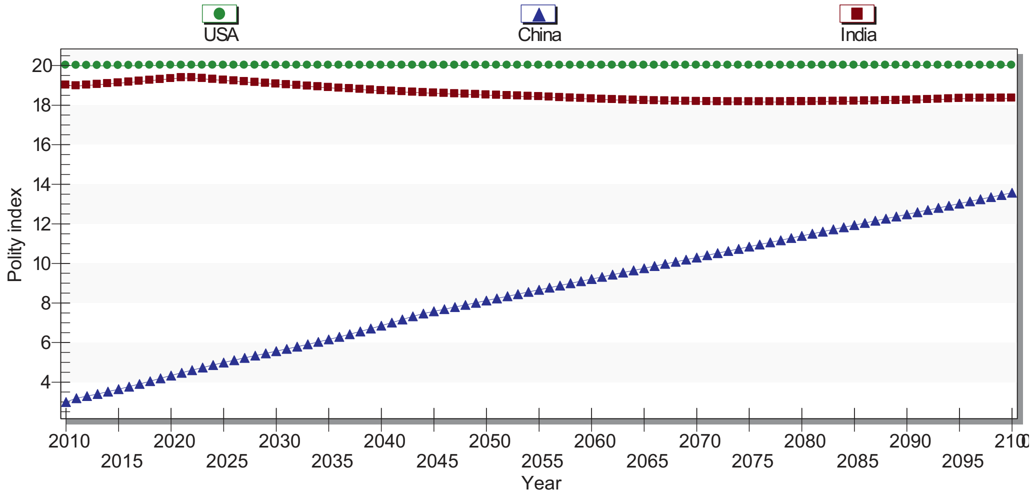

Fig. 8. Democracy level of the big three global powers of the 21st century.
Notes: The Polity index combines10-point sub-measures of democracy and autocracy (Marshall, 2013).
Source: International Futures, version 7.11.

renewable and very low-carbon energy sources, to adapt to the global warming we create, and to solve issues around water scarcity) or on growing environmental challenges to human well-being and the social orders that we have created (including threats from global warming, water shortages, and micro-organism break-out from control regimes). Both the global modeling (including the original Club of Rome sponsored or inspired efforts) and the integrated assessment model tradition have historically been in or close to the second orientation.

In fact, technological advance is very difficult to measure, much less forecast, and models including IFs have not done a very good job of it. Instead, non-modeling based analysis have been more successful. For instance, the McKinsey Global Institute's (2013: 11) analysis of disruptive technologies has pegged the positive impact of the 12 most disruptive technologies on global GDP and consumer surplus (benefits to consumers not captured in GDP) at $13–35 trillion annually by 2025. IFs forecasts that underlying GDP to be about $115 in 2011 dollars, so the proportional impact is huge.

IFs is unable to represent dynamics of the changing technological landscape at the level of detail of individual technologies such as the 12 of the McKinsey report. Instead, we have recognized that most transformative technologies today, including the top 5 of McKinsey (the mobile internet, automation of knowledge work, the internet of things, cloud technology, and advanced robotics) grow out of advance in information and communications technology (ICT). Beginning with our work on infrastructure (Rothman et al., 2013) we have paid special attention to a number of ICT variables including the growth of mobile connectivity and the broadband manifestation of that (see Fig. 9), which proved to be McKinsey's most important disruptive technology. Note that we forecast effectively universal human broadband access to the mobile by 2040, demonstrating the leapfrog nature of that technology for those in the non-OECD countries, even those relatively newly past the cross-over point of female role transformation.

In the IFs system we feed forward the impact of this ICT transition to multifactor productivity in the economic production function (as we also feed forward advances in human and social capital). As always, such forecasting is done at the country level, with our displays aggregating it to desired country groupings for presentation. It is possible in IFs, however, also to do benchmarking analysis that helps in analysis of country-specific performance. Fig. 10 illustrates this with respect to recent historical values of a four-pillar World Bank (2007) knowledge society index for which we take historical values from the World Bank and also create and forecast a two-variable variation of within IFs (Irfan, 2012). By looking at country performance relative to a cross-sectionally estimated function of GDP per capita, we can identify countries that are doing better or worse than we might expect at their developmental level. This benchmarking has a very important secondary function. By looking at the standard errors around such functions we identify levels of high performance that can serve as targets for our scenario interventions. We often refer to "aggressive but reasonable" performance and target levels appropriate to country development levels rather than setting universal targets (like global eradication of poverty by 2030) that can effectively set up some countries for failure because their starting points and reasonably expected values are too far from the target.

The ICT transition only illustrates the tremendous power and speed of the global technological mastery transformation. Moving from that of environmental sustainability, this century will almost certainly be one of major advances in several categories, as well as one of remaining and new challenges in others. A key variable is energy and the IFs energy model forecasts oil, gas, coal, hydroelectric power, nuclear power, and other and new renewables (aggregating sources such as wind, solar, and geothermal).

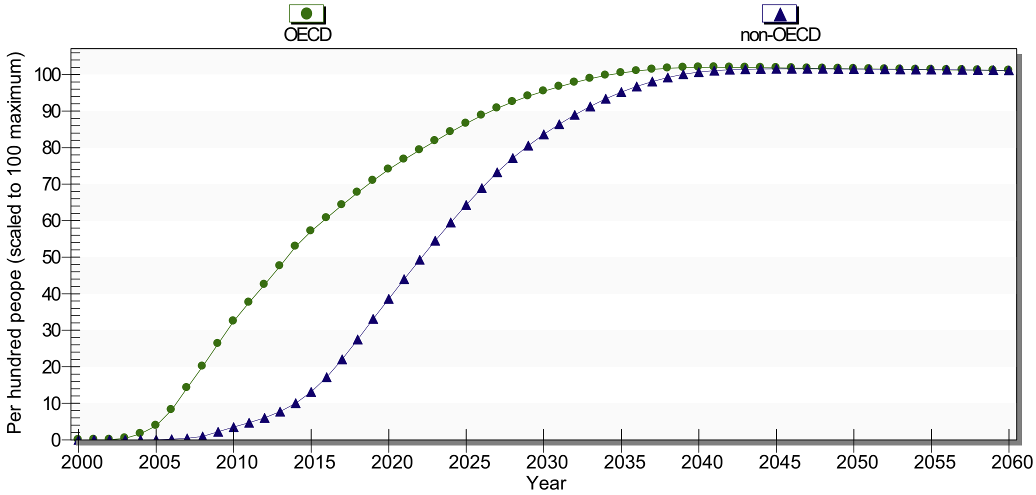

Fig. 9. Mobile broadband connections per 100 people.
Notes: Many have multiple connections and we have scaled the total to 100. Historical data from the International Telecommunications Union.
Source: International Futures, version 7.11.

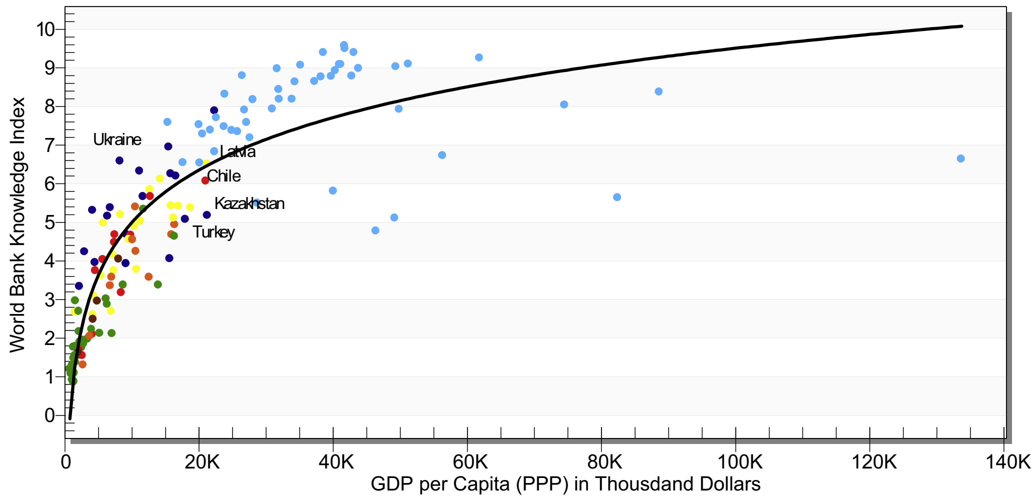

Fig. 10. Benchmark analysis of World Bank knowledge index with most recent data.
Notes: Using World Bank knowledge index (education and training, ICT, innovation system, and institutional-economic regime).
Source: International Futures, version 7.11.

Fig. 11 shows the global history and our Base Case forecasts of these energy types in common units. Many readers will find the other or new renewable forecast optimistic, and it is relative to most other forecasts.[7] The IFs system's forecasts do not assume exhausting of all conventional and unconventional oil and gas before their peaks of production, much less the use of all coal (and lignite). As Sheik Yamani famously said, "Just as the stone age did not end because of lack of stones, the oil age will not end for lack of oil".[8] Our forecast of new renewable production growth at a compound rate of 13% between 2010 and 2040 is high, but very considerably slower than percentage growth in recent years.

[7] By comparison, in the Baseline scenarios of the Global Energy Assessment, non-fossil fuel sources contribute only 20–25% of total global primary energy in the year 2100 (Johansson et al., 2012). The MESSAGE model does produce a fossil/non-fossil breakdown similar to that seen in IFs, but only in scenarios with a strong sustainability focus. At the same time, total energy use is significantly lower in these scenarios, so the absolute growth in energy from non-fossil sources is much less than in the IFs Base Case.

[8] Quoted at http://www.thefreedictionary.com/Ahmed+Zaki+Yamani. Other sources use somewhat different wording.

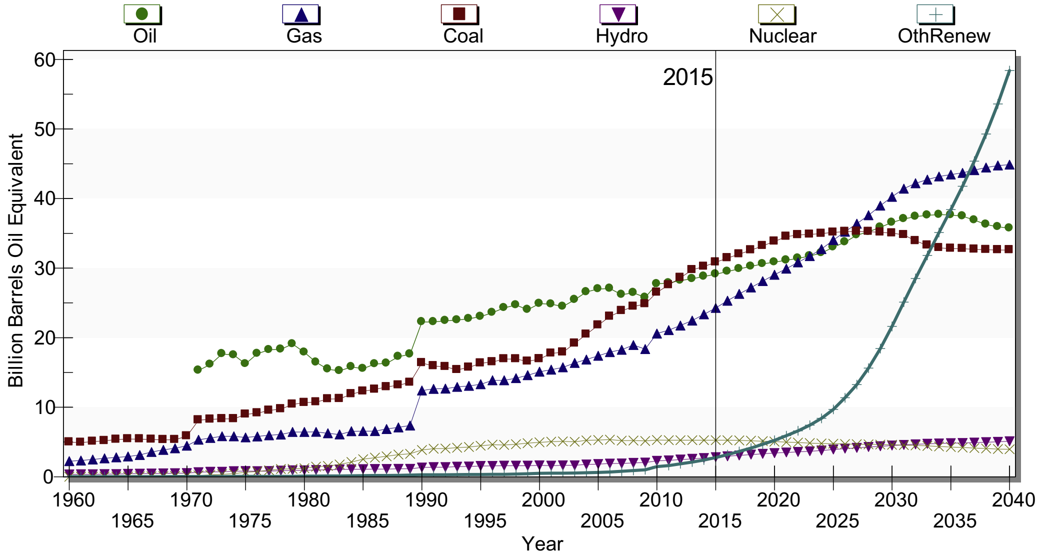

Fig. 11. Global energy production.
Notes: Historical data from the International Energy Agency. The inclusion of formerly communist countries in 1990 creates transients in the historical pattern.
Source: International Futures, version 7.11.

Beyond 2040 the growth of new renewables continues in the Base Case but the definition of what those will be becomes increasingly difficult to foresee and could easily include new generations not just of wind and solar power, but of nuclear energy, even some early forms of fusion later in the century, or perhaps a "negawatt" revolution on the demand side (Lovins, 1990).

Fig. 12 shows the implications of our energy forecasts for those of atmospheric carbon. That figure uses scenarios to map some of the great uncertainty in drivers and outcomes (including different fossil fuel production patterns with fuel-specific carbon emissions and the deeper drivers of economic growth and energy use efficiency). Prepared initially in connection with supporting work for the United Nations Environment Progamme's *Global Environment Outlook 4* (UNEP, 2007), the four scenarios produce quite different levels of atmospheric carbon. We should note, however, that even the Sustainability First scenario, which was the most aggressive that we could somewhat realistically imagine at the time, does not hold the level

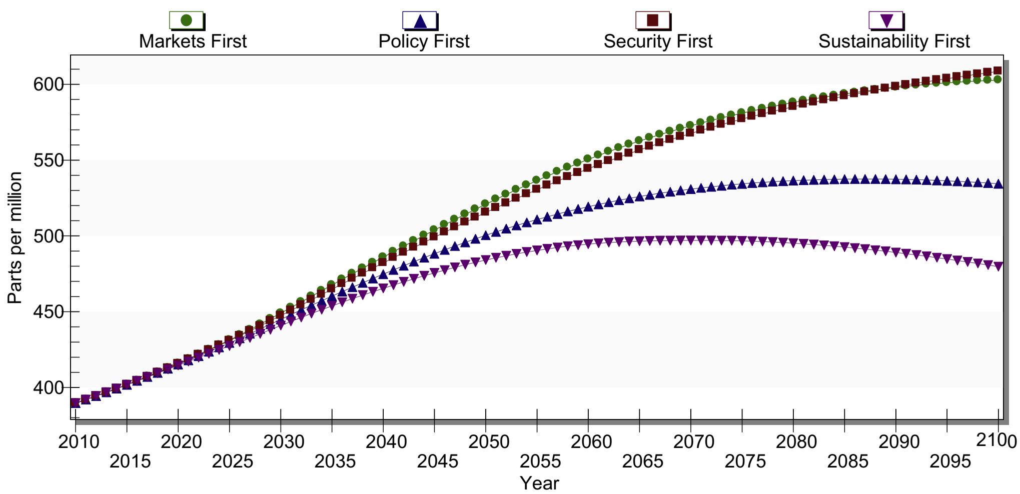

Fig. 12. Atmospheric carbon dioxide in four scenarios.

below the often-targeted 450 parts per million. At the same time, our higher forecasts tend to fall below those that many integrated assessment models produce.[9]

The alternative atmospheric carbon forecasts produce alternative average world temperature forecasts, which in turn feed through to country-specific temperature and precipitation forecasts (relative to 1990 levels). Those then affect agricultural yields and globally push them down. Like the energy model the agricultural model is, however, one of equilibration involving prices. The price elasticity of food demand is relatively low but the price responsiveness of production is in the longer run quite high. Thus somewhat higher prices direct more investment to agricultural production and partially offset the impact of environmental change.

Overall, this discussion has led us into the importance of scenario analysis as a way in which we need to treat both uncertainty and exploration of policy and social leverage, as well as into the interrelatedness of forecasts across the issue domains of the system. We turn now to further discussion of scenario analysis.

4. Forecasting with IFs: scenario analysis

The three main functionalities of the IFs interface are historical data analysis (longitudinal and cross-sectional), display of the Base Case and other scenarios (with many specialized displays such as that for age-sex-education of countries), and scenario development. Fig. 13 shows the main form for development of scenarios, a form that makes all model parameters and initial conditions available for change and allows parameters to be changed year-by-year if desired. The top portion of that form is organized by the categories for systemic uncertainties of Technological Change (in sub-categories such as agriculture/food and energy) and Environmental Uncertainties and the bottom portion is organized by three agent categories, namely Households, Governments, and Firms. The dialog displayed in the figure for picking a specific parameter to change illustrates the result of clicking on the Household category and the Demographic/Population subcategory.

We will illustrate the results of scenario analysis with one example in each of the three global transformation arenas, namely human development, social development, and sustainable development. The first illustration comes from our analysis of the potential for accelerating the global reduction in extreme (below $1.25 per day in 2005 dollars) poverty rates and numbers.[10] In the volume dedicated to that (Hughes et al., 2009) the project developed two sets of possible interventions, domestic and international in primary origin. Each set contained multiple interventions, such as reduction in fertility, acceleration of advance in education, and increase in intra-population transfers domestically or more foreign aid and foreign direct investment internationally.

One of the most common questions the project faces when students or others undertake scenario analysis is "how do I know what a reasonable value is for parameter change?" The discussion above around Fig. 10 and benchmarking analysis indicated one of the approaches to seeking "aggressive but reasonable" intervention levels. Another issue around interventions is that IFs, in spite of the very considerable detail in most of its models, remains at a macro level of analysis that means many interventions do not really represent policy interventions (such as Bolsa Familia in Brazil to encourage school attendance and use of neo-natal support systems) but rather represent the possible results of such policies (such as increased primary enrolment and completion rates, reduced child mortality due to respiratory infections, and increased domestic income transfers). This means that "policy analysis" in IFs is often a matter of analyzing the larger impact of reaching policy targets rather than of gauging the impact of actual policies (in some cases, such as taxing carbon, interventions are much closer to actual policy levers).

Fig. 14 shows the updated result of the full panoply of domestic and international interventions of earlier poverty analysis and illustrates two general findings of the analysis. First, the leverage of interventions in the longer term is substantial but often somewhat less than might be anticipated. It is hard to change the dynamic behavior of complex, fully interactive systems that have many negative or equilibrating loops (for instance, expenditures on education and health can reduce those on infrastructure or raise taxes and reduce investments on renewable energy, offsetting positive impacts on growth with negative ones). Related to this, policy-related interventions can sometimes actually work very differentially across time. In the case of our combined interventions, some such as increased investment and spending on education can, in the short- or middle-run, actually work against the longer-term aim of reducing poverty by diverting funds from immediate assistance. Second, we were uncertain before the analysis whether we would find in the longer run that policies were offsetting in their impacts, in part because of the competition effects just noted, or whether a significant set of policies would cumulatively produce reinforcing and larger effects than would one or a small set. In the case of our poverty analysis we found that the set together was synergistically very considerably more powerful than any policy individually, supporting the utility of creating larger and complex alternative futures with the system (as we saw also for the four UNEP scenarios in Fig. 12).

Any intervention in the global system will, of course, have a ripple of far-reaching consequences not unlike the throwing of a stone into a pond, and that is true of interventions in IFs as well. For instance, the combined set of poverty interventions increase economic growth in Africa and related energy demand and use, leading to annual carbon emissions that are

[9] By comparison, the Baseline Scenario in the Global Energy Assessment forecasts atmospheric carbon dioxide to approach 1000 parts per million by 2100 (Johansson et al., 2012). This is closely tied to the differences in projections of the share of energy coming from non-fossil fuel sources discussed in a prior footnote.

[10] Turner et al. (2015) have moved analysis of poverty with IFs to newly released and often rebased 2011 purchasing power parity economic values.

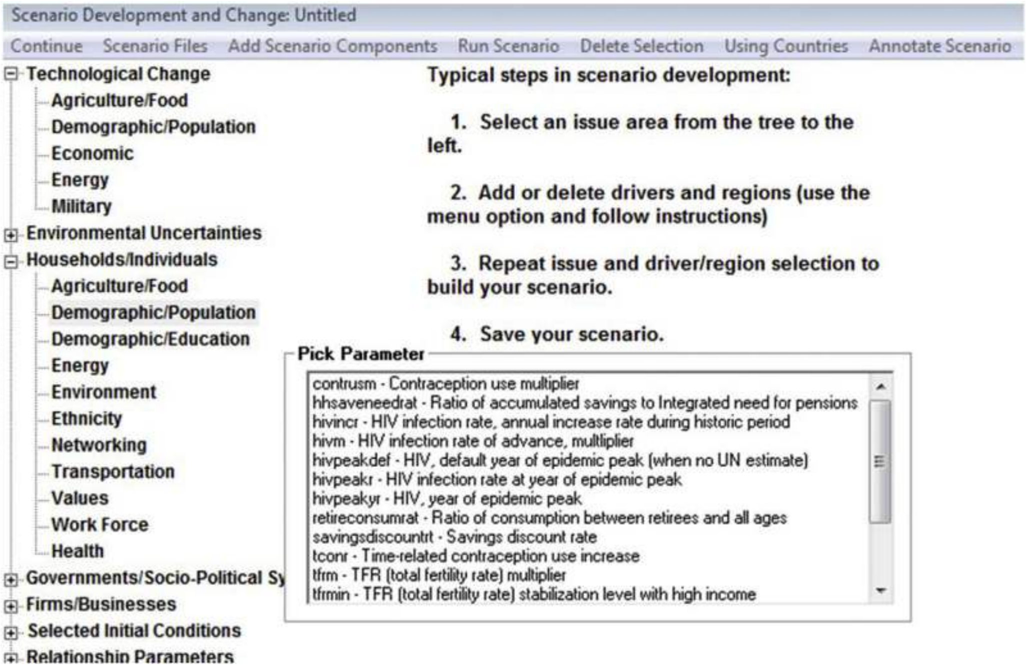

Fig. 13. The scenario menu or "tree" of the IFs system.
Source: International Futures, version 7.11.

11 percent above those of the Base Case scenario by 2060 (see Fig. 15) and still growing as opposed to declining in the Base Case. That is, changes that affect human development have important consequences for sustainability—some will be positive, but many will not.

In our analysis of governance we similarly created a combined intervention scenario, targeted toward strengthening national governance on three dimensions: security (reduced probability of internal conflict, but without repression, and improved performance on variables associated with instability), capacity (greater revenue raising ability and reduced

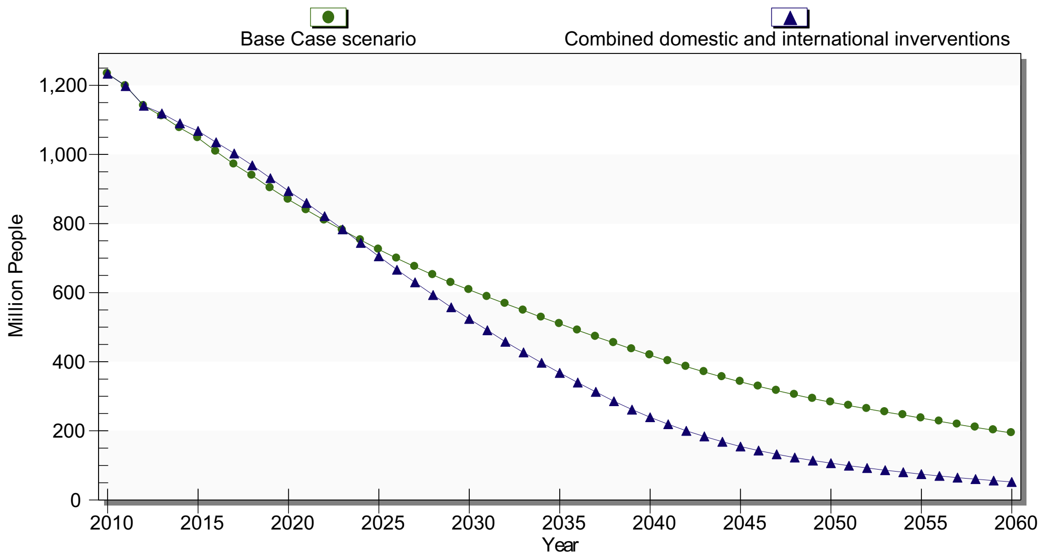

Fig. 14. The poverty reduction impact of a package of combined domestic and international interventions.
Note: Scenario packaged for general use as World Integrated Scenario Sets/Pardee PPHP Vol Series Main Cases/A3 Poverty Combined Dom Intl Interventoins.sce.
Source: International Futures, version 7.11.

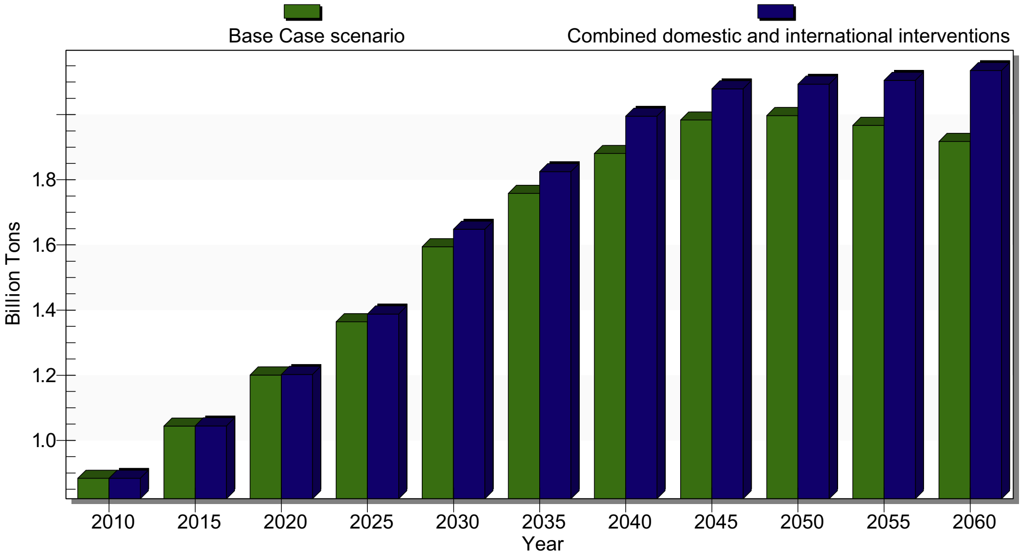

Fig. 15. Annual carbon emissions implications in South-Central Asia of combined poverty reduction interventions.
Note: Scenario packaged for general use as World Integrated Scenario Sets/Pardee PPHP Vol Series Main Cases/A3 Poverty Combined Dom Intl Interventoins.sce.
Source: International Futures, version 7.11.

corruption in using it), and inclusion (more democracy and inclusion of women, in part as a proxy for more general inclusiveness). See Fig. 16 for the resulting shifts in the strength of governance across the countries of the world.

An early finding, however, was that such strengthening of governance improved human well-being in societies around the world, but not as much as we expected. Our expectations on this issue had been somewhat naïve, because we had structured relatively limited forward linkages from governance to other variables beyond some improvement in economic productivity. In reality, of course, improved governance would in most societies strengthen policies as well, and this finding simply reinforced the known adage that in models you do ultimately get out what you put in, even if in complex ones the secondary and tertiary results can be surprising. Thus we constructed and exogenously added a set of policies we determined were consistent with strengthened governance (Hughes, Joshi, et al., 2014: 159). Fig. 17 shows the result for the human development index (HDI) globally. It adds 0.067 points on the 0–1 scale, a very significant boost by 2060.

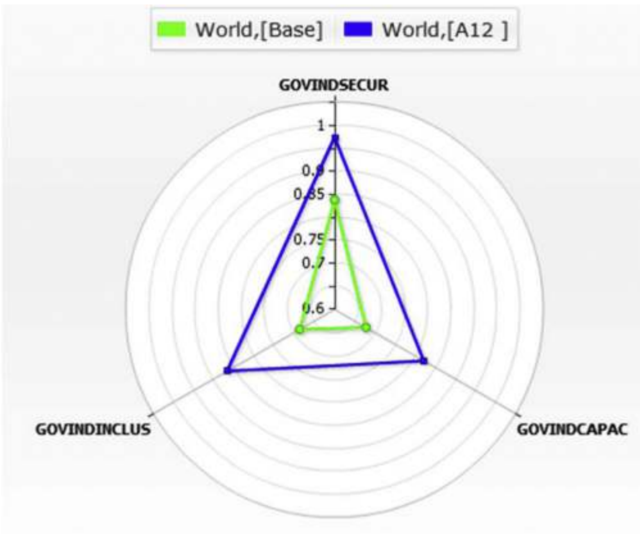

Fig. 16. Global governance in 2060 on three dimensions with strong interventions relative to the Base Case.
Note: Scenario packaged for general use as World Integrated Scenario Sets/Pardee PPHP Vol Series Main Cases/A12 Strengthened Governance and Policies.sce.
Source: International Futures, version 7.11.

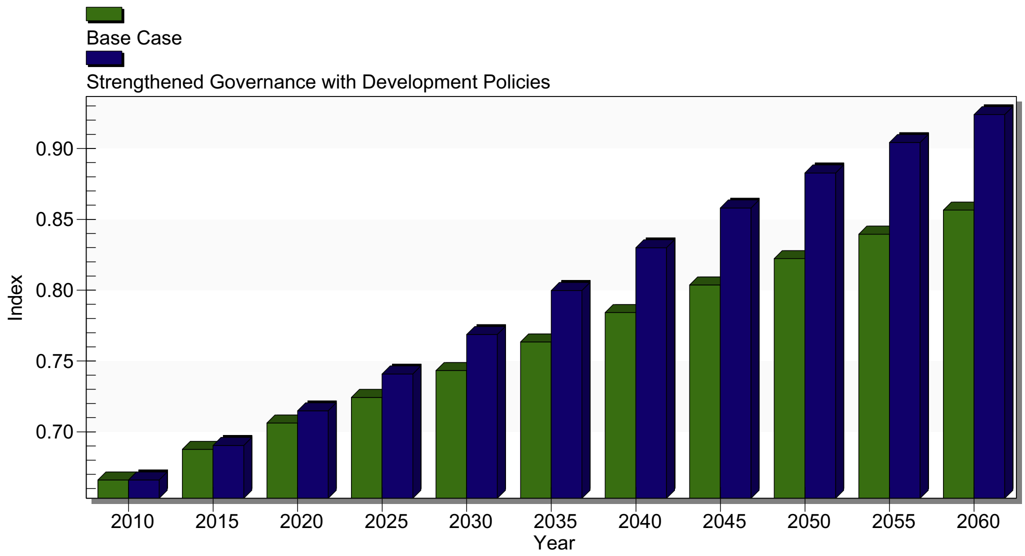

Fig. 17. Human development index globally in the Base Case and strengthened governance with policies scenarios.
Note: Scenario packaged for general use as World Integrated Scenario Sets/Pardee PPHP Vol Series Main Cases/A12 Strengthened Governance and Policies.sce.
Source: International Futures, version 7.11.

Our final scenario illustration comes from revisiting one of the policy briefs we prepared as part of our African Futures project in collaboration with the Institute for Security Studies (Moyer Jonathan & Firnhaber, 2012). The work on that brief, on the possibility of a Green Revolution in Africa, began with the development of a scenario (in this analysis only through 2030) of increased yields as might be the result of increased governmental research, improved credit systems, or many other policies (see Fig. 18). Note in terms of calibration of our intervention that the Base Case scenario is largely a continuation of the relatively flat and variable production per capita of the long-term historical period, but the improved yields scenario picks up on the somewhat better performance of the last two decades and accelerates that somewhat more. Thus both are inherently credible futures.

One of the early findings of that scenario analysis, however, was also one that we should have anticipated, namely that increasing agricultural production might not as significantly increase incomes and food purchasing/acquisition capability of

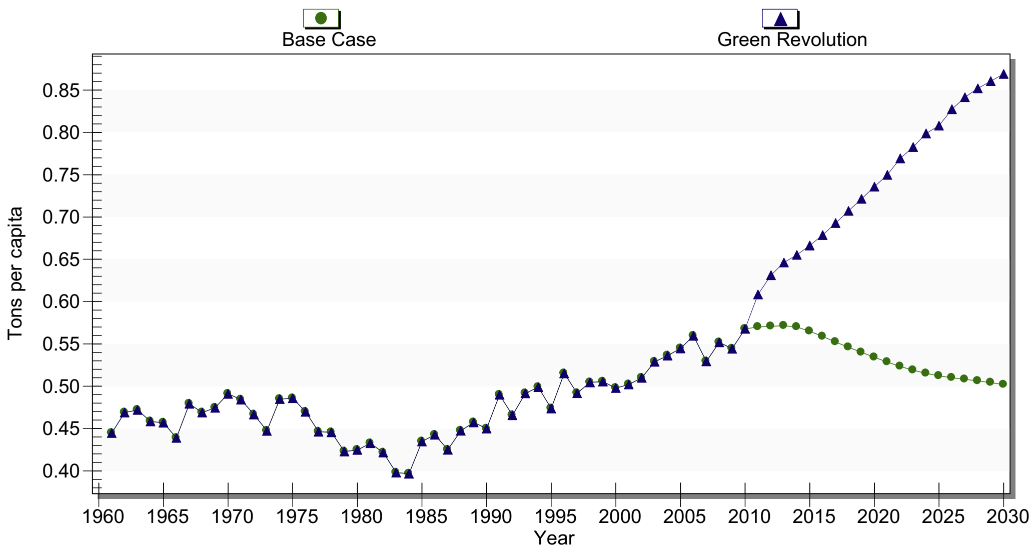

Fig. 18. African agricultural crop production per capita in the Base Case and Green Revolution with development scenarios.
Note: Scenario packaged for general use as World Integrated Scenario Sets/African Policy Briefs/Green Revolution/Green Rev.sce.
Source: International Futures, version 7.11.

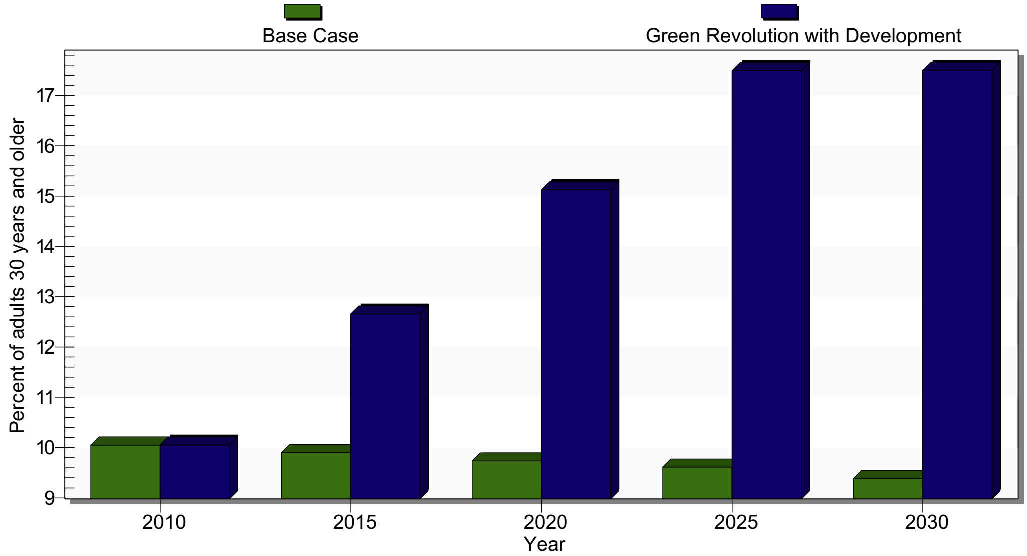

Fig. 19. African obesity rates in the Base Case and Green Revolution with development scenarios.
Note: Scenario packaged for general use as World Integrated Scenario Sets/African Policy Briefs/Green Revolution/Green Rev for Human Development.sce.
Source: International Futures, version 7.11.

African populations as we would like, but rather would lead to some substitution of domestic production for imported food and increased levels of exported agricultural production. This might be very beneficial for the continent, but our aim was improving caloric intake and reducing undernutrition. We found it necessary to expand the scenario to also assume increase in the incomes of Africans so as to increase their food demand. Not surprisingly, we then found that the combined scenario of enhanced local production and improved development did reduce undernutrition. We also found, however, that even with our optimistic assumptions about yield increases, Africa would need substantial rise in food imports.

Yet no intervention, regardless of its good intentions and even good effects, is likely to be without its costs or downside. Moving beyond the earlier analysis of the policy brief, Fig. 19 shows the rates of obesity in Africa in the two scenarios—the intervention nearly doubles those by 2030.

5. Conclusion

Global modeling has come a long way since its first emergence in the 1970s. The availability of data and empirical analysis, the sophistication of conceptualization and theory, and the capabilities of computing hardware and software have advanced so incredibly much that an observer looking back on those 40 plus years might wonder at the arrogance of the effort itself in the early years.

Then again, one might be impressed by the strong desire of the researchers who built those first models to help us better understand the world. And in spite of the dramatically expanded base for the effort that we have now, global model development and use remain at least as much an art as they are a science. The building of them has the character of a hand craft, with an improving tool kit in hand, but an enterprise more analogous perhaps to the early workshops and factories of Karl Benz and Henry Ford than to the automated production facilities of today's Volkswagen and Toyota. Hence an observer today might still recognize the enterprise to be at a fairly early stage.

Just as we have looked at the dramatic transformations of human, social, and sustainable development transformations over the past half century and used the IFs system to help us think about those of the next half century and more, this progression in modeling and its current status makes one think about the next decades of efforts in our own work and that of others. In the IFs project we know some of what needs to be done and that now can be done or soon may be possible. But that is a subject for another day.

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The IFs team has grown over the years and, under the leadership of Barry Hughes, many members have contributed very substantially to its development and therefore to the work reported here. Mohammod Irfan developed the education model. Randall Kuhn, Cecilia Peterson, and José Solórzano were critical in the development of the health model. Dale Rothman and

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References

Birkmann, J., Cutter, S. L., Rothman, D. S., Welle, T., Garschagen, M., van Ruijven, B., et al. (2013). Scenarios for vulnerability: Opportunities and constraints in the context of climate change and disaster risk. In J. Birkmann & R. Mechler (Eds.), *Advancing climate change adaptation and risk management, a special issue of climatic change* http://dx.doi.org/10.1007/s10584-013-0913-2

Braudel, F. (1979). *The perspective of the world. Vol. 3 of civilization and capitalism: 15th–18th century*. New York: Harper and Row.

Bremer, S. (Ed.). (1987). *The GLOBUS model: Computer simulation of world-wide political and economic developments*. Boulder, CO: Westview Press.

Bremer, S., & Hughes, B. B. (1990). *Disarmament and development: A design for the future?* Englewood Cliffs: Prentice-Hall.

Burt, A., Hughes, B. B., & Milante, G. (2014). Eradicating poverty in fragile states: Prospects of reaching the 'High-Hanging' fruit by 2030. In *World Bank policy research working paper 7002*. Washington, DC: World Bank Available at http://documents.worldbank.org/curated/en/2014/08/20040315/eradicating-poverty-fragile-states-prospects-reaching-high-hanging-fruit-2030

Cantore, N. (2011). *Future paths of poverty: A scenario analysis with integrated assessment models. CPRP working paper 200*. London: Overseas Development Institute.

Cantore, N. (2012). Sustainability of the energy sector in the Mediterranean region. *Energy, 48*(1), 423–430.

Cantore, N. (2014). The impact of temporary migration on source countries: A simulation exercise. *International Migration Review*.

Casetti, E. (2003). Power shifts and economic development: When will China overtake the USA? *Journal of Peace Research, 40*(3), 661–675.

Cave, J., van Oranje-Nassau, C., Schindler, H. R., Shehabi, A., Brutscher, P.-B., & Robinson, N. (2009). Trends in connectivity technologies and their socio-economic impacts. In *Final report of the study: Policy options for the Ubiquitous Internet Society. RAND technical report*. Cambridge, UK: RAND Europe.

Centro Nacional de Planeamiento Estratégico (CEPLAN) (2014). *Modelo International Futures (IFs): Fundamentos, adaptacíon uso para el Planeamiento Estratégico Nacional*. Available at http://www.ceplan.gob.pe/content/modelo-international-futures-ifs-fundamentos. See also #IFS_Perú.

Chadwick, R. W. (2006). Korea 2020, national security futures, development, democracy and choices: Building a Korea peace structure. *Journal for Peace and Justice Studies, 12*(2), 1–20.

Cilliers, J., Hughes, B. B., & Moyer, J. (2011). *African futures 2050: The next 40 years*. Pretoria, South Africa and Denver, CO: Institute for Security Studies and Frederick S Pardee Center for International Futures.

Cilliers, J., & Schúnemann, J. (2013). *The future of intrastate conflict in Africa: More violence or greater peace?* Pretoria, South Africa: Institute for Security Studies.

Cilliers, J., & Sisk, T. D. (2013). *Assessing long-term state fragility in Africa: Prospects for 26 "More Fragile" countries*. Pretoria, South Africa: Institute for Security Studies ISS Monograph Number 188.

Cole, H. S. D. (1977). *Global models and the international economic order*. Oxford: Pergamon Press.

Dickson, J. R., Hughes, B. B., & Irfan, M. T. (2010). Advancing global education. In *Patterns of potential human progress series* (vol. 2). Boulder, CO, and New Delhi, India: Paradigm Publishers and Oxford University Press.

Eshbaugh, M., Firnhaber, E., McLennan, P., Moyer, J. D., & Torkelson, E. (2011, August). *Taps and toilets: How greater access can radically improve Africa's future. African Futures Project: African Futures Paper No. 1*. Available at http://pardee.du.edu/sites/default/files/PolicyBrief_AFP_TapsToilets.pdf

Forester, J. W. (1971). *World dynamics*. Cambridge, MA: Wright-Allen Press.

Goldstone, J. A., Bates, R. H., Epstein, D. L., Gurr, T. R., Lustik, M. B., Marshall, M. G., et al. (2010). A global model for forecasting political instability. *American Journal of Political Science, 54*(1), 190–208. http://dx.doi.org/10.1111/j.1540-5907.2009.00426.x

Hedden, S., Moyer, J. D., & Rettig, J. (2013, December). *Fracking for shale gas in South Africa: Blessing or curse? African Futures project: African Futures paper no. 9*. Available at http://pardee.du.edu/sites/default/files/PolicyBrief_AFP_FrackingSA.pdf

Hillebrand, E. E. (2008). The global distribution of income in 2050. *World Development, 36*(5), 727–740. http://dx.doi.org/10.1016/j.worlddev.2007.05.013

Hillebrand, E. E. (2010). Deglobalization scenarios: Who wins? Who loses?. *Global Economy Journal, 10*(2), 1–19. http://dx.doi.org/10.2202/1524-5861

Hillebrand, E. E., & Closson, S. (2015). *Energy, economic growth, and geopolitical futures*. Cambridge, MA: MIT Press.

Hughes, B. B. (1980). *World modeling: The Mesarovic-Pestel world model in the context of its contemporaries*. Lexington, MA: Lexington Books.

Hughes, B. B. (1984). Review of groping in the dark by Donella Meadows, John Richardson, and Gerhardt Bruckmann. *Journal of Forecasting, 3*(4), 460–461. http://dx.doi.org/10.1002/for.3980030409

Hughes, B. B. (1984b). *World futures*. Baltimore: The Johns Hopkins University Press.

Hughes, B. B. (1985). World models: The bases of difference. *International Studies Quarterly, 29*(1), 77–101.

Hughes, B. B. (1993, 1996, 1993, 1999). *International Futures: Choices in the search for a new world order*. Boulder, Colorado: Westview (three editions published with computer simulation).

Hughes, B. B. (1997). Rough road ahead: Global transformations in the 21st century. *Futures Research Quarterly, 13*(2), 83–107.

Hughes, B. B. (1999). The International Futures (IFs) modeling project. *Simulation and Gaming, 30*(3), 304–326.

Hughes, B. B. (2001). Choices in the face of uncertainty: The International Futures (IFs) model. *Futures, 33*, 55–62.

Hughes, B. B. (2001b). Global social transformation: The sweet spot, the steady slog, and the systemic shift. *Economic Development and Cultural Change, 49*(2), 423–458. http://dx.doi.org/10.1086/452510

Hughes, B. B. (2002). *International Futures (IFs) model, UNESCO Encyclopaedia of Life Support Systems (EOLSS), developed under the auspices of the UNESCO*. Oxford: Eolss Publishers; United Nations.

Hughes, B. B. (2004). Regimes and social transformation. In A. Underdal & O. Young (Eds.), *Regime consequences: Methodological challenges and research strategies*. Dordrecht, the Netherlands: Kluwer Academic Publishers.

Hughes, B. B. (2004b). *The Base Case of International Futures (IFs): Comparison with other forecasts*. Denver, CO: Pardee center for International Futures working paper prepared for the national intelligence council project 2020 and International Futures (IFs) project use Available on IFs website: http://www.ifs.du.edu/documents/reports.aspx

Hughes, B. B. (2005). *Forecasting productivity and growth with International Futures (IFs), part 1: The productivity formulation. Working paper*. Denver, CO: University of Denver Available on the IFs website: http://www.ifs.du.edu/documents/reports.aspx

Development-oriented policies and alternative human development paths: Aggressive but reasonable interventions (2013). Hughes, B. B. (Ed.). *Prepared by the Frederick S. Pardee Center for International Futures, and published as UNDP HDRO Occasional Paper 2013/05* Available at http://hdr.undp.org/sites/default/files/hdro_1305_pardee.pdf

Hughes, B. B., & Hillebrand, E. E. (2006). *Exploring and shaping International Futures*. Boulder, CO: Paradigm Publishers.

Hughes, B. B., & Hossain, A. (2003). *Long-term socio-economic modeling: With universal, globally-integrated social accounting matrices (SAMs) in a general equilibrium model structure. Working paper*. Denver, CO: University of Denver http://www.ifs.du.edu/assets/documents/economyandsamdocument46.pdf

Hughes, B. B., & Irfan, M. T. (2007). Assessing strategies for meeting the millennium development goals. In R. Reuveny & W. R. Thompson (Eds.), *North and south in the world political economy*. Carlton, Australia: Blackwell Publishing.

Hughes, B. B., Irfan, M. T., Moyer, J. D., Rothman, D. S., & Solórzano, J. R. (2011). Forecasting the impacts of environmental constraints on human development. *Prepared by the Frederick S. Pardee Center for International Futures, and published as UNDP 2011a/08* Available at http://hdr.undp.org/en/reports/global/hdr2011/papers/HDRP_2011_08.pdf. Revised version published May 10 in special issue of Sustainability on the Socioeconomic and Political Outcomes of Climate Change (with Appendix on the model). Available at http://www.mdpi.com/2071-1050/4/5/958

Hughes, B. B., Irfan, M. T., Moyer, J. D., Rothman, D. S., & Solórzano, J. R. (2012). Forecasting the impacts of environmental constraints on human development. *Sustainability, 4*(5), 958–994. http://dx.doi.org/10.3390/su4050958. Available at http://www.mdpi.com/2071-1050/4/5/958

Hughes, B. B., Irfan, M. T., Khan, H., Kumar, K., Rothman, D. S., & Solórzano, J. R. (2009). Reducing global poverty. In *Patterns of potential human progress series* (vol. 1). Boulder, CO, and New Delhi, India: Paradigm Publishers and Oxford University Press.

Hughes, B. B., Joshi, D. K., Moyer, J. D., Sisk, T. D., & Solórzano, J. R. (2014). Strengthening governance globally. In *Patterns of potential human progress series* (vol. 5). Boulder, CO, and New Delhi, India: Paradigm Publishers and Oxford University Press.

Hughes, B. B., Kuhn, R., Peterson, C. M., Rothman, D. S., & Solórzano, J. R. (2011). Improving global health. In *Patterns of potential human progress series* (vol. 3). Boulder, CO, and New Delhi, India: Paradigm Publishers and Oxford University Press.

Hughes, B. B., Kuhn, R., Peterson, C. M., Rothman, D. S., Solórzano, J. R., Mathers, C. D., et al. (2011). Projections of global health outcomes from 2005 to 2060 using the International Futures integrated forecasting tool. *Bulletin of the World Health Organization, 89*, 478–486. http://dx.doi.org/10.2471/BLT.10.083766 Available at http://www.who.int/bulletin/volumes/89/7/10-083766.pdf

Hughes, B. B., Kuhn, R., Margolese-Malin, E. S., Rothman, D. S., & Solórzano, J. R. (2015). Opportunities and challenges of a world with negligible senescence. *SENS Foundation, 99*, 77–91. http://dx.doi.org/10.1016/j.techfore.2015.06.031

Hughes, B. B., Moyer, J., & Sisk, T. D. (2011). *"Vulnerability to interstate conflict: Evaluating quantitative measures." Peaceworks report no. 72*. Washington, DC: United States Institute of Peace Available at http://www.usip.org/sites/default/files/Vulnerability_to_Intrastate_Conflict.pdf

Irfan, M. T. (2012). Knowledge capacities and their impact on well-being. *Sketch of working paper for the Frederick S. Pardee Center for International Futures*.

Irfan, M. T., & Margolese-Malin, E. S. (2012). SADC higher education futures 2050. In P. Kotecha (Ed.), *Building higher education scenarios 2025: A strategic agenda for development in SADC. SARUA leader dialogue series* (vol. 3, pp. 6–24). South Africa: Southern African Regional Universities Association.

Jaeger, A., & Henrichs, T. (2008). *Modeling environmental change in Europe: Towards a model inventory (SEIS/ZForward). EEA technical report no. 11*. Copenhagen: European Environment Agency.

Johansson, T. B., Patwardhan, A., Nakićenović, N., & Gomez-Echeverri, L. (Eds.). (2012). *Global energy assessment (GEA)*. Cambridge: Laxenburg, Austria: Cambridge University Press; International Institute for Applied Systems Analysis Scenario data accessible at http://www.globalenergyassessment.org/

Johnston, P. D., & Hughes, B. B. (2004). Sustainable futures: Building policy options into a scenario for development in a global knowledge society. *Futures, 37*, 813–831.

Joshi, D., Hughes, B. B., & Sisk, T. D. (2015). Improving governance for the post-2015 sustainable development goals: Scenario forecasting the next 50 years. *World Development*.

Kuhn, R., Rothman, D., Turner, S., Solórzano, J., & Hughes, B. (2014). Beyond attributable burden: A scenario-based dynamic forecast of the avoidable burden of disease associated with household pollution. *Lancet* (manuscript under review).

Lovins, A. B. (1990). The Negawatt Revolution. *Across the Board, 27*(September (9)).

Marshall, M. G. (2013). *Polity IV project: Political regime characteristics and transitions 1800–2012*. http://www.systemicpeace.org/polity/polity4.htm

Mathers, C. D., & Loncar, D. (2006). Projections of global mortality and burden of disease from 2002 to 2030. *PLOS Medicine, 3*(11), 2011–2030. http://dx.doi.org/10.1371/journal.pmed.0030442

McCauley, D. (2014). U.S.–Iran rapprochement. *Small-Wars Journal* Small Wars Foundation. http://smallwarsjournal.com/jrnl/art/us-iran-rapprochement

McKinsey Global Institute (2013). *Disruptive technologies: Advantages that will transform life, business, and the global economy*. Available at http://www.mckinsey.com/insights/high_tech_telecoms_internet/disruptive_technologies

Meadows, D. L., Behrens, W. W., III., Meadows, D. H., Naill, R. F., Randers, J., & Zahn., E. K. O. (1974). *Dynamics of growth in a finite world*. Cambridge, MA: Wright-Allen Press.

Meadows, D., Richardson, J., & Bruckman, G. (1984). *Groping in the dark*. New York: John Wiley and Sons.

Moyer, J. D. (2015). *Measuring and forecasting relative national power over long-time horizons*. Frederick S Pardee Center for International Futures Working Paper.

Moyer Jonathan, D., & Firnhaber, E. (2012). *Cultivating the future: Exploring the potential and impact of a green revolution in Africa (August)*. African Futures project: African Futures Paper No. 4 Available at http://pardee.du.edu/sites/default/files/PolicyBrief_AFP_GreenRevolution.pdf

Moyer, J. D., & Hughes, B. B. (2012). ICTs: Do they contribute to climate change or sustainable development? *Technological Forecasting and Social Change*. http://dx.doi.org/10.1016/j.techfore.2011.12.005 Available at http://www.sciencedirect.com/science/article/pii/S0040162511002836

Nakicenovic, N., Lempert, R. J., & Janetos, A. C. (2014). A framework for the development of new socio-economic scenarios for climate change research: Introductory essay. *Climatic Change, 122*(3), 351–361. http://dx.doi.org/10.1007/s10584-013-0982-2

Oeppen, J., & Vaupel, J. W. (2002). Broken limits to life expectancy. *Science, 296*(5570), 1029–1031.

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., et al. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change, 122*(3), 387–400. http://dx.doi.org/10.1007/s10584-013-0905-2

Pearson, R. (2011). Using the International Futures global modeling system (IFs) for alternative scenarios by the numbers. *Foresight, 22*, 13–19.

Piketty, T. (2014). *Capital in the twenty-first century*. Cambridge, MA: Harvard University Press.

Rothman, D. S., Irfan, M. T., Margolese-Malin, E. S., Hughes, B. B., & Moyer, J. D. (2013). Building global infrastructure: The next 50 years. In *Patterns of potential human progress series* (vol. 3). Boulder, CO and New Delhi, India: Paradigm Publishers and Oxford University Press.

Rothman, D. S., Siraj, A., & Hughes, B. B. (2014). Enhancing the quantitative representation of socioeconomic conditions in the shared socioeconomic pathways (SSPs) using and integrated modeling system. *Frederick S. Pardee Center for International Studies Working Paper*.

Sargent, R. G. (1998). Verification and validation of simulation models. In D. J. Medeiros, E. F. Watson, J. S. Carson, & M. S. Manivannan (Eds.), *Proceedings of the 1998 Winter Simulation Conference*.

Shepherd, A., Mitchell, T., Lewis, K., Lenhardt, A., Jones, L., Scott, L., et al. (2013). *The geography of poverty, disasters and climate extremes in 2030*. London: Overseas Development Institute Available at http://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/8633.pdf

Shepherd, A., Scott, L., Mariotti, S., Kessy, F., Gaiha, R., da Corta, L., et al. (2014). *The chronic poverty report 2014–2015: The road to zero extreme poverty*. London: Overseas Development Institute Available at http://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/8834.pdf

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., et al. (2014). *Integrated assessment of global environmental change with IMAGE 3.0 – Model description and policy applications*. Utrecht, the Netherlands: PBL Netherlands Environmental Assessment Agency Available at http://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0

Turner, S., Cilliers, J., & Hughes, B. (2015). *Reducing poverty in Africa: Realistic targets for the post-2015 MDGs and agenda 2063. Africa Futures Paper 10*. Pretoria, South Africa and Denver, Colorado: Institute for Security Studies and Frederick S Pardee Center for International Futures.

United Nations Development Programme (2011). *Human development report (UNDP HDR): Sustainability and equity: A better future for all*. New York: United Nations Development Programme.

United Nations Development Programme (2013). *Human development report: Global partnership for building shared prosperity*. New York: United Nations Development Programme.

United Nations Environment Programme (UNEP) (2007). *Global environment outlook (GEO) 4: Environment for development*. Valletta, Malta: United Nations Environment Programme.

United States Agency for International Development (USAID) (2013). *Getting to zero: A discussion on ending extreme poverty*. Washington, DC: US AID.

United States National Intelligence Council (NIC) (2004). *Mapping the global future: Report of the National Intelligence Council's 2020 project*. Washington, DC: NIC.

United States National Intelligence Council (NIC) (2008). *Global trends 2025: A transformed world*. Washington, DC: NIC.

United States National Intelligence Council (NIC) (2012). *Global trends 2030: Alternative worlds*. Washington, DC: NIC.

West, J. J., Smith, S. J., Silva, R. A., Naik, V., Zhang, Y., Adelman, Z., et al. (2013, October). Co-benefits of mitigating global greenhouse gas emission for future air quality and human health. *Nature Climate Change, 3*, 885–889 DOI:101038/Climate2009.

World Bank (2007). *Building knowledge economies: Advanced strategies for development. WBI development studies*. Washington, DC: World Bank.