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Supportive Measures and Policies for Developing Countries: a Paradigm Shift

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Background paper

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Introduction

The last fifty years of unprecedented development in the world have improved human condition enormously but at the same time have resulted in increasing gaps between the poor and the rich and in adverse environmental impacts on all scales, from indoor air pollution to climate change and biodiversity loss. The current development patterns are thus clearly unsustainable. A fundamental paradigm change is needed for a shift toward more sustainable development paths.

The recent financial crisis and the ensuing ever deeper economic depression are no doubt going to bring additional hardship especially to those without access to basic human needs. A predominant social issue that is increasingly becoming a major preoccupation for world leaders is addressing social inequality and poverty, especially in the developing world (Karekezi and Sihag, 2004). The longer the economic crisis deepens, the more threatened will be those living in poverty.

In response to the call to fight social inequality and poverty, the world leaders endorsed the United Nations Millennium Goals (MDGs) as agreed upon by the Millennium General Assembly of the UN in 2000 and as further advanced in 2002 at the World Summit on Sustainable Development. The MDGs include eight specific goals but the primary objective is to half extreme poverty by 2015 (Elliot, 2005). It is becoming increasingly evident that at current trends this goal will not be achieved even decades later in the poorest countries and regions of the world. Thus, it is urgent to devote significant effort toward the achievement of the MDGs and a more sustainable development paths thereafter.

Currently, it is estimated that about 2.6 billion people live on less than two and a half dollars a day (Chen and Ravallion, 2008; World Bank, 2008) — 75 percent of whom reside in rural areas (IADB, undated). Furthermore, it is estimated that 1.4 billion people live in extreme poverty (World Bank, 2008). This estimate is an upward revision from the previous one of one billion people in extreme poverty. This trend underscores the importance for increasing efforts to meet MDGs.

Affordable access to modern energy services has a significant role to play in meeting development goals as it is a fundamental prerequisite for reaching virtually all MDGs. However, modern energy services in the majority of developing countries are characterized by inequitable access, notably between the poor and affluent; as well as, between rural and urban areas. At the national level, this is demonstrated by the low levels of modern energy in the primary energy supply mix; low electrification levels; and, low electricity consumption levels.

About two billion people in the world, a third of the world population, are without access to modern energy and about 1.6 billion are without access to electricity – the very symbol of affluence and modernity – while still about 2.4 billion cook with traditional forms of biomass. Limited access to cleaner energy services supplied by modern energy carriers is an important contributor to rising levels of poverty in some sub-Saharan African countries (UNDP, 2007a and b).

It is estimated that connection of a household without access to electricity costs on the order of thousand dollars (Goldemberg, 2009) resulting in total capital needs of about $400 billion, assuming on average about five persons per household and two billion without access. Distributed over say twenty years, this translates into annual investment requirements of some $20 billion. This represents a huge investment that is lacking but that does not appear excessive in comparison to gigantic scale of the government guarantees and dept cancellation in the financial sector since the crisis has emerged. To be effective, this kind of investment would have to be enhanced with a certain level of free energy for the poorest, say 200 kWh per year or about half a kWh per day.

Thus, there is a clear need to embark on a new development path toward sustainable and affordable access to adequate energy services. Fortunately, many policies and measures directed toward increasing access to modern energy services have multiple benefits for other development goals, from the reduction of in-door air pollution and its assaults on human health to reductions of GHG emissions.

Some may argue that this transformation toward more sustainable development paths and energy patterns in the world will be difficult to achieve because falling consumer demand leads to a vicious circle that results in ever less employment decreasing further the demand for traditional goods and services.

At the same time, this crisis of the “old” is an opportunity for the “new” to emerge. This is an opportunity that needs to be sized and should not go to waste. Joseph Schumpeter has referred to this kind of paradigm-changing transformations as “gales of creative destruction” (Schumpeter, 1942). As old techno-economic and institutional development paths saturates, the chances for fundamentally new development paths to emerge and eventually diffuse are more likely.

Decarbonization of the global economy toward a carbon-free future is such a paradigm-changing transformation. It appears to be a must, given the ever more threatening manifestations of the global climate change. The unequivocal message of the IPCC Fourth Assessment Report is that climate change is accelerating and that it is almost certainly largely man-made. Anthropogenic greenhouse gas emissions (GHGs) over the last two centuries, since the beginning of the industrial revolution, have increased atmospheric concentrations of carbon dioxide from some 280ppm to over 380ppm today. The IPCC estimates that the global average surface temperature has increased by some $0.8^{o}C$ during the last century. The negative effects of the climate change can already be felt and determined action from the international community is required to promote innovation and technological developments for climate protection. This is particularly critical for the developing parts of the world as they are much more vulnerable to adverse consequences of climate change due to lower adaptive capacity associated with poverty and insufficient investment.

Historical Development and the Evolution of Energy Systems

In 1750, the world’s population was approximately 750 million people after some ten thousand years of slow but steady increase that resulted from the spread of ever better agricultural practices throughout the world as the aftermath of the Neolithic revolution. It is estimated that during the last thousand years the population has been growing at some 0.1 percent per year, or doubling on the order of every 500 years. The characteristic size of the global population was less than 50 million throughout the age of agriculture since the beginning of the Neolithic revolution (Graham Zabel, Population and Energy, August 2000, http://dieoff.org/).

With the emergence of the industrial revolution things changed radically. Table 1 shows that in 1800 global population was about one billion compared to over 6.5 billion today. This represents more than a six fold increase and corresponds to an annual growth rate of close to one percent per year. At this rate, the global population would continue to double every 80 years. Clearly, this historical rate of population growth is not sustainable. The explosive population growth was a result of drastic mortality decrease. Improved water quality, diet, sanitary conditions and medicine have all contributed. Today, the life expectancy is twice as high in the industrialized regions compared to that still prevailing in some regions of the world (75 years compared to about 35 in pre-industrial agricultural societies).

	1800	**2000**	**Factor**
Population (billion)	**1**	**6**	**x6**
GDP PPP (trillion 1990 $)	**0.5**	**36**	**x72**
Primary Energy (EJ)	**13**	**440**	**x34**
CO2 Emissions (GtC)	**0.3**	**6.4**	**x21**
Mobility (km/person/day)	**0.04**	**40**	**x1000**

Table 1. Absolute growth and corresponding factors from 1800 to 2000. Global population has increased to 6.5 billion in the meantime along with other factors. The growth of GDP (measured at purchasing power parietals, PPP) has outpaced the population growth by more than an order of magnitude meaning that an average person today is more than ten times more affluent compared to an average one in 1800. Primary energy increased at half the rate compared to GDP meaning that energy intensity of the global economy has declined at about one percent per year. The carbon dioxide emissions increased even less indicating a pervasive historical trend toward decarbonisation of the global economy at about 1.3 percent per year. Some of human activities like mobility and information increased orders of magnitude faster compared to GDP and energy.

Human productivity has increased enormously in terms of physical and monetary output per hour of work. To a large extent this was possible because of the replacement of human and animal work by machines fuelled by fossil energy releasing most of the agricultural land for food production. This historical transition is reflected in the enormous increase in global energy needs by a factor of 34 during the last two centuries.

As a result of this impressive increase in affluence, those who are fortunate to benefit from formal employment work roughly half the time compared to workers and farmers at the beginning of the industrial revolution. The annual work effort is somewhere between one and a half and to two thousand hours per annum in most of the developed countries. The reduction in working time in conjunction with long life expectancy means that today those engaged in formal work have about four times as much “free-time” over their lifetime, compared to two hundred years ago. Free or leisure time is often expended in consumptive mode such as increased mobility. Table 1 illustrates that the mobility has increased by three orders of magnitude during the last tree centuries. For example, in 1800 an average person in France travelled some twenty meters per day mostly on horseback and to a much lesser extent by boat, whereas today the average mobility is some fifty kilometres per person per day, mostly by car and by bus and about one kilometres per person per day by rail and air (Gruebler, 1998a).

Industrialization has changed the very fabric of human society and existence. An aggregate characterization of the multitude of changes is the Gross World (Economic) Product (GDP, which is an acronym for Gross Domestic Product) that measures the value of all goods and services associated with the formal economies. Table 1 shows the global GDP increasing more than seventy fold during the last two centuries, corresponding to an annual increase of two percent per year and a doubling in thirty five years.

However, two-thirds of the global population is excluded from the benefits of this development. Bringing them to the same levels of affluence and consumption would mean that the planetary process would be starched beyond the limits of the carrying capacities. In other words, further development in the world must take an alternative path and not follow the unsustainable one of the now industrialized and wealthy parts of the world.

An essential prerequisite of this continuous development process has been the ever-increasing quantity and quality of energy services with steadily improving efficiency of the energy systems. Figure 1 shows that in 1800 the world depended on traditional biomass (mostly fuelwood and agricultural waste) as the main energy source for cooking, heating and manufacturing. Human physical labour and work of animals were the main sources of mechanical energy, with some much more humble contributions of wind and hydraulic power. Figure 1 shows how drastically the nature of energy services has been transformed through replacement of traditional (non-commercial) energy sources by coal. In 1850 coal provided some twenty percent of global primary energy needs and peaked in the 1920s at almost seventy percent. This can be characterized as the first energy transition. The coal age brought railways, steam power, steel, manufacturing and telegraph to mention some of the technologies that constituted the “coal cluster.”

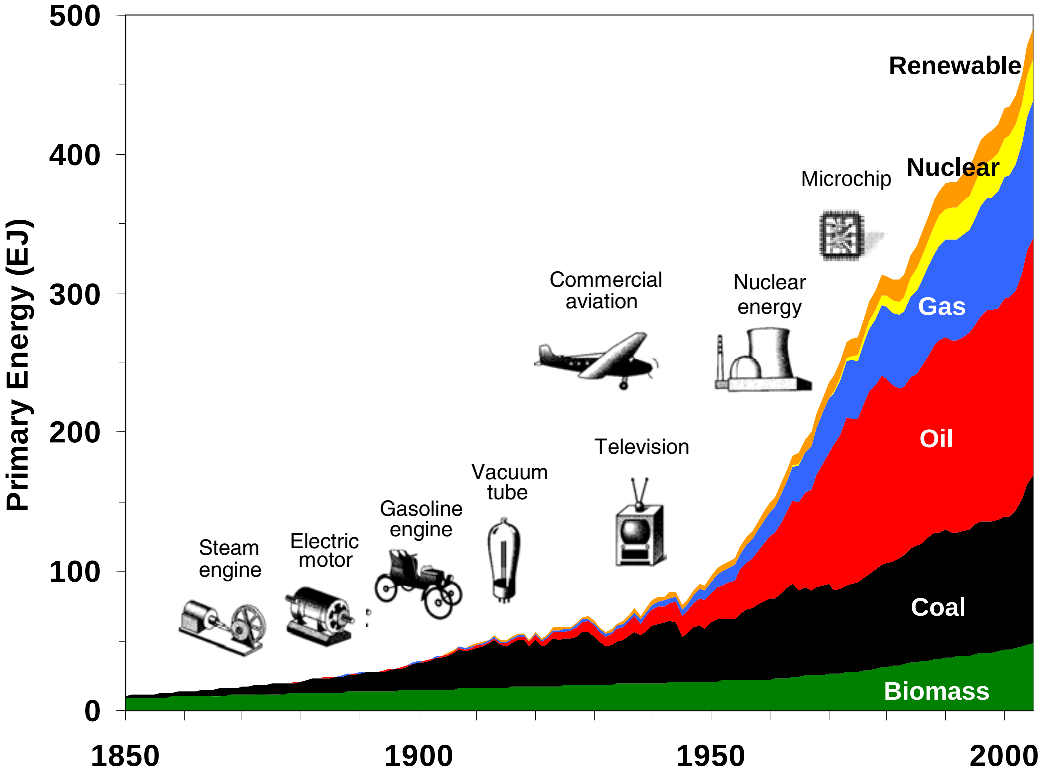


Figure 1: Global primary energy requirements since 1850, shown the six most important energy sources. Biomass is mostly traditional use of fuelwood. Hydropower includes all other modern renewable energy sources except biomass. Two development phases are clear visible, the replacement of traditional biomass by coal from 1850 to about 1920 and replacement of coal and traditional biomass by crude oil and later natural gas. Fossil energy sources provide about 80 percent of global energy needs. The fasted growth is for the modern renewables such as wind power and solar energy. Also shown are some of the more important technological changes that accompanied vigorous growth of global energy requirements.

Around 1900 motor vehicles were introduced along with petrochemicals, electricity and many other technologies that constitute the "oil cluster." It took another seventy years for oil to replace coal as the dominant source of energy in the world. Today, the global energy system is much more complex with many competing sources of energy and many high-quality and convenient energy carriers ranging form grid-oriented forms such as natural gas and electricity, to liquids that are mostly used in transportation to solids (coal and biomass) still used in the developing parts of the world (where a third of global population lives that still does not have access to modern energy services). Taken together, fossil energy sources provide some eighty percent of global energy needs, while fuelwood, hydropower and nuclear energy provide the rest.

Affordable and convenient energy services were one of the primary drivers for the emergence of the Anthopocene (Crutzen, xxx). They helped increase human productivity in all sectors from agriculture to industrial production and provision of services, and replaced human and animal work by abundant sources of power. Table 1 shows that the energy intensity of economic activities has in fact declined two fold but the 72 fold increase in economic activities required ever more energy. As the share of fossil energy sources, taken together, increased from 20 to 80% between 1850 and now, so did the emissions of carbon dioxide (as an unavoidable by-product of combustion). Consequently, energy-related emissions of CO_2 increased 22 fold to about 6 billion tons of carbon (6 GtC) today. Nevertheless, they have increased at a substantially lower level than energy requirements indicating substantive historical trend toward decarbonisation of our societies.

Human Development and Climate Change

The more than twenty-fold increase in global carbon dioxide emissions resulted in a dramatic increase of its atmospheric concentrations from about 280 parts per million (ppm) volume in 1750 to over 380 ppm today. (The difference of 100 ppm is equivalent to atmospheric concentrations changes between glacial and inter-glacial periods during the past million years that were associated of with global mean temperature changes of about 6 degrees Celsius.) Emissions of other radiatively active gases in the atmosphere have accompanied the increase in carbon dioxide. Methane concentrations have doubled over the same period. CFCs are a fundamentally new, anthropogenic constituent of the atmosphere that did not exist in nature. Another indication of the involved complexities is that emissions of sulphur aerosols and particulate matter increase along with the energy consumption and emissions of greenhouse gases (GHGs). Aerosol emissions are now regulated in most of industrialized countries and are in decline, but they have resulted in regional cooling that has offset some of the climate warming caused by increasing concentrations of GHGs.

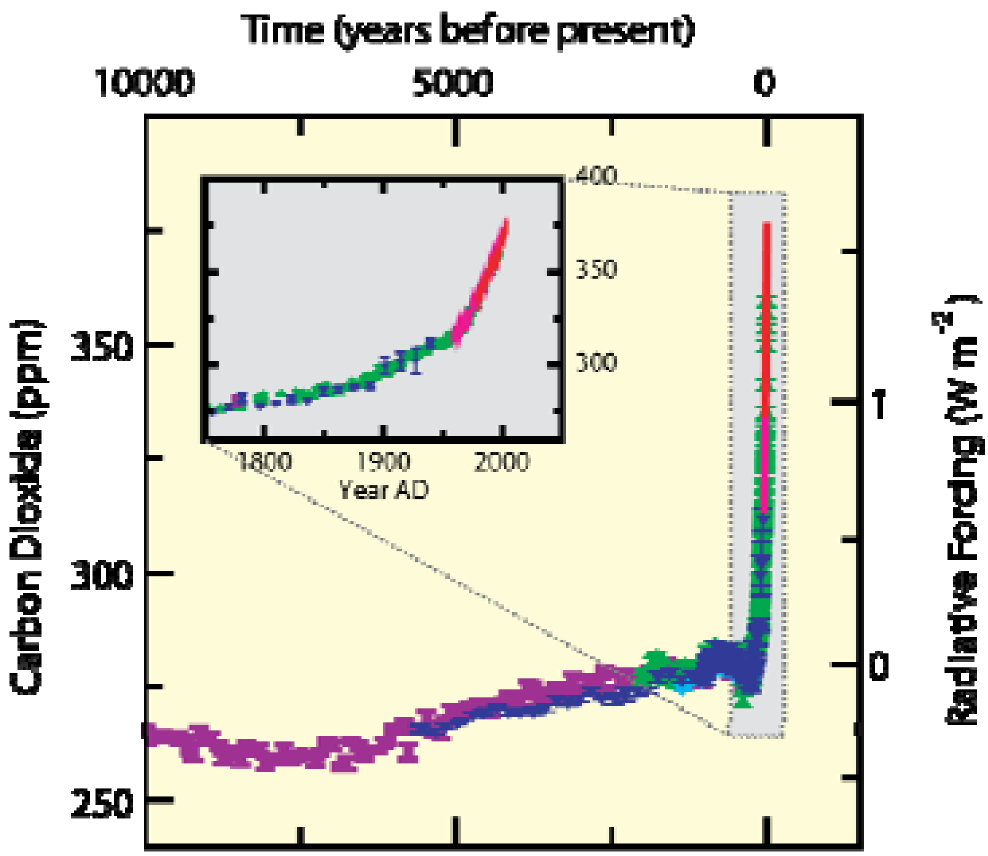


Figure 2. Increase of atmospheric carbon dioxide concentrations during the last ten thousand years and the resulting increase in radiative forcing (that measures the warming effect) compared to the radiative forcing of the solar radiation at the top of the atmosphere of 343 W/m2. The insert shows the concentrations increase since 1750 from about 2800 ppm to over 380 ppm today. Source: IPCC, 2007.

Intergovernmental Panel on Climate Change (IPCC) concluded that the climate change is unequivocal and that global mean temperature has increased by some 0.8 degrees Celsius since the beginning of the industrialization (IPCC, 2007). This is likely to double even if anthropogenic emissions were to cease immediately due to the huge inertia of the climate system. Eleven of the last dozen years have been warmest on the record. This is just one telltale sign of the unsustainability of current trends and consumptions patters; another of many reasons why the development path of now industrialized countries should not be replicated by the developing world with the vast majority of global population. The question we pose in this paper is whether there are alternative development paths that can lead to alleviation of poverty, increase of human living standards and protect climate and environment at the same time.

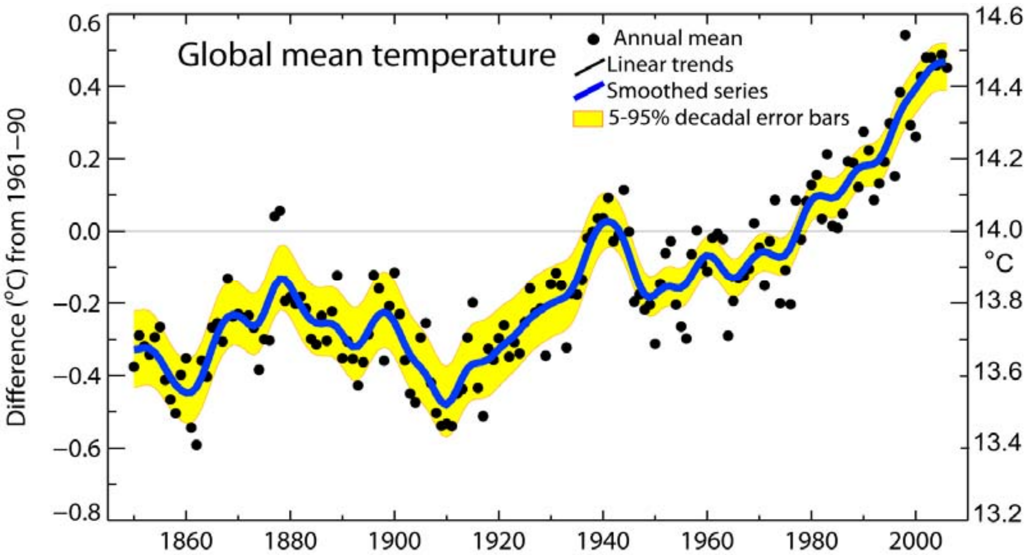


Figure 3. Increase of the mean temperature increase since 1850 of about 0.8 degrees Celsius. Most of the increase is attributed to human activities and the warming is "unequivocal". Source: IPCC, 2007.

Essentially, any specific concentration or radiative forcing target, from the lowest to the highest, requires emissions to eventually fall to very low levels as the removal processes of the ocean and terrestrial systems saturate. For low to medium stabilisation targets, this would need to occur during this century. However, to reach a given stabilization target, emissions must ultimately be reduced well below current levels. For achievement of the very low stabilization targets from many high baseline emissions scenarios, *negative net* emissions are required toward the end of the century. One of the few technologies that results in negative emissions in carbon capture and storage (CCS) in conjunction with sustainable biomass.

Mitigation efforts over the next two or three decades will have a large impact on opportunities to achieve lower stabilization levels (Fisher et al., 2007).

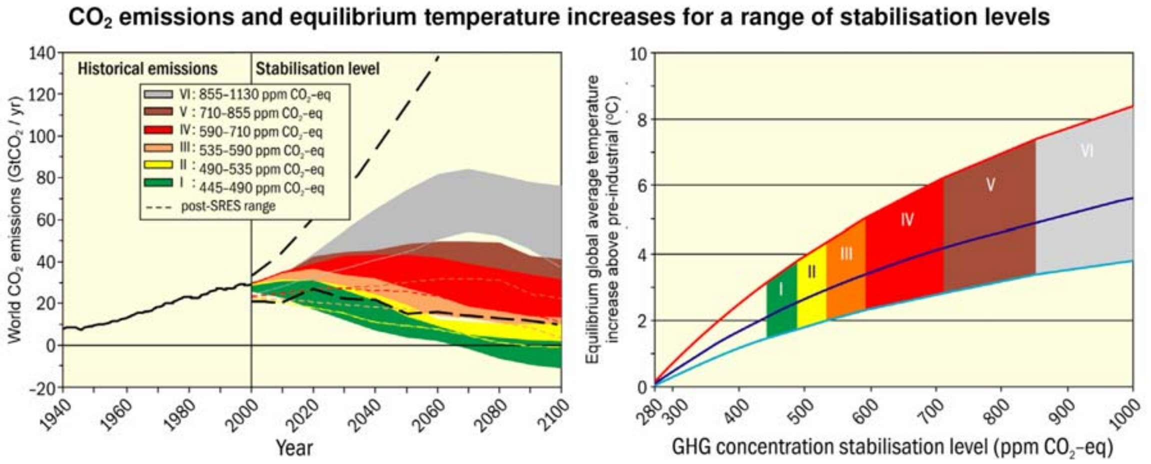


Figure 4. Global CO2 emissions for 1940 to 2000 and emissions ranges for categories of stabilisation scenarios from 2000 to 2100 (left-hand panel); and the corresponding relationship between the stabilisation target and the *likely* equilibrium global average temperature increase above pre-industrial (right-hand panel). Approaching equilibrium can take several centuries, especially for scenarios with higher levels of stabilisation. Coloured shadings show stabilisation scenarios grouped according to different targets (stabilisation category I to VI). Right-hand panel shows ranges of global average temperature change above pre-industrial, using (i) "best estimate" climate sensitivity of 3°C (black line in middle of shaded area), (ii) upper bound of *likely* range of climate sensitivity of 4.5°C (red line at top of shaded area) (iii) lower bound of *likely* range of climate sensitivity of 2°C (blue line at bottom of shaded area). Black dashed lines in the left panel give the emissions range of recent baseline scenarios published since the SRES (2000). Emissions ranges of the stabilisation scenarios comprise CO2-only and multi-gas (all GHGs and other radiatively active substances) scenarios and correspond to the 10th-90th percentile of the full scenario distribution. Note: CO2 emissions in most models do not include emissions from decay of above ground biomass that remains after logging and deforestation, and from peat fires and drained peat soils.

The timing of emission reductions depends on the stringency of the stabilization target. Lowest stabilization targets require an earlier peak of CO_2 and CO_2-equivalent emissions. In the majority of the scenarios in the most stringent stabilization category (a stabilization level below 490 ppm CO_2-equivalent, see Figure 4 above), emissions are required to decline before 2015 and are further reduced to less than 50 percent of today's emissions by 2050. For somewhat higher stabilization levels (e.g. below 590 ppm CO_2-equivalent) global emissions in the scenarios generally peak around 2010–2030, followed by a return to 2000 levels, on average around 2040. For high stabilization levels (e.g. below 710 ppm CO_2-equivalent) the median emissions peak around 2040 (Fisher et al., 2007). These kind of radical emissions reductions depart fundamentally from the current trends and will thus require paradigm changing transition of the global energy system toward full decarbonisation.

Thus, the need for fundamental changes of the global energy system, land-use patterns and also human behaviour is evident. Of outmost importance are technology improvements, diffusion of advanced technologies, learning-by-doing, and induced technological change, both for achieving the stabilization targets and cost reductions. While the technology improvement and use of advanced technologies have been employed in scenarios largely exogenously in most of the literature, new literature covers learning-by-doing and endogenous technological change. The latter scenarios show different technology dynamics and ways in which technologies are deployed, while maintaining the key role of technology in achieving stabilization and cost reduction (Fisher et al., 2007). This literature outlines the fundamental paradigm change and the transition from current to future decarbonised global economy. In this scenario literature, the “new” replaces the “old”, emissions intensive, human activities and consumption patterns.

Decarbonization of energy trends are persistent in the majority of reference and mitigation policy scenarios. The medians of scenario sets indicate decarbonisation rates of around 0.9 and 0.6 percent per year compared to historical rates of about 0.3 percent per year. Improvements of carbon intensity of energy supply and the whole economic need to be much faster than in the past for the low stabilization levels. On the upper end of the range, decarbonisation rates of up to 2.5 percent per year are observed in more stringent stabilization scenarios, where complete transition away from carbon-intensive fuels is considered (Fisher et al., 2007).

The scenarios that report quantitative results with drastic CO_2 reduction targets of 60 to 80 percent in 2050 (compared to today’s emission levels) require increased rates of energy intensity and carbon intensity improvement by two to three times their historical levels. This is found to require different sets of mitigation options across regions, with varying shares of nuclear energy, carbon capture and storage (CCS), biomass and hydrogen and other advanced energy carriers.

The costs of stabilization crucially depend on the choice of the baseline, related technological change and resulting baseline emissions; stabilization target and level; and the portfolio of technologies considered. Additional factors include assumptions with regard to the use of flexible instruments and with respect to revenue recycling. Some literature identifies low-cost technology clusters that allow for endogenous technological learning with uncertainty. This suggests that a decarbonised economy may not cost any more than a carbon-intensive one, if technological learning is taken into account (Nakicenovic and Gritsevsky, 2000 and Fisher et al., 2007).

There are different metrics for reporting costs of emission reductions, although most models report them in terms of macro-economic indicators, particularly GDP losses (GDP decline in stabilisation scenario in comparison with the baseline). For stabilization at about 590 to 710 ppm CO_2-equivalent, macro-economic costs range from -1 to 2 percent of GDP below baseline in 2050 (negative number means above the baseline, or GDP gains due to mitigation efforts). For a more stringent target of about 535 to 590 ppm CO_2-equivalent, the costs range from slightly negative to 4 percent GDP loss. GDP losses in the lowest stabilization scenarios in the literature in the range of 445 to 535 ppm CO_2-equivalent are generally below 5.5 percent by 2050, however the number of studies is relatively limited and is developed from predominantly low baselines (Fisher et al., 2007).

Multi-gas emission-reduction scenarios are able to meet climate targets at substantially lower costs compared to CO_2-only strategies (for the same targets, Fisher et al., 2007). Inclusion of other nonGnonnon-CO_2 (GHG) gases provides a more diversified approach that offers greater flexibility in the timing of the reduction programme.

Including land-use mitigation options as abatement strategies provides greater flexibility and cost-effectiveness for achieving stabilization. Even if land activities are not considered as mitigation alternatives by policy, consideration of land (land-use and land cover) is crucial in climate stabilization for its significant atmospheric inputs and withdrawals (emissions, sequestration, and albedo). Recent stabilization studies indicate that land-use mitigation options could provide 15 to 40 percent of total cumulative abatement over the century. Agriculture and forestry mitigation options are projected to be cost-effective abatement strategies across the entire century. In some scenarios, increased commercial biomass energy (solid and liquid fuel) is a significant abatement strategy, providing 5 to 30 percent of cumulative abatement and potentially 1 to 15 percent of total primary energy over the century (Fisher et al., 2007).

IPCC concluded that the decision-making concerning the appropriate level of mitigation in a cost-benefit context is an iterative risk-management process that considers investment in mitigation and adaptation, co-benefits of undertaking climate change decisions and the damages due to climate change. It is intertwined with development decisions and pathways. Cost-benefit analysis tries to quantify climate change damages in monetary terms as the social cost of carbon (SCC) or time-discounted damages. Due to considerable uncertainties and difficulties in quantifying non-market damages, it is difficult to estimate SCC with confidence. Results depend on a large number of normative and empirical assumptions that are not known with any certainty. SCC estimates in the literature vary by three orders of magnitude. Often they are likely to be understated and will increase a few percent per year (i.e. 2.4 percent for carbon-only and 2 to 4 percent for the social costs of other greenhouse gases (IPCC, WGIII, Chapter 3 and Working Group II, Chapter 20). SCC estimates for 2030, range between 8 and \$189/tCO_2-equivalent (WGII, Chapter 20), which compares to carbon prices between \$1 to 24 per tonne of CO_2-equivalent for mitigations scenarios stabilizing between 485-570 ppm CO_2-equivalent) and \$31 to 121 per tonne of CO_2-equivalent for scenarios stabilizing between 440-485 ppm CO_2-equivalent, respectively.

Figure 5 shows vividly the connection between stabilisation levels and adverse impacts on ten important sectors. All of the stabilisation levels above two degrees Celsius corresponding to concentrations of about 445 to 490 ppm CO_2-equivalent lead to “dangerous interference” with the climate system and vulnerabilities in all ten sectors associated with human well being. In contrast, lower stabilisation levels allow for adaptation in most of the ten sectors and for the very low levels (comparable to today’s climate) fall into the coping range.

All stabilisation scenarios indicate that a huge share of emissions reductions would come from the energy systems, in the range of 60 to 80 percent. In all of them, energy efficiency plays a key role in achieving radical emissions reductions. In a way, it is a prerequisite for increasing shares of zero-carbon energy systems. Including non-CO2 and CO2 land-use and forestry mitigation options provides greater flexibility and cost-effectiveness. Low stabilisation levels require early investments and substantially more rapid diffusion and commercialisation of advanced low-emissions technologies. Without substantial investment flows and effective technology transfer across the world, it would be difficult to achieve emission reduction at a significant scale. Mobilizing financing of incremental costs of low-carbon technologies is essential component of any long-term climate stabilization strategy (Fisher et al., 2007).

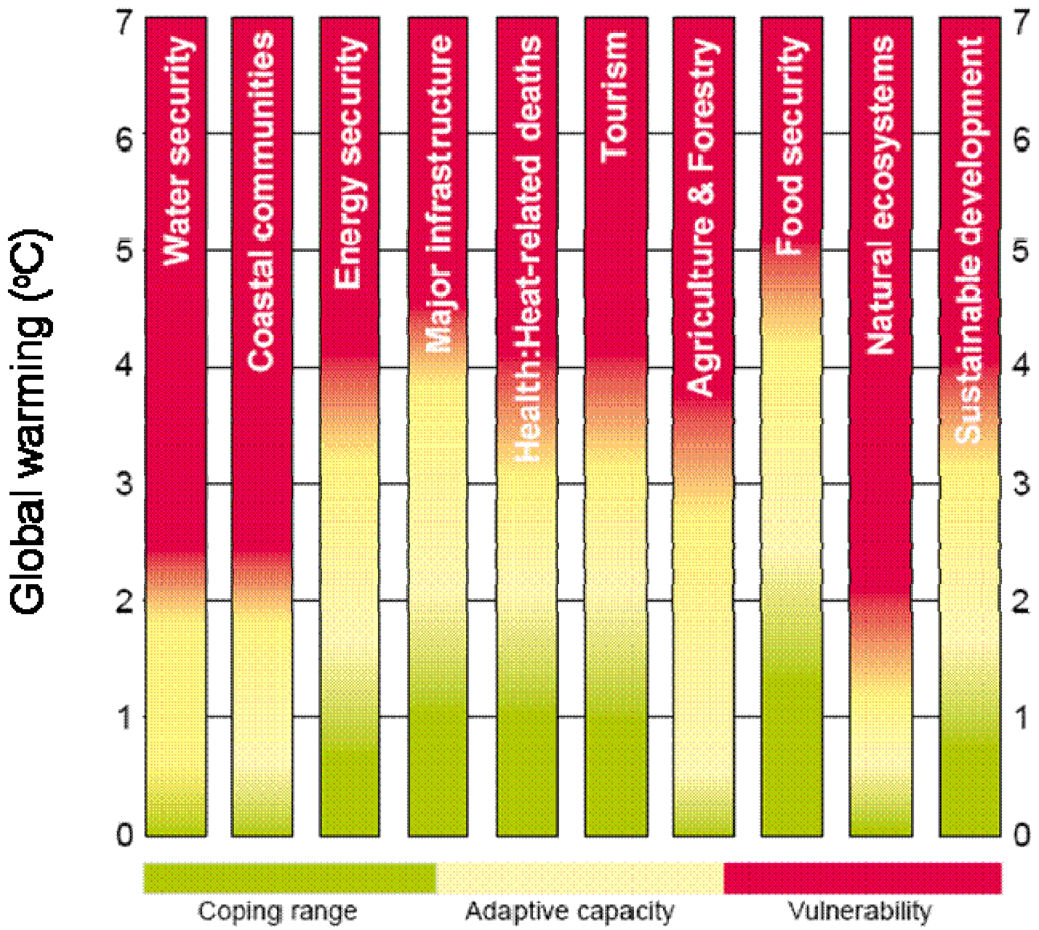


Figure 5. The vulnerabilities of ten key sectors to climate change, from water security and coastal communities to natural ecosystems and sustainable development. The colours of range from coping to adapting and vulnerability that leads to adverse impacts of climate change. The current global temperature increase of 0.8 degrees Celsius is shown to lead to the need to adapt to the adverse impacts of climate change in four of the ten sectors. Stabilisation at two degrees is still in the coping range for eight of the ten sectors. Higher levels of stabilization clearly lead to the possibility of dangerous climate change that is beyond the estimated adaptive capacity. See Figure 4 for stabilisation of atmospheric concentrations of greenhouse gases that correspond to the average global temperature change. Source: IPCC, 2007.

Technological Change as a Learning Process

It is becoming widely accepted among historians of technology and economists that technological change is a fundamental determinant of social progress and economic development. This is well illustrated by the above example (see Figure 1) of technological change in energy systems that expanded through more than an order of magnitude in two centuries, typical long-term growth rates being in the order of three to four percent per year. Yet the dynamics of technological change is external to most models of economic development and the resulting emissions scenarios be they for a whole country, or energy, transport or agriculture sectors alone. Technological change is as of now an exogenous determinant of growth in practically all models of economic and environmental interactions.

Drawing on the historical examples of technological change and development, we will outline a possible way of endogenising technological learning as driving force of social and economic change.

Every new technology has its roots in an invention, but it is through an innovation process, diffusion and pervasive adoption that technological change is perceived and impacts all of us in daily lives. In a highly stylized manner each technology undergoes a number of development phases starting with an basic invention and early development, followed by diffusion, if the technology turns our to be successful at the market place, and ending with a period of maturity and possibly also senescence. This is the simplified life-cycle model of technological development borrowed from analogies with biological growth and development. The actual process of technological change as illustrated for energy systems in Figure 1 is more complex. In detail, it encompasses patterns and drivers of technological change across sectors, over time, and across space. In terms of systems hierarchy, technological change arises from the spatial and temporal diffusion of individual innovations all the way up to the emergence of new technological *combinations* that could fundamentally redefine products, services, even entire markets. The complexities are intricate and include phenomena of deep technological uncertainty, spatial heterogeneity, as well as the potential economic, societal and environmental impacts that could result from pervasive diffusion and adoption of new technologies (Gruebler et al., 1999).

Each technology starts with some kind of invention, and its economic significance starts with innovation. According to Freeman (1986) the extremely important distinction between invention and innovation goes back to Schumpeter and has since been generally incorporated into economic theory. An *invention* is an idea, a sketch or model for a new or improved device, product, process or system. Inventions may often (not always) be patented but they do not necessarily lead to technological innovations. In fact the majority do not. An innovation is accomplished only with the first practical application of an invention, sometimes meaning the first commercial transaction involving the new product, process, system or device, although the word is more often used to describe the whole process of going from invention to the market.

Today, invention usually refers to basic research and development, but it can also be an unexpected breakthrough, a completely new idea. In fact, efforts to generate discoveries and inventions have been increasingly promoted by specialized public and private programs generally referred to as R&D efforts. This reflects the increasing recognition by public and private institutions that R&D efforts are an intrinsic prerequisites for economic development. Today, innovation process is as an important element of public and private technology polices. Usually it is based on applied research often with an explicit objective to achieve practical demonstration or a pilot project with a promise of commercialization (Gruebler et al., xxx and xxx).

Both of these two phases, invention and innovation, are usually resource intensive, they take a lot of time and have relatively low success rate. Like in biology, the selection mechanisms are stringent and only a few are chosen. Most importantly, neither invention nor innovation have any direct economic importance (except in terms of expectations), rather they are a precondition for early deployment of the technology in a market place and its commercialization. Economic significance of a technology really starts with its introduction in a market place and onset of competition with its alternatives. This usually occurs in niche markets. The distinction between the initial innovation and technology transfer disappears from this point on the development of technology. New technologies are generally more expensive and in many ways inferior compared to their more mature alternatives. But often they provide a new service of function not possible with the old technologies; e.g. precision of a digital clock compared to the best analog counterpart or speed of a jet airplane compared to the best piston engine powered model, zero-emissions compared to uncontrolled pollution.

The main attractiveness of new technologies, however, is that they hold the promise of improving market competitiveness in time. This applies equally to transfer of new technologies. The expectation is of declining costs and improving performance with accumulated knowledge. Figure 6 shows declining price of new technology starting with the introduction phase and accelerating during the growth phase, ending with only incremental improvements with onset of maturity. Thus, the improvement rates of new technologies can be more rapid compared to their more mature counterparts provided that niche markets exist or are created and provided that this is a continuous process. Innovation continues throughout the life cycle of a technology. Basic innovation that creates a new technology is followed by incremental innovations for improving performance and reducing costs. This requires investments in new technology often well before it becomes really competitive and brings profitability. With successful commercialization and diffusion, innovation continues in order to achieve even lower costs and better performance. Standardization, mass production, economics of scale are some of the characterizations of technological changes during the diffusion process.

Common to all of these innovative activities is accumulated knowledge, often called technological learning. Some of it is embodied in capital; some is much less tangible. Technological leaning is basically a process of learning through experience, through doing and using. It is a process of experimentation, competitive selection of a few among many innovations. Experimentation and selection of best ways of improving performance at least costs and reducing costs at least effort. Foremost, it is a process whereby new technological combinations that eventually merge into full *clusters* of new technological systems, e.g. an airplane, mobile phone, CCS power plant, etc.

History of technology is full of examples of wrong choices and promotions of new technologies. The track record of picking the winners is notoriously bad. Thus, diversity and richness of technological alternatives is generally desirable during the early, pre-commercial research and development phase of new technologies. During the diffusion phase the emphasis shifts to selective and gradual change under competitive conditions.

Learning

The performance and productivity of individual technologies and technological systems typically improves as organizations and individuals gain experience with them. Long-studied in human psychology, technological learning phenomena were first described for the aircraft industry by Wright (1936), who reported that unit labour costs in air-frame manufacturing declined significantly with “accumulated experience”, measured as cumulative production. Technological learning has since been analyzed empirically for numerous manufacturing and service activities (e.g., ship building, petrochemicals, steam and gas turbines, farming of broiler chickens). Learning concepts have also been applied in a wide range of human activities, such as the success rates of new surgical procedures, productivity in kibbutz farming, and reliability of nuclear plant operation (Argote and Epple, 1990).

In economics, “learning by doing”' and “learning by using” have been highlighted since the early 1960s (Arrow, 1962; Rosenberg, 1982). Learning phenomena are generally described in form “learning”' or “experience”' curves, which typically show the decline in unit costs of production as experience is gained. Because learning depends on accumulation of

actual experience and not just on the passage of time, learning curves generally take the form of a power function where unit costs decrease exponentially as a function (Gruebler et al., Energy Policy 27 (1999) 247}280, Gurebler et al., 1999 and 2000) of cumulative output. Other measures include cumulative investments, installed hardware, or other proxies for

“experience”.

The mechanisms for learning by doing are numerous. These include experience gained by individuals in performing routine tasks, improvement in the functioning of organizations (eg, plant management, logistics, marketing), and economies of scale (Cantley and Sahal, 1980).

The causal mechanisms are well established, but learning is not the only means of reducing costs. Other factors that are external to learning by doing, such as improvements in upstream technologies, can also lower costs and are correlated with growing experience.

Figure 6 gives an impressive example of technological learning in a developing country. It shows the rapid decline of renewable ethanol price in Brazil (Gurebler, 2009 private communication and Goldemberg, 2007). Ethanol is produced from sugarcane and used in automobiles as a replacement of gasoline. Today, most of the new cars in Brazil are so-called flex-fuel vehicles and are capable of using ethanol and/or gasoline in any mixture.

Figure 6 illustrates that at the beginning the new technology, namely ethanol, was costlier than mature technology alternatives, in this case gasoline. However, the new technology became increasingly competitive through continued improvements that were sustained by substantial investments. Overall, the cost per unit energy declined three-fold as cumulative experience increased. This was not a “free lunch”, but rather the result of long-term and sustained commitment to promote advanced technology while it is costlier and often also inferior to the more conventional alternatives. Cumulative additional investment (based on the difference between ethanol and gasoline price shown in Figure 6) was about US $2 billion. The actual total investment in the agricultural and industrial sectors for automotive ethanol is estimated at some US $5 billion (Goldemberg, 2007). However, Total savings from avoided oil import accrued to more than US $50 billion.

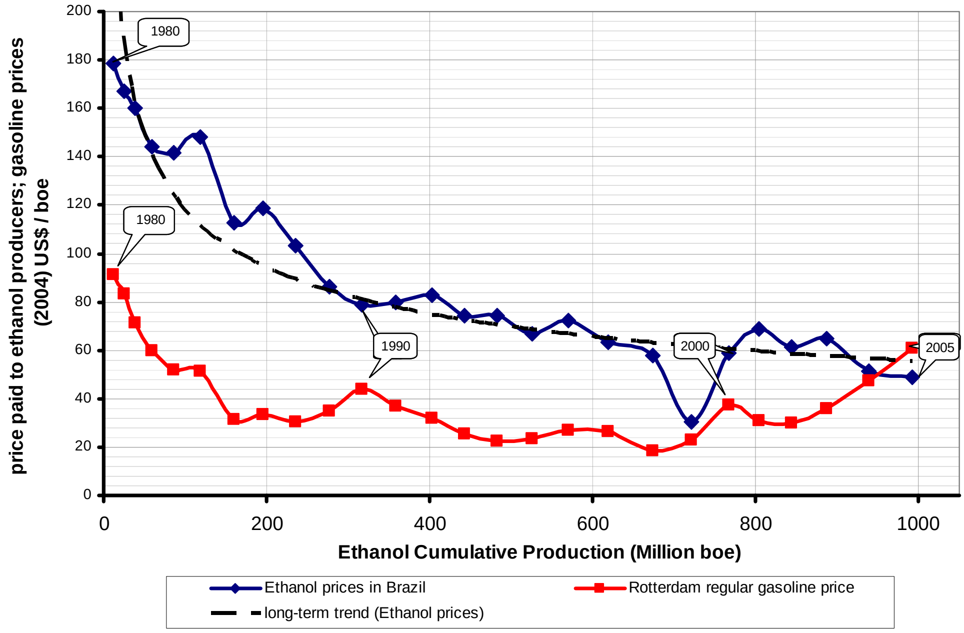


Figure 6. Producers price of ethanol compared to gasoline price in Brazil. Source: Gruebler, 2009 and Goldemberg, 2007.

In fact, the figure of US $5 billion matches well our estimate for the total investments in many new energy technologies before they became economically competitive with traditional technologies beyond special niche markets. However, the exact cost of applied R&D is difficult to estimate because statistics on such spending by private firms is typically not publicly available. Moreover, this figure does not include any of the original public and private investments into other closely related technologies that many have had “spill-over” effects on diffusion. Examples are military jet engines and their conversion for civilian passenger aircraft.

Together, research, development and demonstration (RD&D) are vital to the improvement of performance and the lowering of costs in the early stages of technological development. Essentially, the same applies to technology transfer. For example, the cost of photovoltaics produced in Japan halved between 1973 and 1976, but none of this improvement is evident in observed prices because it was prior to any installation of demonstration units and thus cumulative installed capacity was zero. Such RD&D expenditures are a small factor in the cost improvements of technologies that are already advanced to the stage of commercial niche markets and are candidates for pervasive diffusion, such as gas turbines in 1980. But in the earlier stages, RD&D accounts for a larger share of performance improvements and cost reductions. Thus learning curves must be expanded from their standard formulation if they are to be of practical use in modelling technological change that results from the changing competitive position of technologies. Doing so requires accurate and comparable data on applied research and development, which are usually scarce.

Emergence of new systems

The recent financial crisis and the ensuing ever deeper economic depression are no doubt going to bring additional hardship especially to those without access to basic human needs. At the same time, the crisis of the "old" is an opportunity for the "new" to emerge. This is an opportunity that needs to be sized and should not go to waste. Joseph Schumpeter has referred to this kind of paradigm-changing transformations as "gales of creative destruction" (Schumpeter, 1942). As old techno-economic and institutional development paths saturate, the chances for fundamentally new development paths to emerge and eventually diffuse are more likely.

Cleary, such possible emergence of the new and innovative that could lead toward more sustainable and equitable energy futures is not automatic nor autonomous. The crisis of the old needs to be sized through effective policies and measures before there can be an opportunity for the new to emerge. To realize this opportunity, global societies would need to invest in new technologies and behaviours over sufficiently long time so as to reap the benefits from technological learning. Hopefully, this would lead to a pervasive diffusion of carbon-saving technologies forming completely new technology clusters, behaviours and eventually new, decarbonised energy systems. It is this kind of transition that is at the core of Schumpeterian gales of creative destruction and creation of the new.

Equally, this kind opportunity that crisis gives to fundamental change can be wasted if societies chose instead to subsidise the old systems and paradigms further postponing the change to the new and at the same time creating conditions for ever-deeper crisis and depression. These risks are probably higher in the developing parts of the world because of the limited financial resources and institutional capabilities to establish effective policies and measures to lead toward a new phase of growth characterised by pervasive decarbonisations.

Here we propose that global decarbonisation and universal access to energy services are two important opportunities created the current financial crisis and the ensuing economic depression. While the depression is very disruptive and particularly destructive for the poor it does at least potentially sew the seeds of the renewal provided we are prepared to make the necessary institutional and financial investments.

The nature of the challenge

We have shown above that there is a significant global mitigation potential by 2030 at costs up to $100/tCO2 (~$380/tC) which corresponds to less than $50/bbl or roughly the current oil price. This potential is larger thereafter especially if the price of carbon should increase (Fischer et al., 2007). In mid 2008 the oil price was almost three times as high with $140/bbl indicating that the price of carbon in this range is not outside our recent experience of energy price volatility. We have illustrated above that such levels of carbon price would be necessary to achieve low stabilization levels in the range of two degrees Celsius. Staring slowly, the carbon prices would have to increase monotonically to many hundred dollars by the end of the century. This is an important prerequisite in most stabilisation scenarios for limiting temperature change to two degrees by the end of the century (see Figure 5).

Technological learning and the consequent change are essential for reducing mitigation costs and increasing mitigation potentials. Increasing carbon (and other GHGs) price would induce some of the technological, institutional and behavioural changes required for effective emissions reduction. Today, mitigation costs are generally lowest in the developing parts of the world. This means that the least-cost mitigation efforts also during the next decades would imply large investments in developing courtiers and/or carbon trade assuming that appropriate institutional arrangements can be made.

To realize benefits of technological learning, "upfront" investments would need to be made in new and advanced, carbon-saving technologies that would after scale-up and adoption lower the mitigation costs and increase the mitigation potentials. In other words, early upfront investments would have to be made to enable potential "buy-downs" along the learning curves. This means that large upfront investments would have to be made in now developing countries assuming again that they will have the lowest costs and highest mitigation potentials.

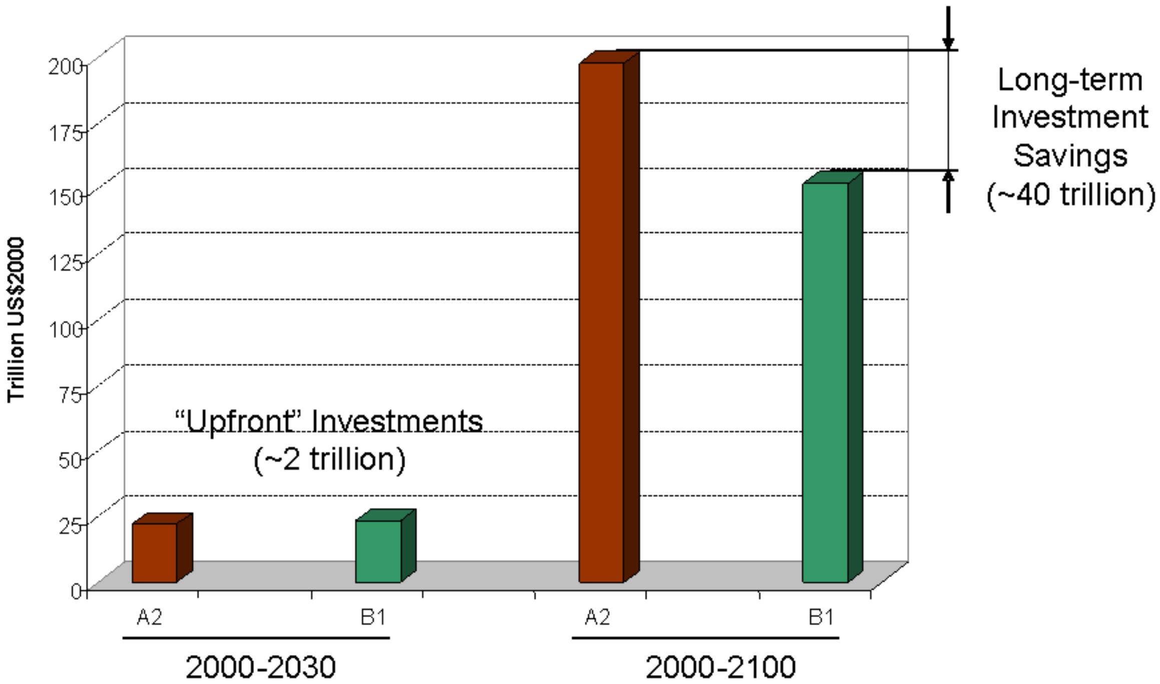


Figure 7. Energy system investments are shown for two scenarios, A2 and B1. A2 world is similar to "business-as-usual" scenarios in the literature with high increase of GHG emissions leading to global temperature change in the range of about 4.5 degrees Celsius. B1 is a more sustainable future with vigorous investment in new technologies and life-style changes that results in less than 3 degrees Celsius global temperature change. The total investments are in the range of US $20 trillion by 2030 and are slightly higher for the more sustainable future B1 due to build-up of capital-intensive energy systems. However, in the long-turn, beyond 2030, the capital costs of the more sustainable future are significantly lower due to induced technological change and learning. Source: Nakiceniovic, Riahi, 2007.

Investment in R&D and adoption of technologies improve performance of carbon-saving technologies and reduce their costs. However, the process is surrounded with deep uncertainties and very few technologies actually achieve the potentials. This is why it appears essential to make investments in a whole range of new technologies and systems. Each might require investments in R&D and early deployment on the order of about five billion dollars (as was the case with ethanol in Brazil, see Goldemberg, 2007, and many other technologies).

We will argue below that additional reason for deploying new and advanced technologies in developing parts of the world is that there will be largest energy market across both baseline and stabilization scenarios.

Catch-Up and Leapfrogging

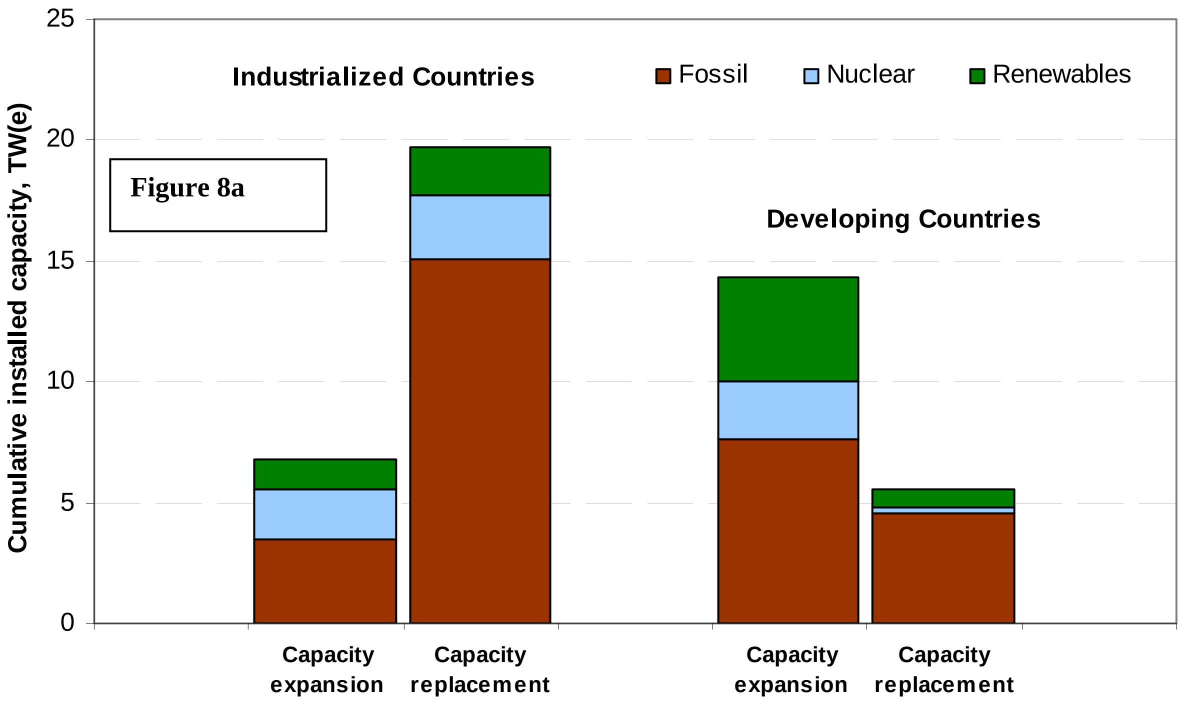
A part of the vast potential future markets for energy are those people today who are excluded from access either because of the lack of service or because the services are unaffordable. The actual figure of those excluded varies substantially. It ranges from some 1.6 billion (WEO, 2005 and 2008) to 2 billion (Nakicenovic et al., 1998 and WEA, 2000 and 2004). Most of those excluded live in rural areas; about 260 million are estimated to be urban dwellers (WEO, 2005). Provision of access over the next two decades would create a huge energy market increasing the potential benefits from technological learning through much larger scale of technology deployment. In addition, this would be equitable and very positive for creating new economic activities and development.

Assuming an average connection cost for those excluded at thousand dollars per house hold (Goldemberg, 2009, private communication) results in global investment needs of some $20 billion per year. This is a huge sum for the poorest of the developing countries but is humble in comparison with other financial flows. It is a pale shade of the hundreds of billions pledged by many OECD governments to rescue the financial sector, automotive industry and many other sectors of the economy. In comparison, saving 2 billion without access is a real bargain. ODA on energy is about $4 billion annually (4% of total ODA estimated at $100 billion in 2007, Ref. xxx). Therefore, connection of those excluded exceeds substantially the sums the developing regions are prepared to invest in energy development in the rest of the world.

In scenarios of future energy development, substantial improvement of energy access is assumed. With the large share of global population this renders the developing countries into the largest future energy markets. Figure 8a shows the cumulative installed capacity in A2r scenario of all power plants in industrialised countries (the North) and the developing countries (the South) from 2010 to 2030 (Riahi, 2007).

The capacity expansion is less than half in the North compared with the South. This illustrates how huge is the growing energy market in the developing parts of the world. Clearly, the capacity replacement is much larger in the North because of its huge stock of power plants and their substantial aging. Most of the capacity is fossil in this scenario. As mentioned, this scenario resembles "business-as-usual" future worlds with continuous reliance on fossil energy, especially coal in the US, China, India, Russia and so on. The total new capacity to be installed is almost 50TWe or at least twelve time the current total electric installed capacity in the world! Developing parts of the world would expand with the renewable installed capacity through 2030 with equivalent of all power plants in the world today and half as much in addition in nuclear plants. The potential improvements of this installed capacity are truly huge in the developing countries alone indicating how important the investment there would be for the private sector.

Figure 8b shows that this picture radically changes toward zero-emissions power plants in the stabilisation worlds even if they are based on fossil-intensive A2r scenario. Stabilisation at 670 ppm CO2-equivalent by 2100 leads to substantial restructuring especially for the new power plants that shift to be predominantly based on renewable energy sources and much more nuclear power. Here (and in stabilisation versions of B1 scenario) we assume a universal global mitigation effort, based on minimum costs and free trade in carbon and other goods and services.



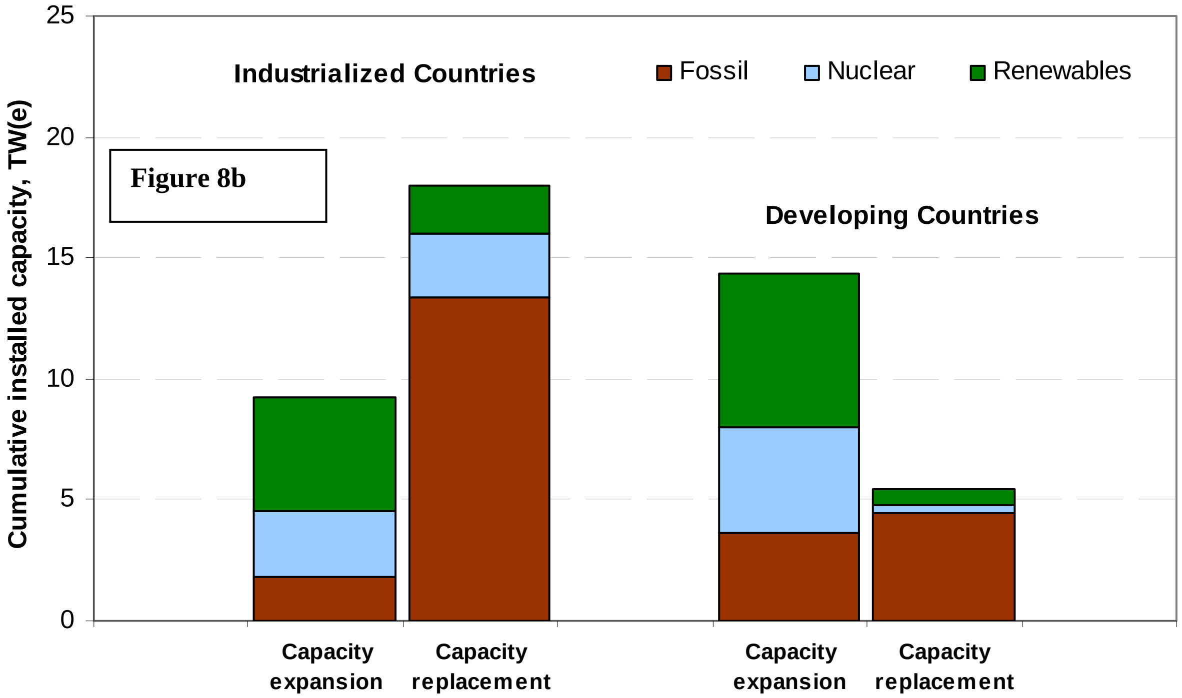


Figure 8. Electrical capacity expansion and capacity replacement by 2030 in the developed countries (industrialized) and in developing countries in the reference A2r scenario (Figure 8a) and in stabilisation at 670 ppm CO2-equivalent A2r-670 scenario (Figure 8b). Capacity expansion are new power plans while replacement capacity refers to those power plants that are build in place of those that are retired between now and 2030. Source: Riahi, xxx.

The total capacity additions are somewhat lower due to additional efficiency improvements beyond those in the baseline A2r. Nevertheless, the capacity additions and replacements are huge especially of renewable and nuclear power plants. About 4TWe of capacity expansion are foreseen in the developed parts of the world and 2TWe as capacity replacements. In the developing regions the corresponding installations are about 6TWe of capacity expansion and about 0.5TWe as capacity replacement. Together, over 12TWe of renewable and about 10TWe of nuclear power plants would be installed, or five and half times more than the total installed capacity of all power plants in the world. The interesting feature is that half of all of these plants would be built in the now developing parts of the world and most of them as new capacity expansion and not replacement of aging power plants. This leads to two considerations: 1. it offers the possibilities of leapfrogging to the most advanced technologies as the market is huge and would likely lead to large cost reductions and performance improvements; and 2. there is a potential risk of lock-in in the traditional technologies if this needed new capacities are not built with the best technologies. In other words, there is a huge incentive that the capital is attracted to the newest technologies and that there is a free access to those in the now developing parts of the world.

Figure 9 illustrates the dangers of the lock-in if some parts of the world that are excluded from access to newest technologies. It shows the hypothetical case where China remains outside the stabilization regime through 2030, namely it develops along the original path outlined by the reference scenario while the rest of the world embarks on a 670 ppm CO2-equivalent stabilisation development path.

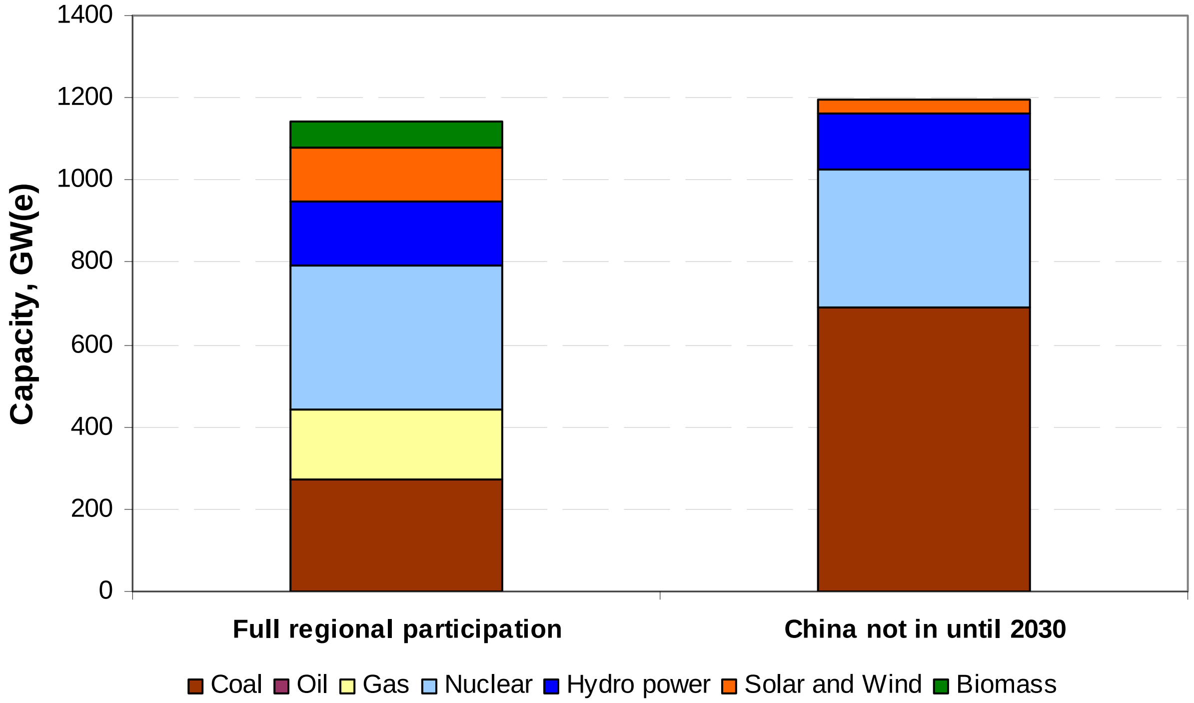
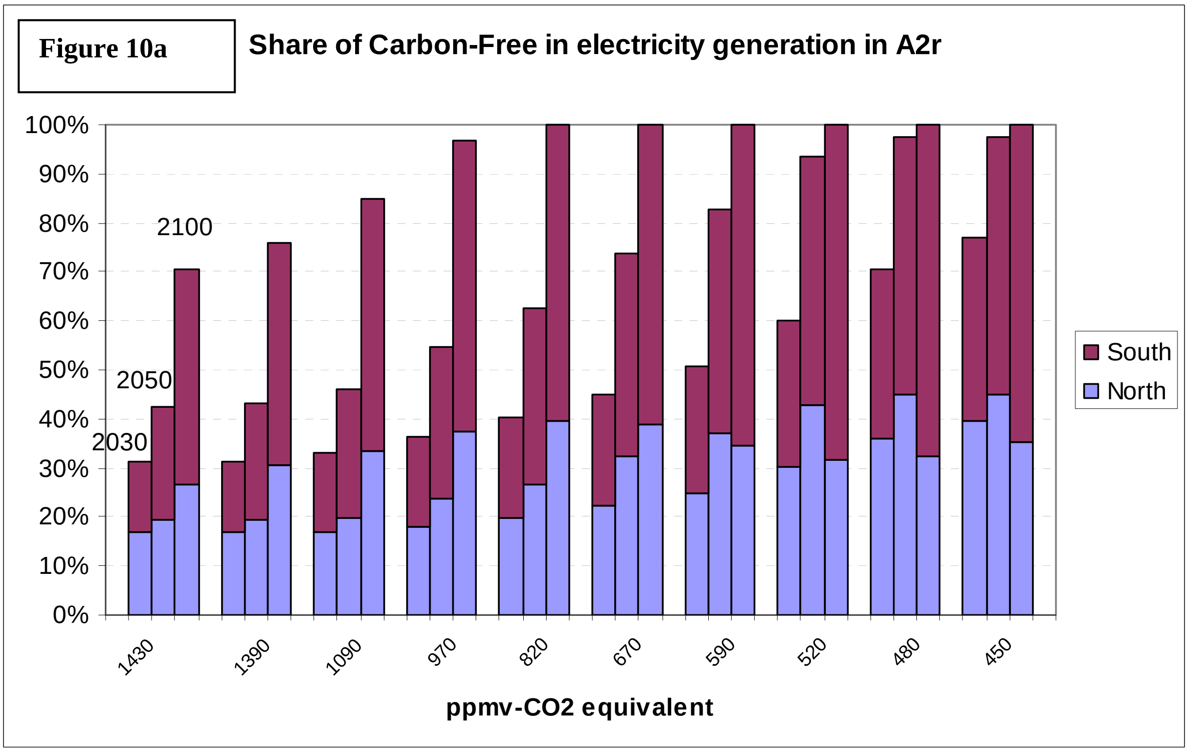


Figure 9. Installed power plant capacities in China by 2030 in the A2r-670 stabilisation scenario with full participation of all regions in the global participation, assuming free trade in carbon, other GHGs and other goods and services. Also shown is a hypothetical sensitivity analysis where China does not join the global mitigation efforts until 2030 (after the observation period). The differences in the resulting power plant mix are stark. Full participation in mitigation leads to a significant shift toward decarbonisation of electricity as well as additional efficiency improvements. Source: Riahi, xxx.

Clearly, this will lead to changes of the energy system in China as well, but the overall nature of fossil-dependence would remain while the rest of the world stabilises. In this case, about 1.2TWe would be constructed of which 700GWe would be fossil, predominantly coal, power plants, the rest mostly nuclear and hydropower. In the other case, where China participates in the common and shared goal of achieving stabilisation at 670 ppm CO2-equivalent, coal share would drastically fall to less than half or just below 300GWe with almost 100GWe gas and the rest would be completely CO2 free.



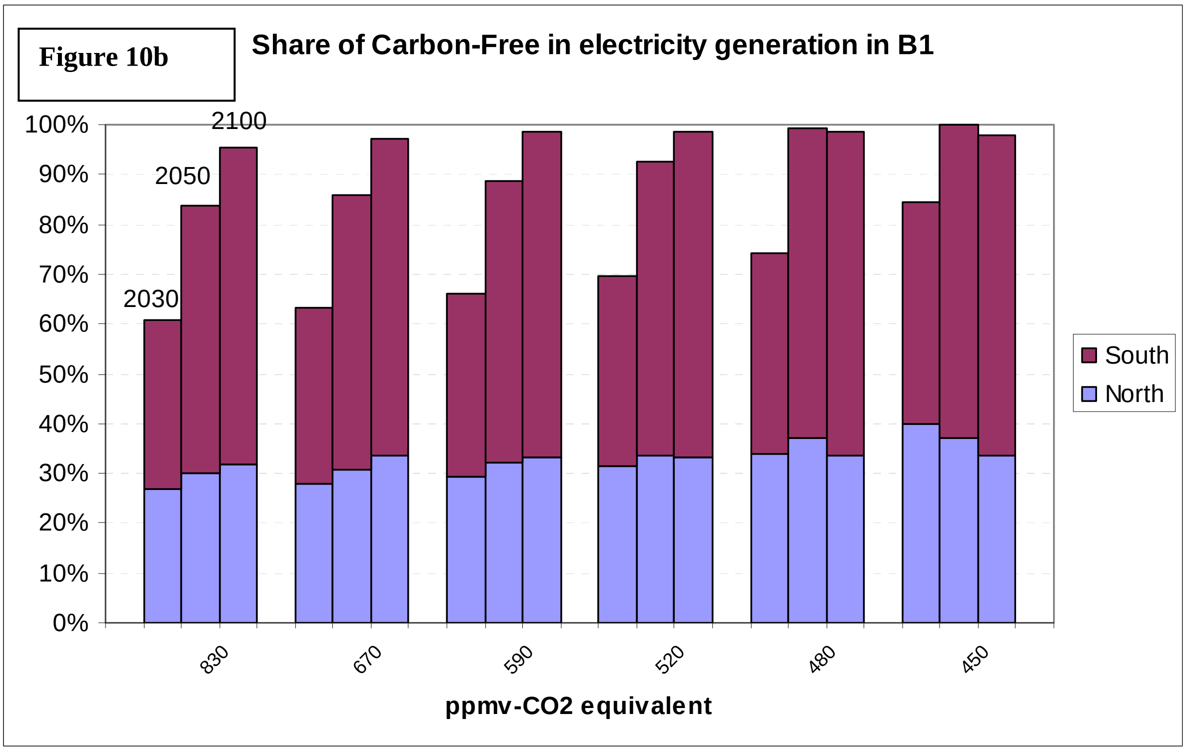
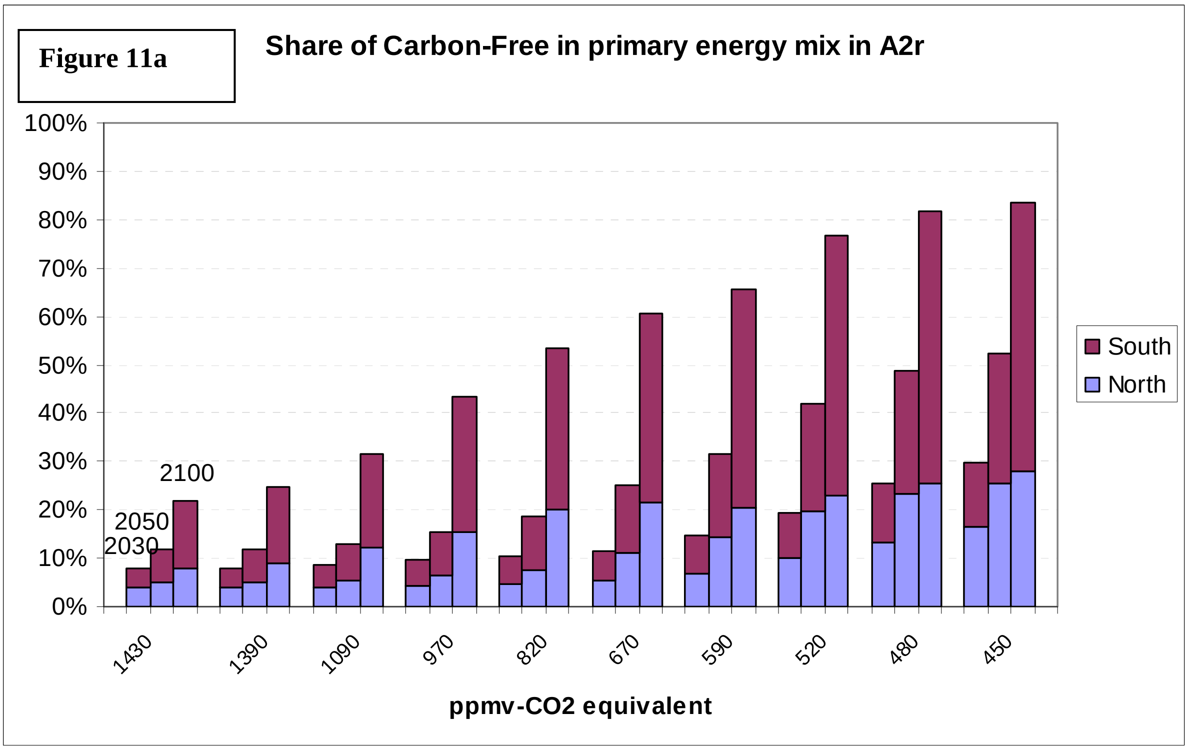


Figure 10. Share of carbon-free electricity generation in A2r scenario (Figure 10a) and in B1 scenario (Figure 10b). Shown are shares in the developed regions (North) and developing regions (South) with the rest being the global fossil generation. Fossil power plants with carbon capture and storage are included in the carbon-free shares as well as nuclear and all renewable power plants. Shown are shares in 2030, 2050 and 2100. On the left is the reference scenario that leads to CO2-equivalent atmospheric concentrations of 1430 ppm by 2100 and increasing for A2r scenario (Figure 10a) and 830 ppm reference for B1 scenario (Figure 10b) while on the extreme right is the very-low stabilisation scenario that leads to 450 ppm concentrations that corresponds to

about two degrees Celsius warming above pre-industrial levels (for correspondence of concentrations and temperatures see Figure 4 above). In between are the intermediate stabilisation levels.



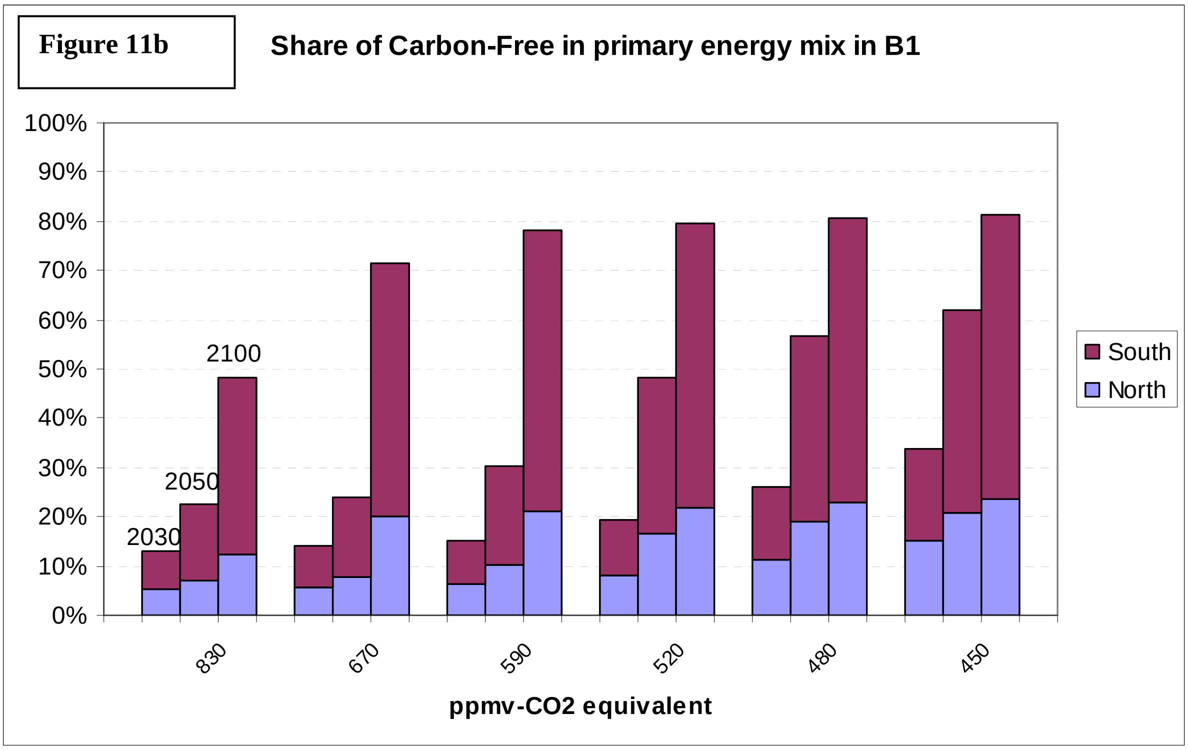


Figure 11. Share of carbon-free primary energy in A2r scenario (Figure 11a) and in B1 scenario (Figure 11b). Shown are shares in the developed regions (North) and developing regions (South) with the rest being the global fossil generation. Fossil energy with carbon capture and storage is included in the carbon-free shares as well as nuclear

and all renewable energy. Shown are shares in 2030, 2050 and 2100. On the left is the reference scenario that leads to CO2-equivalent atmospheric concentrations of 1430 ppm by 2100 and increasing for A2r scenario (Figure 11a) and 830 ppm reference for B1 scenario (Figure 11b) while on the extreme right is the very-low stabilisation scenario that leads to 450 ppm concentrations that corresponds to about two degrees Celsius warming above pre-industrial levels (for correspondence of concentrations and temperatures see Figure 4 above). In between are the intermediate stabilisation levels.

This example clearly illustrates the power of lock-in if appropriate energy systems restructuring policies are not pursued and in case the are that significant shift toward decarbonisation can be achieved by 2030 provided adequate financing and institutional arrangements to support transfer and diffusion of advanced technologies.

Figures 10 and 11 illustrate the shift toward decarbonisation of electricity generation and primary energy with increasing stringency of climate stabilisation goals. Figure 10 shows this trend for A2r and B1 scenarios for electricity generation and Figure 11 the same for the total primary energy. With increasing stringency of stabilisation, there is a significant shift toward decarbonisation and increasing investment in carbon-free and carbon-saving technologies. As we have seen above, the largest growing market for these technologies is in the now developing parts of the world (South). This means that increasing financing needs to be secured for these critical investments, but also that most of the induced technological learning and thus const reductions are likely to occur in these regions. In other words, there is a strong potential incentive to invest there assuming appropriate institutional arrangements.

Supportive Measures and Policies

The called-for change toward wider access to modern energy services together with climate protection and decarbonization is effectively blocked today by the addictive dependence on fossil energy sources. This explains the need for the Schumpeterian “gales of creative destruction”. Today, 80 percent of global energy is from fossil sources and this needs to be reversed so that 80 percent of energy would be carbon-free or carbon neutral. The old energy systems need to be replaced by the innovation, environmentally and climate friendly alternatives. In parallel, the reliance on inadequate access to traditional energy by the poor which constitutes perhaps upto 20 percent of primary energy also needs to be replaced by modern renewable and other clean energy sources. For that to occur, we need strong research and development in order to create the necessary scientific foundations for the paradigm-changing transformations.

We need science and research to gain better understanding of the complexity of processes and interactions within the climate system and the earth system. The important aim is to create fundamental innovations to help achieve structural changes in the society, the economy, institutional structures, and the lifestyle and consumption patterns. We need to establish a foundation for the deployment and adoption of new systems and services that lead toward complete decarbonisation in the world.

In other words, research and development of innovations that lead to diffusion of new and advanced technologies and practices are a possible solution to the double challenge of providing the development opportunities to those who are excluded and allowing for further development of the more affluent. This needs to occur without risking the irreversible changes in ecological, biophysical and biochemical systems. In the energy area, this implies a shift from traditional energy sources, in the case of those who are excluded from access, to clean fossils and modern renewable energy, and in the more developed parts of the world a shift from fossil energy sources to carbon-free and carbon neutral energy services. In all cases this means a vigorous improvement of energy efficiencies, from supply to end use, expanding shares of renewables, more natural gas and less coal, vigorous deployment of carbon capture and storage, and in some cases where it is socially acceptable and economically viable also nuclear energy.

We have shown that the B1 scenario can achieve these goals in conjunction with measures and policies for stabilising at 450 ppm CO2-equivalent by the end of the century. This would require carbon taxes that increase monotonically, say to some $100/tCO2 by 2030 and ever higher thereafter toward the end of the century. The same goal could be achieve with cap and trade measures by the introduction of universal carbon emissions certificates, including also developing parts of the world. At the same, other policies need to be introduced to assure a more sustainable development path. Foremost, this includes efficiency improvements. For example, this includes providing energy services with much less primary energy. Doing more with less. Rational energy use and saving would be required implying substantial changes of life styles and human behaviour, for example, toward more collective transport modes and smaller vehicles. However, this need not mean austerity measures. Small and efficient cars can be a lot of fun to drive.

Foremost, would be the measures toward enhancing early introduction and transfer to technologies to the developing regions. We have argued that this might be a way out of the crisis as investments in these parts of the world would lead to the largest growing market with lower costs and highest potential for induced technological learning. Thus, developing regions have also to potentially highest “buy-downs” along the learning curves of the new technologies.

Figure 12 shows the historical evolution of the energy system and one possible future development path toward decarbonisation as spelled out in the B1 stabilisation scenario. It is an illustration of the needed transformational change of the global energy system. New energy technologies, practices but also lifestyles and behaviour are prerequisites to turn the energy system from the current dependence on fossil energy toward a complete decarbonisation by the end of the century.

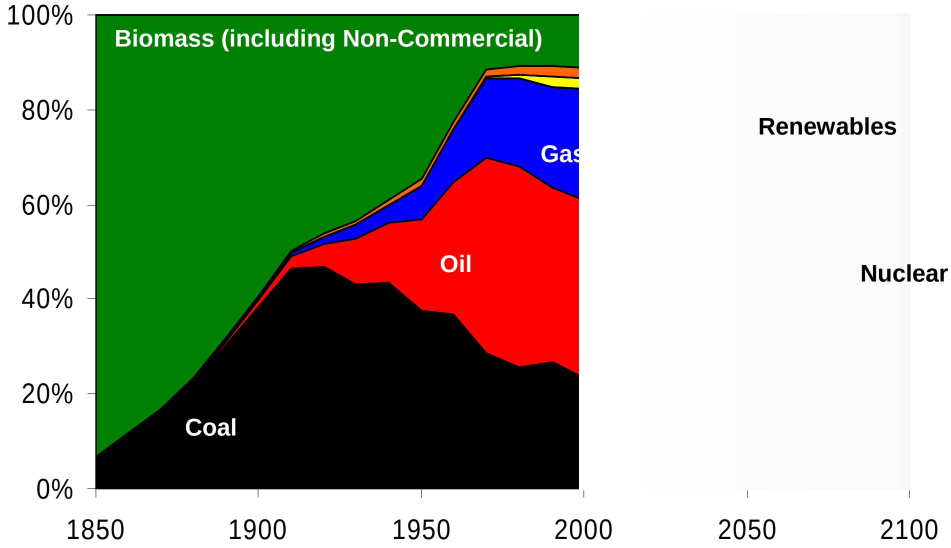


Figure 12: History and a possible future of the global energy system in B1 stabilisation scenario showing relative shares of most important energy sources (Nakicenovic and Riahi, 2007)

This particular scenario describes a future world that stabilizes concentrations of the GHGs just above the current levels and thereby limits the temperature change to about 2°C by the end of the century. The implied climate change will be no doubt disruptive. Even a global temperature increase of 2°C can lead to significant vulnerabilities and disruptions of natural ecosystems, water availability and communities in costal areas, see Figure 3 above (IPCC, 2007). Nevertheless, a 2°C world avoid the most severe adverse and perhaps also irreversible consequences associated with higher rates of climate change. It is the poor and those who are excluded that bear the biggest brunt of such changes. This B1 stabilisation scenario can be characterized as a transition toward sustainability that leads to fulfilment of MDGs in most of the world while simultaneously avoids more drastic climate changes.

The current investments in the global energy system are estimated at some $500bn per year. The sustainable scenario depicted in Figure 12 would require at least twice this effort during the coming decades to the tune of about one trillion per year or about $20 trillion by 2030. In comparison the share for the access is relatively small with about $400 billion.

This should all be compared with the current estimate of some $2 trillion being promised as securities and guarantees to the financial and other sectors to curb investments in new goods and services. A small share of these guarantees are likely to be sufficient to stimulate investments in new carbon-saving technologies and decarbonisation particularly in the developing countries as they have the largest potential future markets and investment needs.

The nature of technological change and the associated deep uncertainties require innovations to be adopted as early as possible in order to lead to lower costs and wider diffusion in the following decades. The longer we wait to introduce these advanced technologies, the higher the required emissions reduction will be. At the same time, we may miss the opportunity window for achieving substantial cost buy-downs. This requires both research, development and deployment (RD&D) as well as investments to achieve accelerated diffusion and adoption of advanced energy technologies.

Current energy RD&D trends are unfortunately in the opposite direction. Public expenditures in OECD countries have declined to some $8 billion from about $12 billion two decades ago, while private ones have declined to $4.5 billion compared to almost $8 billion a decade ago. This means that today we are investing barely about $2 per person in the world per year in energy-related RD&D activities. Many studies indicate that this needs to increase by at least a factor of two to three in order to enable the transition toward new and advanced technologies in the energy systems (Bierbaum *et al*., 2007). However, it needs to be noted that Finland, Japan and Switzerland constituted important exceptions with substantially higher public and private energy RD&D efforts.

As mentioned, the required investments in energy are at least a factor hundred larger compared to RD&D efforts with estimated $20 trillion needed from now to 2030. This translates into about one trillion dollars per year or at least twice the current level of investments with most of the requirements being in developing parts of the world. To achieve a transition toward more sustainable development paths requires substantially larger investment in energy and energy RD&D. All told, RD&D efforts need to be tripled and energy investments at least doubled in order to assure the timely replacement of energy technologies and infrastructures.

The salient finding of a number of recent integrated assessment studies is that additional costs for achieving more sustainable futures and climate stabilization are relatively small in comparison to these overall investment needs. Often they are “negative”, namely lower, compared to traditional scenarios of future developments, sometimes called business-as-usual (BAU). However, the more sustainable futures require higher “up-front” investments by about 2030. The great benefit of these additional investments into a future characterized by a carbon-leaner energy systems and a more sustainable development path is that in the long-run (to 2050 and beyond) the investments would be substantially lower compared to the BAU alternatives. The reason is that the cumulative nature of technological change translates the early investment into a carbon-leaner futures into lower costs of the energy systems in the long run along with the co-benefits of stabilization. This all points to the need for radical change in energy policies in order to assure sufficent investment in our common future and thereby promote accelerated technological change in the energy system and end use. In other words, the global financial and economic crisis offers a unique opportunity to invest in new technologies and practices that would both generate employment and affluences as well pave the way for a more sustainable future with lower rates of climate change. The crisis of the “old” is a historical chance to saw the seeds of the “new”.

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