Book

Technology and innovation for sustainable development

Technology and Innovation for Sustainable Development
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Chapter 1. Introduction: The Imperative of Sustainable Development[*][1]

Diana Alarcón and Rob Vos

Business as usual is not an option

Humankind has made enormous progress in improving material welfare over the last two centuries. However, this progress has come at the lasting cost of degradation of our natural environment. About half of the forests that covered the earth are gone, groundwater resources are being depleted and contaminated, enormous reductions in biodiversity have already taken place, and, through increased burning of fossil fuels, the stability of the planet is being compromised.

The fifth assessment (AR5) of the Intergovernmental Panel on Climate Change (IPCC) leaves little doubt about the human influence on climate change. IPCC concludes with 95–100 percent certainty (thus, *extremely likely*) that the concentration of greenhouse gases (GHG) in the atmosphere has its origin in current production and consumption patterns.[2]

Changes in the global climate system are already having a negative impact on the livelihoods of people in the most vulnerable regions of the world. The contrast between wet and dry regions and between wet and dry seasons is increasing; ocean temperatures are rising and, with it, ocean acidification, threatening ocean life and likely affecting ocean circulation with further impacts on surface climate. The melting of the glaciers and ice sheets is *very likely*[3] to accelerate, leading to further sea level rise with potentially devastating consequences for low lands, especially in Small Island Development States.[4]

Even as these threats are looming, more economic progress is needed in order to lift nearly 1 billion out of poverty and hunger and to provide a decent living for all of the 9 billion people that will inhabit the planet by mid-century—2 billion more than today.

Continuation along previously trodden economic growth pathways will further exacerbate the pressures exerted on the world's resources and natural environment and sooner than later approach limits where livelihoods are no longer sustainable. Business as usual is thus not an option. Yet, even if we were to stop global engines of growth now, the depletion and pollution of our natural environment would still continue because of existing consumption patterns and production methods. IPCC confirms this where it indicates that even if CO_2 emissions are halted now, the negative impact of climate change will persist for many centuries[5] with unbalance adverse effects on the life of people everywhere.

Thus, there is an urgent need to find new development pathways, which will ensure environmental sustainability and reverse global warming and ecological destruction, while managing to provide, now and in the future, a decent livelihood for all of humankind.

A transformative technological revolution is needed

To achieve this goal, a radically new economic strategy will be needed. Economies will need to "go green." The objective of the green economy is to ensure that the boundaries of planetary sustainability are not crossed. One option for achieving this would be to limit income growth, as it would also, given existing production methods, limit the growth of resource use, waste, and pollutants. However, doing so would complicate efforts to meet the developmental objectives, such as lifting those at the bottom out of hunger and extreme poverty. Global redistribution could be an answer, but likely will be politically too difficult for a full response. More importantly, even if it could resolve the problems of hunger and poverty, global redistribution would still need to face the challenge of continuing environmental destruction and climate change. Reducing population growth could be another option, but we know from experience that is best achieved by improving living standards. Reducing nonrenewable energy and resource use, reducing waste and pollutants, and reversing land degradation and biodiversity losses would then seem key to greening the economy.

The latter will require transformative changes to production and consumption patterns supported by a fundamental technological overhaul. Technologies will need to undergo drastic changes so as to become more efficient in the use of energy and other resources and minimize the generation of harmful pollutants.

Many of the technologies needed for a green economy are already available, as evidenced, for example, by the range of options for generating renewable energy (wind, solar power, and biofuels, among others), technologies for carbon capture and more efficient energy use, techniques to replace nonbiodegradable resources, and sustainable farming and forestry techniques, as well as technologies to render coastlines and infrastructure less prone to natural disasters.

These options offer readily usable starting points. The main challenges to jump-starting the shift to a green economy lie in how to further improve these techniques, adapt them to specific local and sectoral needs, scale up the applications so as to bring down significantly their costs, and provide incentives and mechanisms that will facilitate their diffusion and knowledge sharing. Apart from scaling up existing technologies, efforts toward enhancing the development of new technologies should as well be redoubled. These are all difficult challenges that will require a long-term vision, political will, additional investments, and strengthen coordination of actions at global, regional, and national levels.

As so many of the components of existing economic systems are "locked into" the use of nongreen and nonsustainable technologies, much is at stake in terms of the high cost of moving out of those technologies. For instance, developing countries, especially low-income ones with relatively low rates of electricity usage, may be able to "leapfrog" into electricity generation based on renewable forms of primary energy.

The question is how to enable those countries to access, utilize, and, above all, afford green technologies. Further innovation and scaling up are also needed to drive down unit costs. Technologies will need to be "transferred" and made accessible, since most innovation takes place in the developed countries and private corporations in those countries are the main owners of the intellectual property rights covering most green technologies. The new technologies will also need to be introduced into new production processes. This would imply improving much existing infrastructure and actively promoting green technologies and industries.

Consequently, the technological revolution for a green economy will be fundamentally different from previous revolutions in three ways.

First, it will have to take place within a specific and limited time period. Given existing pressures on our ecosystem, especially those associated with climate change, the goal would need to be achieved within the next three to four decades—a huge challenge given that innovation and diffusion of technologies is a slow process. Previous technological revolutions typically required a substantially longer period of time than that available now to accomplish the required green technology revolution.

Second, while not their sole responsibility, governments will have to assume a much more central role. The limited time available is one important reason for this. Under current circumstances, there needs to be an acceleration of technological innovation and diffusion, which is unlikely to occur if they are left to market forces. Equally important is the fact that the natural environment is a public good and not "priced" by the market. Markets for green technologies are in early stages of their development and are being shaped by government policy. Governments will also have to play a key role in promoting further research on and development of green technologies and their diffusion, inasmuch as the benefits will accrue to whole societies. In addition, since at present existing "brown" technologies are locked into the entire economic system, a radical shift to green technologies will mean improving, adjusting, and replacing much of existing infrastructure and other invested capital. Such transformations will be costly and necessitate large-scale, long-term financing, which is unlikely to be mobilized in full through private initiative and will require government support and incentives. Thus, not only will strong technology policies be needed but they must go hand in hand with active industrial and educational policies aimed at inducing the necessary changes in infrastructure and production processes.

Third, since the environmental challenges are global, the green technological revolution will need to be facilitated by intense international cooperation. The global dimension is most obvious in the case of climate change, but problems of food insecurity and deforestation have significant cross-border effects as well, stemming, for example, from food price instability and GHG emissions. Through international trade and investment, incomes and consumption in one country are linked to the ecological footprints left in the country of production. Multilateral environmental agreements, trade and investment rules, financing facilities, and intellectual property rights regimes would all need to be aligned so as to facilitate the green technological transformation. Since many, although not all, existing new technologies are owned by the advanced countries and the cost of inducing green technological change will be much higher for developing countries relative to their incomes, there will be important distributional challenges connected with greening the global economy, which will need to be addressed through traditional and other new mechanisms of international cooperation. Strengthened international cooperation will be especially important before the background that emission production has been highly concentrated in a few countries, while the negative effects of climate change are most pronounced in developing countries.

These huge challenges inspired a major United Nations report, the *World Economic and Social Survey 2011: The Great Green Technological Transformation*,[6] which was released on the eve of the United Nations Conference on Sustainable Development (often labeled as "Rio+20"). The Rio+20 outcome document confirmed the *urgent* need to take action in reversing "unsustainable patterns of production and consumption, [. . .] addressing environmental sustainability and promoting conservation and sustainable use of biodiversity and ecosystems, regeneration of natural resources and the promotion of sustained, inclusive and equitable global growth."[7] In a follow-up to the conference, all of the UN membership initiated a comprehensive process of consultation, at a global scale, to identify a set of sustainable development goals (SDGs) that would help to build consciousness and political will around the need to act simultaneously across the economic, social, and environmental dimensions of development.[8]

This book

This book emanates from the background studies to the *Great Green Technological Transformation* report. While covering less ground, it deepens insights as to how such a technological transformation could come about from a variety of perspectives. It spells out the kinds of behavioral and policy changes that may need to accompany such a transformation, taking into account the complexity of inducing technological overhauls in energy and agricultural sectors. The assessment suggests that this will require major, but doable, improvements in national innovation systems and major, but affordable, shifts in investment patterns (and related macroeconomic adjustments).

Can we live up to the challenge?

Chapter 2 by Tim Jackson makes a compelling argument about the need to modify the philosophical and social foundations of conventional economics in order to enact the economic transformation needed for sustainable development. He defines sustainability as "living well" by creating strong, healthy, and just societies within the ecological limits of a finite planet.

In the conventional narrative, social progress depends on economic growth. Such narrative, Jackson argues, has its roots in the libertarian idea that the social good is best accomplished when people have the freedom to pursue their own happiness. In the postwar years, this notion was codified through the measurement of gross domestic product, which aggregates the sum total of public and private consumption and investment expenditures and provides a "universal metric" of social progress—increasing economic output leads to higher living standards and better quality of life.

However, after decades of continuous growth, this model of progress based on economic expansion has failed to deliver minimum well-being evenly. There are millions of people who still suffer from hunger, and there remain large gaps among countries in basic indicators of well-being such as life expectancy. Simultaneously closing these gaps and meeting the needs of a population estimated to reach 9 billion in 2050 would require an economy fifteen times the size of today's global economy, but with staggering consequences for the environment and pressure on natural resources. Unless substantial technological innovation in the use of natural resources unleashes a process of "decoupling" of economic growth from material inputs, reaching minimum levels of well-being for all in the future would have devastating consequences for the environment.

For Jackson, the crux of the problem is that capitalist economies are structurally dependent on continuous growth just to prevent economic and social collapse. This intrinsic need for continuous growth stands in stark contrast with the finite limits of the ecosystem on which we depend on for survival. Under this logic, sustainable development is confronted with an apparently impossible dilemma unless "absolute decoupling" allows for an absolute reduction of the resources' impact of economic growth on natural resources.

Public policy, in this context, has a key role to play, not only in promoting altruistic behaviors but also by increasing investment in public goods and social infrastructure as well as better recognition of housework, child and elderly care, and volunteered work as part of a new "ecological macroeconomics."

Will we be able to induce a green energy transition in time?

Chapter 3 by Charlie Wilson and Arnulf Grubler calls for a major worldwide transformation of the energy system to meet the double task of improving the use of natural resources to stay within planetary boundaries and meeting the demand of millions of people still lacking access to modern energy.

The authors provide a thoughtful review of the historical experience of energy technological change and diffusion and the lessons to be learned in the search for a much needed transition to low-carbon energy. The two major transitions shaping the *structure* of the global energy systems were driven by energy poverty, followed by the building of infrastructure to support industrialization and the expansion of access to modern energy. The first transition took over a century to unfold (between the late eighteenth century until the 1920s), and it was defined by the emergence of steam power from coal, which helped to increase the availability of mechanical power, expand the use of energy, and transport systems. The second energy technology transition is associated with the displacement of coal-based steam technology and the dominance of electricity and petroleum-based technologies (automobiles, aircrafts, and petrochemicals). But, given that there are still 2 billion people lacking access to modern energy services today, this second transition is far from completed.

In the historical evolution of the current energy system, the environmental consequences of emissions were not a preoccupation until recently. For the reasons explained at the beginning of this chapter, there is now an urgent need to accelerate the transformation of the current energy system if we are to prevent dangerous levels of GHG that would trigger irreversible climate change. However, in contrast to the past, the energy technological transition for climate change mitigation will have to take place over a much shorter time horizon. This will require much greater reliance on a strong push induced by policies rather than rest on slow end-use induced innovation through the introduction of new products and services.

Chapter 4 by Alexander Roehrl further develops the analysis of Wilson and Grubler. This chapter reviews recent country experiences in the development of clean energy, including the use of taxes and other policy instruments to stimulate the adoption of and faster diffusion of alternative sources of energy. A rich experience has already accumulated in developing technologies to generate clean energy and in the application of policies aimed at shifting supply of and demand for energy toward sustainability objectives. Current efforts are far from sufficient, however, to meet the double challenge of reducing GHG emissions and expanding access to modern sources to the billions of energy poor people.

Roehrl argues that current efforts have failed to adopt systematic approaches with the result of slowing of both the introduction of clean energy sources and improvements in energy efficiency. Greater efforts will be needed to take account of at least three things. First, a system approach is needed in order to strike the right balance between economic, energy, and environmental concerns. For instance, meeting the current demand of energy with renewable sources is technically possible, but if based on the existing portfolio, it would require that all of the world's arable land be brought under cultivation for the production of biofuels—an obviously unrealistic option. Second, expansion of the generation of clean energy should go hand in hand with the development of technologies and innovations that facilitate the widespread use of clean energy in industrial processes. Third, a power systems approach is also needed to make sure the deployment of intermittent renewables is accompanied by the development of smart grids to guarantee reliable energy services. At present, renewable energy is distributed through existing power systems, which largely rely on coal and other brown technologies for back-up capacity. In addition, policy makers need to balance the biophysical (what is possible within planetary limits), scientific-technical (what is technically doable), economic (what is affordable), and sociopolitical (what is acceptable socially and politically) limitations inherent in an agenda for energy transformation.

Chapters 3 and 4 provide important policy guidance for the acceleration of the future sustainable energy transition, including:

- Public funding is essential to catalyze development of new energy technologies for climate change mitigation.

- The "portfolio" of clean energy sources will need to be diversified. This will allow for prolonged periods of experimentation to support innovation in the diffusion and up-scaling of new clean energy technologies. It will further reduce the risk of "locking in" technologies that may prove suboptimal over time.

- Policies promoting clean energy technologies need to consider the energy system at large, leaving ample space for smaller scale (*granular*) technologies to develop alongside large scale ones. This will help decrease cost, diversify risks, and allow for wider experimentation.

These lessons still have to be internalized to inform policy decisions globally. At present, publicly funded research and development (R&D) is strongly biased toward the development of supply-side technologies (such as wind, solar, and, particularly, nuclear energy). Scenario analysis, as well as past patterns of technology diffusion, suggests that much more emphasis should be put on promoting energy efficiency and end-use adoption of clean energy in order to accelerate the transformation of the energy system needed to drastically reduce GHG emissions.

Are green energy investments affordable?

In Chapter 5, Marco V. Sánchez and Eduardo Zepeda review estimates of the financial resources needed to bring sustainability to the world's energy system. Available estimates of the Global Energy Assessment (GEA, 2012) modeling exercise suggest a wide range of investment requirements. These requirements change with the assumptions made about the choice of technology, timeframe, and policies adopted by countries. Additional investment requirements would range between $1.7 trillion per year (about 1 percent of today's world gross product [WGP]) and $2.2 trillion per year (more than 3 percent of WGP). The latter estimate would include the investment cost associated with adapting devices to the new sources of energy (car engines, boilers, etc.), as well as the likely costs of new regulation and incentives for the promotion of sustainable production and consumption patterns. Yet, by all measures, such investment requirements would seem quite affordable in macroeconomic terms. The challenge thus will be one of political commitment, strong leadership, careful policy design, and much attention to incentives that effectively induce the necessary behavioral change around the globe. Any shortfall in any of these areas would risk entering into a scenario of catastrophic climate change. In the light of the consequences of inaction, the likely cost of a green energy transformation should appear infinitely affordable.

The chapter further analyzes a number of options to make the energy system environmentally sustainable. The investment and policy challenges in the transformation of the energy system are different for developed and developing countries. For developed countries, the main challenges lie in changing the energy mix toward sustainable energy and promoting sustainable consumption patterns. Developing countries have a more difficult challenge. Their transition toward sustainable energy will need to run parallel to the expansion of the supply of energy to meet the needs of millions of people who lack access to modern energy. Simultaneously, developing countries are in need of extending the social and economic infrastructure required to improve living standards. The investment effort that developing countries will have to make to build sustainable energy systems is much larger to that of developed countries (when measured as share of GDP). The authors show that sustainable energy investments tend to be high in low-income regions, moderate in middle-income regions, and low in industrialized regions. In Sub-Saharan Africa, for example, additional energy investment requirements for sustainability are projected to amount to more than 3 percent of GDP by 2020. Together with other investment needs for human development and economic development, this could add to financing burdens beyond the means of many low-income countries, which would require international financial assistance to meet such sustainable development needs.

But even as investment requirements seem affordable, the required macroeconomic adjustment in developing countries likely will be significant. Sánchez and Zepeda illustrate the possible implications using a scenario analysis based on economy-wide models for Bolivia, Costa Rica, and Uganda. The particular interest is to assess whether addressing both the challenge of making the energy transformation and that of achieving human development goals (reducing poverty and improving education, health, and water and sanitation) over the coming decades will be feasible, macroeconomically speaking.

The authors use economy-wide country models to simulate various policy scenarios. In one simulation they assess the implications of the introduction of a carbon tax that would discourage the consumption of fossil fuels. With the additional government revenue, the authors simulate the impact of three policy options: to reduce the fiscal deficit (and strengthen economic growth), to increase investment in economic infrastructure (roads, bridges, and electricity networks), or to increase investment in education.

Results vary depending on country-specific initial conditions. In the case of Bolivia, the model simulations suggest that investment in public infrastructure has the strongest positive impact on economic growth, while investments in tertiary education yield the stronger impact in the case of Costa Rica. In Uganda, additional investments in irrigation for agriculture and in primary education have the strongest impact in terms of overall GDP growth. In contrast with the previous results, when the additional resources are used to invest in education, human development indicators improve, but in Bolivia and Uganda economic growth will slow down. And when the additional resources are used to increase investment in public infrastructure, all human development indicators improve (presumably due to improved access to social services). In sum, these economy-wide model assessments suggest that in each of the three country cases there is clear scope to accelerate sustainable development in terms of its three key dimensions (economic, social, and environmental). Increasing public investment for growth, human development and environmental protection need not compromise basic macroeconomic stability. However, such investments require careful design to secure synergies between economic growth, human development, and environmental sustainability objectives.

Technological innovation in emerging economies

Chapter 6 by Xiaolan Fu and Jun Hou provides evidence from the experience in emerging economies (China and India, in particular, as well as Brazil) in promoting dynamic processes of technological innovation for sustainable development. In a relatively short period, these countries have built successful systems of innovation in green technologies leading to the development of competitive firms in the generation of wind energy, photovoltaic (PV) solar panels, and electric cars.

In all these cases, proactive government policies to stimulate and fund investments in the R&D of the related technologies were critical. Support measures were substantial. In other areas, most transfer of technology to emerging economies still takes place through foreign direct investment and imports of capital goods. The impact in terms of raising technological capacities of recipient countries tends to be rather asymmetric, however, but increases with the degree of absorptive capacity in the country in question. Such absorptive capacity of countries depends on the existence of domestic capacity to engage in R&D and the ability of organizations and firms to identify and assimilate new knowledge. Hence, effective technology transfer is conditional on building synergies between international technology transfer and indigenous innovation capacity.

The authors use the case of the wind power sectors in China and India to illustrate this. The development of wind power in these countries started with the traditional pattern of transfer of technology through foreign direct investment, licensing, and joint ventures in the early face. This evolved to the next stage through publicly supported domestic R&D, further international R&D collaboration, and cross-border acquisitions of technology and plants.

In all this, the role of government policy and support has been critical, both in facilitating the adoption of the technology and the creation of new knowledge. By requiring foreign investors to use local content, imposing national certification, and custom duties favoring components imports over complete wind turbines, as in the case of India, government policies created incentives for local learning and innovation. In all cases, there has also been a substantial increase in public investments for R&D, as a precondition to create domestic technical capacities.

Similarly, government regulations (such as setting up pollution standards for industry or benchmarks to improve energy efficiency) have nurtured incentive driven innovation systems. Policy coherence across regulatory, financial, technological, and industrial policies is particularly relevant in this case. The relatively recent and successful experience of China, India, and Brazil, developing expertise in key areas of environmentally sustainable technology are evidence of the opportunity emerging economies have to lead the creation of green technology. Building dynamic synergies between technology transfer and localized innovation is critical to facilitate the adaptation and diffusion of technology but governments need to take the lead in helping the transition from traditional innovation systems toward sustainable innovation systems.

Toward a truly green revolution in agriculture

In the final chapter of this volume, Diana Alarcón and Christina Boudoroglou argue for a major technological transformation in agriculture to address the double challenge of expanding global food production and remaining within environmentally sustainable boundaries. Population growth and rapidly changing diets add to the demand for food at a time when there is increasing competition for land (including for the production of biofuels), intensification of adverse weather conditions affecting food production, and existing agricultural production methods are a significant source of GHG emissions. Increasing the availability of food at local levels will also be needed to meet the needs of the estimated 805 million people suffering from chronic hunger in 2012–14.

Doubling food production to meet the expected demand in the next thirty years with current technology and production practices is not sustainable. Agriculture, forestry, and other land use already account for 24 percent of global GHG emissions, and, at unchanged trends, the share would increase to 30 percent. Agricultural irrigation accounts for 70 percent of water withdrawals and intensive livestock production together with excessive use of agrochemical pesticides and fertilizers is a major source of water pollution.

At the same time, climate change has severe adverse consequences for agriculture. Land degradation leads to substantial productivity losses; changing temperatures and precipitation are affecting the timing and length of growing seasons and yields, and prolonged droughts and extreme floods are hitting large agricultural areas more frequently.

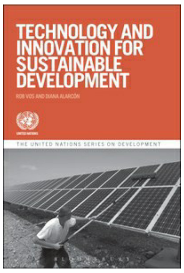
Smallholder farmers are at the heart of the challenge and the solution to food security and environmental sustainability: 80 percent of the world's food is produced in family farms and 90 percent of the food consumed in developing countries is produced locally. Development strategies for food security and environmental sustainability must focus attention on improving the productive capacity and livelihoods of smallholder farming, including by harnessing the technology and innovation needed to increase the productivity, profitability, stability, resilience, and climate change mitigation potential of rural production systems.

The chapter reviews the evidence of multiple experiences among farmers and communities adopting technology and innovative agricultural practices to boost productivity and reduce the environmental impact of production. A large number of successful experiences involve green technologies for pest and weed management, improved water efficiency, and maintenance of biodiversity. Some of these experiences have been replicated with large-scale impacts. Examples include the integrated pest management (IPM) approach and the system of rice intensification (SRI). Much greater efforts are needed, however, in order to facilitate extensive experimentation and continuous R&D to adapt the new technology and production methods to local contexts. This can only be achieved through financial and political support from governments with effective participation from civil society organizations, and especially with direct involvement of local farmers.

Building a sustainable agricultural innovation system (SAIS) would provide the framework to direct resources to boost the productivity of small-scale agricultural producers. A SAIS framework would contribute to secure long-term financial support for R&D, infrastructure, and improved access to inputs, credits, and markets for small-scale farmers; it would help to recognize the dynamic nature of learning and innovation among the multiple actors engaged in the process and the institutional context in which innovation takes place, and it would help to identify the multiple actors that produce knowledge, technology, and capacities to innovate.

The international community has much to contribute to the global agenda for food security and environmental sustainability by increasing the resources for R&D as a global public good but also by introducing the necessary reforms to policies in Organisation for Economic Co-operation and Development (OECD) countries in the area of subsidies to agriculture and biofuels and trade.

In short, the chapters in this book illustrate the many challenges of redirecting global and



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Chapter 2. A New Philosophical Approach to Social Transformation for a "Green Economy"

Tim Jackson

Context

Economic transformation is crucial to the project of sustainable development. The emerging concept of the "green economy" is, potentially, a powerful way to articulate the economic changes needed to achieve sustainability. But the underlying philosophical and social foundations for the green economy depart significantly from the foundations of the conventional economy.

The concept of the green economy emerged, in part, as a response to the financial crisis of 2008–9. Talk of a "green new deal" during late 2008 began to align the interests of economic stimulus with the need for low-carbon transition—and indeed with the "greening" of the economy more generally. Since investment is required for both, it made sense to target some of the stimulus investment toward green technologies and infrastructures. Many nations—most notably South Korea—did exactly that. And there is a sense in which the "green economy" has provided a useful input to the debates about economic renewal.

At the same time, there are clearly some dangers in assuming that the concepts of "green economy" and sustainable development are perfectly aligned. At the very least, there is a need to outline more clearly the relationship between them. Is a green economy a necessary condition for sustainable development? Is it a sufficient condition for sustainable development? Might the introduction of a new language around the green economy support the pursuit of sustainable development? Or does it have the potential to undermine specific aspects of sustainability such as social justice. Could it emerge perhaps as a language that threatens or displaces the political weight that sustainable development has developed around the world?

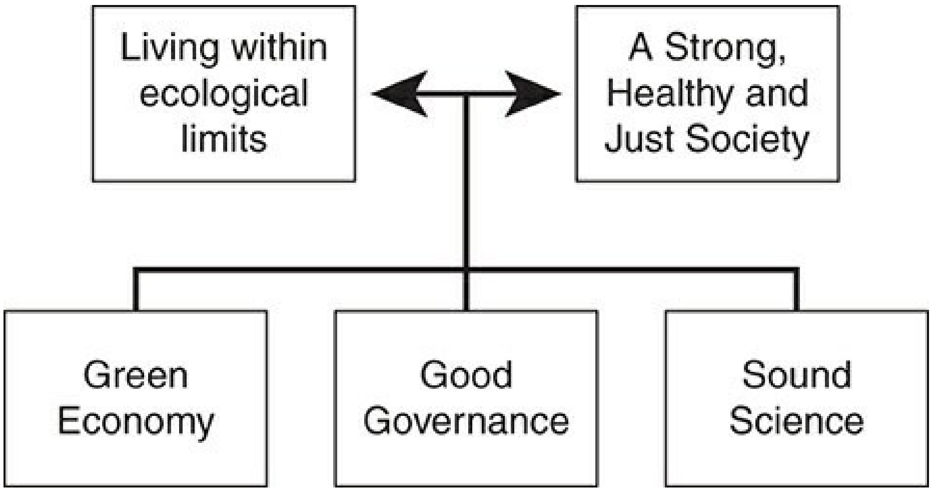
It is beyond the scope of this paper to answer those questions definitively. In fact, it is impossible to answer them definitively, since language itself is always contested. Everything depends on how the international community ends up defining "green economy," how it decides to frame and build the economics that underpin the green economy, and how it decides to articulate the relationship between green economy and sustainable development.

None of this is very surprising. Sustainable development itself has contested meanings. Some see sustainable development as a new framing concept, a potentially radical philosophy for redefining progress. Others see it as a practical tool for achieving incremental improvements in social justice and in environmental protection. Others again have argued that sustainable development is a conservative project, flawed by the aim of trying to protect an economic paradigm, which is itself the cause of so many environmental and social problems.

Trends toward the goals of sustainable development in the twenty years since the Rio Conference on Environment and Development—and indeed in the forty years since the Stockholm Conference on Human Development—might appear to support this view. In certain key respects, environmental and social progress has been going in the wrong direction. Carbon emissions have increased, biodiversity has diminished, and resource extraction has not slowed down. Inequalities—even in Organisation for Economic Co-operation and Development (OECD) nations—are higher than they were two decades ago.[1] And the global financial system, which seemed secure twenty years ago, is still reeling from a crisis that engendered near collapse.

Yet the visionary potential of sustainable development remains intact: its insistence on the importance of human needs, its sense of social justice, its unequivocal support for future generations, its identification of human dependency on the environment, its characterization of limits. The challenge of sustainability is somehow to "live well"—to create "strong, healthy and just societies," and yet remain within the ecological limits of a finite planet (Figure 2.1). This vision still provides a guiding framework for social progress.

Figure 2.1. Principles for sustainable development



Source: DEFRA (2005).

Neither is there any doubt that a strong and resilient economy is a vital prerequisite in this task. When economies collapse, bad things can happen. Economic success brings social stability. Indeed, as Keynes once argued, the principal task of economics is to ensure social stability. Economics in the service of human well-being is an idea with a long pedigree and is worth hanging onto. In short, the language of "green economy" could in theory provide a way to articulate the economic underpinnings of sustainable development.

That, at least, is the premise of this chapter. Starting from this basic understanding—that a green economy provides the economic underpinnings of sustainable development—the chapter aims to sketch the philosophical, social, and psychological aspects of a transformation of the global economy toward sustainability. It situates the green economy as a critical component in that transition. Further, it elaborates the elements on which green economy must focus if it is to provide a useful underpinning for the task of transformation.

First though, we need to sketch out the philosophical elements of a "conventional" approach to economic progress. It is only from an understanding of the key tenets of this approach that it is possible to identify the distinguishing features of a different kind of economy—a "green economy." Central to the conventional approach is the premise that social progress depends on economic growth. The next section in this paper explores this idea explicitly, expanding the rationale for economic growth, and drawing out its implications in ecological, technological, social, and institutional terms.

Chasing progress

The modern idea of progress can be traced to the Enlightenment—a period of intense intellectual and philosophical creativity concentrated mainly in Northern Europe during the sixteenth and seventeenth centuries. This period gave rise to enormous technological creativity and provided the foundations for the industrial revolution. It was also accompanied by new moral and prudential speculations about the nature of the "good life"—ideas about how individuals and societies can and should thrive. Some of these ideas provided the foundations for classical and later neoclassical economics. Perhaps most notable among these were concepts of utilitarianism and libertarianism.[2]

While utilitarianism held that progress consists in ensuring the greatest happiness for the greatest number, libertarianism suggested that this could best be achieved by delivering people the freedom with which to pursue their own happiness. The libertarian focus on individual freedoms was adopted by the classical economists as an organizing principle of the market economy—formulated as a belief that individual self-interest was the principal motivation underlying human behavior. A key element in this philosophy was the belief—articulated in particular through Adam Smith's much cited doctrine of the "invisible hand"—that the pursuit of individual self-interest gave rise to the social good. So the recipe for social progress was to give these individual interests free rein through the market.

Over the next two centuries these broadly democratizing philosophies slowly began to dissolve conventional hierarchical divisions in the societies of emerging industrialized countries, a process that was accelerated by industrialization itself. Improved access to natural resources, more efficient conversion technologies with which to manufacture material goods, and the rising incomes associated with industrial livelihoods: all of these contributed to a profound technical and societal transformation.

Even at the time, there were critics of this transformation. For instance, it was argued that the Industrial Revolution was built on an access to material resources that was secured only by an expansion of military power. Britain, France, Germany, Japan, Portugal, and Spain all developed strong imperialist ambitions, competing for the rich resources and cheap labor to be found in the still-undeveloped nations around the world. Colonization and slavery, it was claimed, provided the energy and material resources that powered the new industrial economies. Some even suggested that it was the clash of imperial ambitions among the emerging superpowers that led directly to the First and indirectly to the Second World War.

There were also criticisms of the impact that the process of industrialization was having on the working populations of the newly industrialized countries. Working conditions in the early mill-towns were often harsh. Life expectancy was sometimes brutally short. There was evidence that health outcomes actually worsened over the early years of industrialization. Rather than improving the lives of everyone, industrialization bettered the lives of some at the expense of others. There were certainly huge divisions still between the rich—the owners of land and capital—and the poor who still struggled for livelihoods, land, food, health, and a share of the political voice.

A particular criticism of these new arrangements was that the emerging capitalist economy had “disembedded” economic activities from social relations, simultaneously undermining community and social capital and leading to a loss of accountability in economic relationships.[3] This erosion was thought to flow in part from the underlying philosophical idea that individual self-interest should be the driver of social progress. As individual identity became a stronger and stronger force in modern society, the strength of social identities and social ties began to diminish, threatening social cohesion.

In spite of these criticisms—and the disruptions of two World Wars and the Depression—the emerging, predominantly capitalist, form of social organization had dramatically improved the lives of many ordinary people in the industrialized nations by the middle of the twentieth century. The prevailing, increasingly global, notion of economic progress was one that assumed that these advances would continue in much the same way into the future.

The setting up of the UN System of National Accounts (SNA) in the early postwar years provided the institutional bedrock for this view, and through it the gross domestic product (GDP) became the single most important arbiter and indicator of progress. Growth in the GDP emerged as the key political priority in all the advanced Western nations. With the collapse of the Soviet Union and the opening out of trade with Southeast Asia, by the end of the twentieth century, the paradigm of economic growth achieved near global significance.

The SNA established three parallel—and in principle equivalent—measures of GDP. First, the sum of “value added” by all productive activities in the economy; second, the sum of all wages and profits earned in the production of goods and services; and third, the sum of all public and private consumption and investment expenditures in the economy. It is the last measurement that provides the strongest justification for the use of GDP as a measure of social progress.

To the extent that GDP is the sum of all market and nonmarket expenditures on goods and services, as long as markets are free and governments are democratic then expenditures reflect what people value and want. Or, in other words, if we are spending our money on more and more commodities, it’s because we value them. We wouldn’t value them if they weren’t at the same time improving our lives. Hence a continually rising per capita GDP ought to be improving our lives and increasing our well-being.

This model of progress goes some way to explaining why the pursuit of GDP has become one of the principal policy objectives in almost every country in the world in the last few decades. Rising GDP traditionally symbolizes a thriving economy, more spending power, richer and fuller lives, increased family security, greater choice, and more public spending. A declining GDP, by contrast, is bad news. Consumer spending falls, businesses go bust, jobs get lost, homes are repossessed, and a government that fails to respond appropriately is liable to find itself out of office.

In short, modern society is now organized around a particular model of how to pursue human well-being. Baldly stated, this model contends that increasing economic output—growth in the GDP—leads to improved well-being: a higher standard of living and a better quality of life across society. Economies are organized explicitly around the need to increase the GDP; business models are predicated on maximizing profits to shareholders; people are inclined to believe that the more disposable income they have—the more they consume—the better off they are.

Since the global GDP has risen more or less consistently over the last fifty years, aside from the occasional recession, the comforting logic of the conventional view suggests that we have been pretty successful in delivering an increasing standard of living and, by proxy, an improving quality of life over recent decades. Furthermore, if our concern is to ensure that well-being continues to reach new heights, the conventional view provides a ready and familiar formula for achieving this end: to ensure high and stable levels of economic growth across the world.

Limits to growth

In spite of its success in delivering improved access to goods and services, at least to the advanced nations. This model of progress has not gone unchallenged. There has been a growing concern over the ecological and resource implications of an ever-expanding economy. How—and for how long—is continued growth possible without coming up against the ecological constraints of a finite planet?

Concern over limits was raised by Thomas Robert Malthus in his enormously influential *Essay on Population*, first published in 1798. His argument (massively condensed) was that growth in population always runs faster than growth in the resources available to feed and shelter people. So sooner or later the population expands beyond the "means of subsistence," and some people—the poorest inevitably—will suffer.

The global population is now more than six times the size it was in Malthus' day. And this is partly because the means of subsistence expanded considerably faster than population did—completely counter to Malthus' premise. The global economy is sixty-eight times bigger than it was in 1800.[4] Malthus missed completely the longer term implications of technological change and a considerable slowing down of the rate of population increase that accompanied development. Today, the means of subsistence more than kept pace with people's propensity to reproduce, largely because of the easy availability of cheap fossil fuels.

The question was raised again in a different form in the Club of Rome's *Limits to Growth* report.[5] First published in 1972, *Limits to Growth* argued that resource scarcities would inevitably push prices up and slow down the possibilities for future growth.

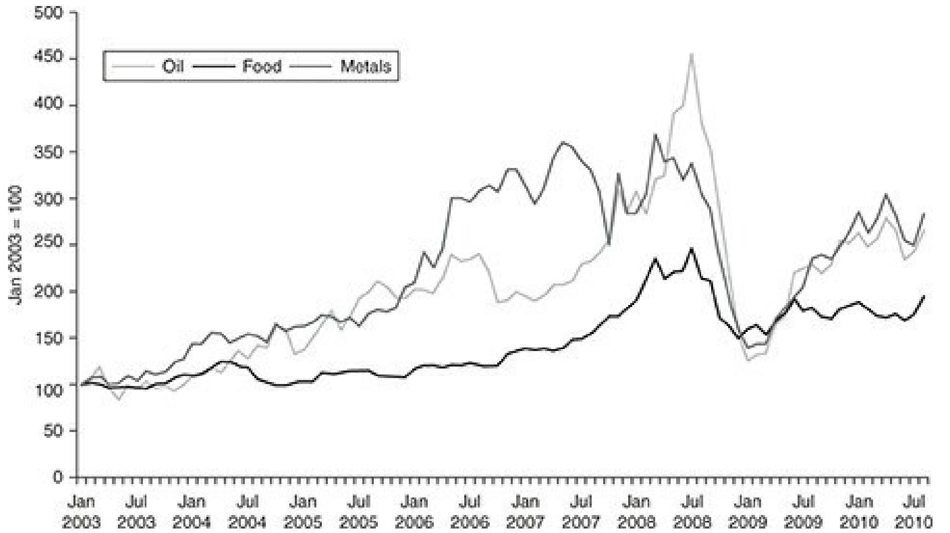
Eventually, if material throughput isn't curtailed, the available resource base would collapse and with it the potential for continued economic activity. Collecting together as much data as they could find on resource extraction rates and available reserves, they set themselves the task of figuring out when the turning points would arrive—the points at which real scarcity might begin to bite.

The Club of Rome predictions were remarkably accurate as the basis for predicting actual resource consumption rates, as a recent Commonwealth Scientific and Industrial Research Organisation CSIRO report attests.[6] *Limits to Growth* foresaw significant resource scarcities emerging during the first few decades of the twenty-first century. In the first decade of this century the question of pressing resource limits has already been raised in relation to oil, phosphate, rare earth metals, and other strategic resources.

Most significantly, the peak oil debate had already emerged as a fiercely contentious issue by the year 2000. The "peak-ists" argued that the peak in oil production was only a matter of years away, possibly already on us. Their opponents pointed to the massive reserves still lying in the tar sands and oil shales. Getting the oil out might be costly and environmentally damaging, but absolute scarcity was still a long way away, claimed the optimists.

Meanwhile the price of oil rose steadily. Oil price hikes had already shown they have the potential to destabilize the global economy and threaten basic securities. Fears peaked in July 2008 when oil prices reached $147 a barrel (Figure 2.2). Though they fell sharply in the following months, the threat of peak oil hasn't gone away. The rising underlying trend had returned by early 2009 and continues to pose a threat to global economic security.

Figure 2.2. Global commodity prices: January 2003—July 2010



Source: Data are from *The Economist* dollar-based Commodity Price Index. Retrieved at:

www.economist.com.

The International Energy Agency has suggested that the “peak” could arrive as early as 2020. Oil will not disappear beyond that peak, but it will be significantly more costly to extract, both in economic and in environmental terms. The era of cheap oil would to all intents and purposes be gone and the economics of energy would be irrevocably altered as a result.[7]

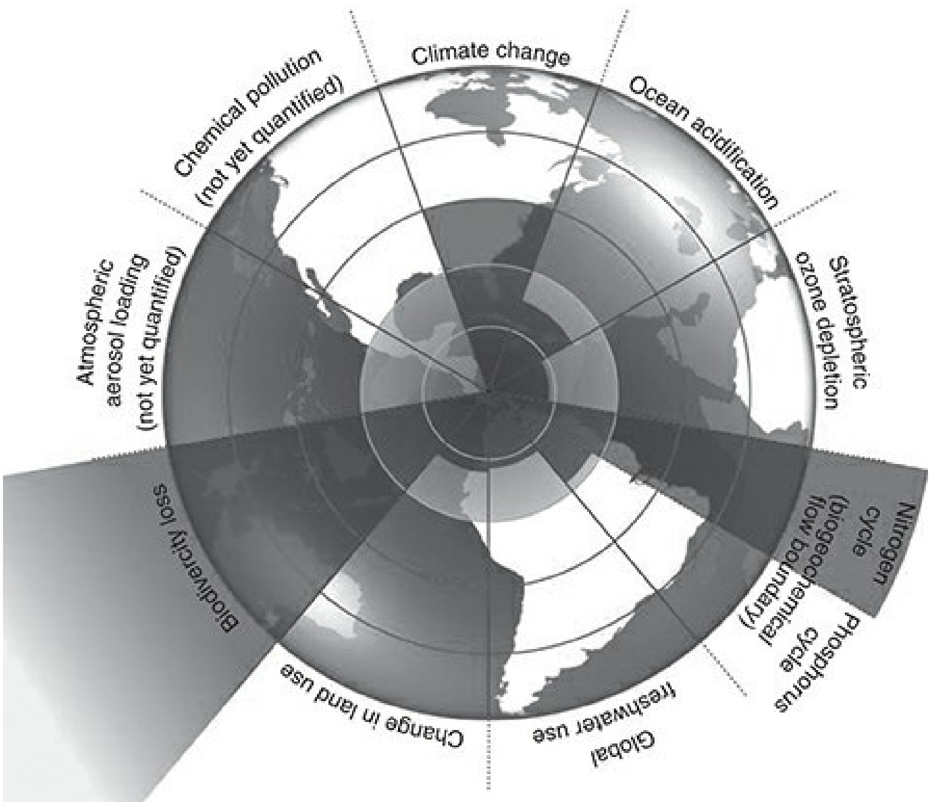
Oil is not the only commodity for which resource scarcity has already become an issue. Food prices also rose sharply leading up to July 2008 (Figure 2.2), sparking riots on the streets in some countries. Beyond the spike, the underlying trend rose once again. Conflicts over land use, particularly related to the use of land for growing biofuels, were certainly one of the factors pushing food prices up through 2008.

The trend in mineral prices has been rising too as demand is growing and even at current extraction rates, a number of important minerals measure their time to exhaustion in decades rather than centuries. If the whole world consumed resources at only half the rate the United States does, for example, copper, tin, silver, chromium, zinc, and a number of other “strategic minerals” would be depleted in less than four decades. If everyone consumed at the same rate the United States does today, the time horizon would be less than twenty years. Some rare earth metals will be exhausted in a decade even at current global consumption rates.[8]

Resource scarcity—the problem of “sources” in the language of environmental economists—is only part of the concern. The debate is driven even more strongly by the problem of “sinks”—the capacity of the planet to “assimilate” the environmental impacts of economic activity. “Even before we run out of oil,” explains ecologist Bill McKibben, “we’re running out of planet.”[9]

In 2009, the Tällberg Foundation convened a group of distinguished scientists, led by Johan Rockström, to examine a variety of global ecosystem limits, which they described as “planetary boundaries” (Figure 2.3). Rockström’s team concluded that humanity was already operating beyond the safe space defined by at least three of these boundaries: climate change, global nutrient cycles, and the loss of biodiversity. It’s now widely acknowledged that an estimated 60 percent of the world’s ecosystem services have been degraded or overused since the mid-twentieth century.[10]

Figure 2.3. Planetary boundaries and “safe operating space”



Source: Rockström et al. (2009).

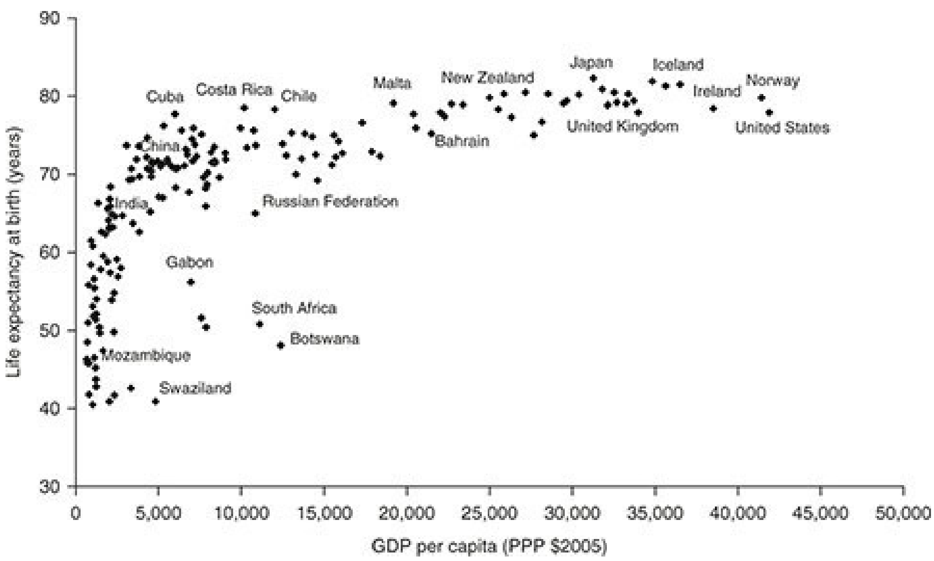
During the same period of time the global economy has grown more than five times, a rate of growth that has no historical precedent and at odds with our scientific knowledge of the finite resource base and the fragile ecology on which we depend for survival. Most telling of all, even as the richest nations achieve unprecedented material affluence, the poorest still struggle for survival.

Making room for growth

Among the charges against growth is that it has delivered its benefits, at best, unequally. A fifth of the world's population earns just 2 percent of global income. The richest 20 percent by contrast earn 74 percent of the world's income. Huge disparities characterize the difference between rich and poor. Basic aspects of human flourishing such as life expectancy still vary widely between the richest and the poorest nations (Figure 2.4).

Life expectancy is as low as forty years in parts of Africa and almost double that in many developed nations (Figure 2.4). Such disparities are unacceptable from even the most basic humanitarian point of view and they also generate rising social tensions.[11]

Figure 2.4. Life expectancy at birth versus average annual income



The conventional growth-based paradigm suggests that the best way to address this problem is through growth itself. As the world economy grows, according to this conventional view, it will inevitably lift the poorest out of poverty and perhaps even become more equal as it does so. Simon Kuznets famously hypothesized that inequalities grow at first as nations develop, but after a while a peak of inequality is reached, and then inequalities begin to decline.

It has to be said that evidence in support of this hypothesis is hard to find. Even within the advanced economies, inequality is higher than it was twenty years ago.[12] Middle-class incomes in Western countries were stagnant in real terms long before the 2008/9 recession and still show little sign of recovery. Far from raising the living standard for those who most needed it, growth let much of the world's population down over the last fifty years.

But the question of ecological limits raises another more fundamental challenge to this conventional viewpoint; continuous economic growth pushes inexorably against ecological limits. If the economy continues to grow at the same rate that it has done in the last fifty years, it will be eighty times bigger in 2100 than it was in 1950.[13]

A world in which things simply go on as usual is already inconceivable. But what about a world in which 9 billion people all achieve the level of affluence expected in the OECD nations, with incomes still growing at 2.5 percent per year?[14] Such an economy would need to be fifteen times the size of today's economy by 2050 (seventy-five times what it was in 1950) and forty times bigger than today's (by the end of the century).[15] The resource and environmental implications of such an economy are staggering.

The only possible answer to this conundrum would be to achieve substantial technological improvements in the efficiency with which material resources are converted into economic output. In a later section of this chapter, we will explore the potential for such a technological "decoupling" of economic growth from material throughput in more detail. But for now, it is clear that the question of limits fundamentally changes the moral dimensions of social progress.

In a world without limits, it would be acceptable to lift the poorest out of poverty by growing the entire economy. But the existence of ecological or resource limits poses a more pressing moral question. How much of the world's resources any one nation or individual has a right to in the pursuit of human well-being?

Alongside this moral issue lies a prudential one; beyond a certain point at least, continued pursuit of economic growth doesn't appear to advance human well-being. As shown in Figure 2.4, as incomes rise, the additional benefits in terms of increased life expectancy are markedly reduced. Very similar patterns can be found in relation to infant mortality, participation in education, and even happiness or life satisfaction.

If the returns to growth in the richest nations are lower than they are in the poorest nations, the best way to improve human well-being overall would clearly be to redistribute growth from the richest to the poorest part of the population. Or in other words, there is a moral pressure on the rich nations to make room for growth in the poorer parts of the world.

To the extent that they can achieve this through technological efficiency, the conventional paradigm might attempt to defend continued growth even in the richest nations. But if there are limits to this technological capacity, then the moral imperative on the rich is to curtail further increases in levels of economic throughput.

Beyond, this moral imperative, however, lies a puzzle that will need to be solved if any moral progress is to be made in terms of distributing limited economic output to places where it is needed most. Why is it that rich countries continue to pursue economic growth, even after the point at which material needs are satisfied? It is clear that a meaningful approach to the green economy must certainly address the plight of the 2.5 billion people across the world still chronically undernourished, living on less than $2 a day. But does the same logic hold for the richer nations, where subsistence needs are largely met, human development outcomes (life expectancy, for instance) are already high, and increases in availability of consumer goods add little to social well-being? Talk of a growing "social recession" in advanced economies has accompanied the relative economic success of the last decade. [16]

In spite of these apparent costs from "uneconomic growth," it appears to be impossible simply to halt the growth process. Why does enough never seem to be enough? Is it that human needs are somehow insatiable after all? Or is it something to do with the structure of economies that forces them to grow? To answer these questions, we must explore a little further the underlying dynamics of the modern economy.

The dilemma of growth

Capitalist economies place a high emphasis on the efficiency with which inputs to production (labor, capital, and resources) are utilized. Continuous improvements in technology mean that more output can be produced for any given input. Efficiency improvement stimulates demand by driving down costs and contributes to a positive cycle of expansion. But crucially it also means that fewer people are needed to produce the same goods from one year to the next.

As long as the economy grows fast enough to offset this increase in "labor productivity," there isn't a problem. But if it doesn't, then increased labor productivity means that someone somewhere loses their job.[17]

If the economy slows for any reason, then the systemic trend toward improved labor productivity leads to unemployment. This in turn, leads to diminished income, a loss of consumer confidence, and further reduces demand for consumer goods. From an environmental point of view, this leads to lower resource use and fewer polluting emissions. But it also means that retail falters and business revenues suffer. Investment is cut back. Unemployment rises and the economy falls into a spiral of recession.

Recession has a critical impact on public finances. Social costs rise with higher unemployment, but tax revenues decline and lower expenditures risk real cuts to public services with negative impacts on well-being.

Governments must borrow more not just to maintain public spending but to try and restimulate demand. But in doing so, they inevitably increase the national debt. The best that can be hoped for here is that demand does recover and begin paying off the debt. This could take decades. It took Western nations almost half a century to pay off public debts accumulated through the Second World War. It has been estimated that the "debt overhang" from the financial crisis of 2008 could last into the 2030s.[18]

There is little resilience within this system. Once the economy starts to falter, feedback mechanisms that had once contributed to expansion begin to work in the opposite direction, pushing the economy further into recession. With a growing (and aging) population these dangers are exacerbated. Higher levels of growth are required to protect the same level of average income and to provide sufficient revenues for (increased) health and social costs.

In short, modern economies are driven toward economic growth. For as long as the economy is growing, positive feedback mechanisms tend to push this system toward further growth. When consumption growth falters, the system is driven toward a potentially damaging collapse with a negative impact on human flourishing. People's jobs and livelihoods suffer. The capitalist model has no easy route to a steady state position. Its natural dynamics push it toward one of two states: expansion or collapse. Capitalism has a structural reliance on growth, thus the high emphasis placed on labor productivity in the modern economy. Continuous improvements in technology mean that more output can be produced for any given input of labor.

As long as the economy expands fast enough to offset labor productivity there isn't a problem. But if the economy doesn't grow, people lose their jobs, output falls, public spending is curtailed, and the ability to service public debt is diminished. A spiral of recession looms. Growth is necessary within this system just to prevent collapse.

As a result society is faced with a profound dilemma. To resist growth is to risk economic and social collapse. To pursue it relentlessly is to endanger the ecosystems on which we depend for long-term survival. This dilemma looks at first like an impossibility theorem for sustainable development. But it cannot be avoided and has to be taken seriously. The failure to do so is the single biggest threat to sustainability.

The arithmetic of growth

The conventional response to the dilemma of growth is to appeal to the concept of "decoupling." Production processes are reconfigured. Goods and services are redesigned. Economic output becomes progressively less dependent on material throughput. In this way the economy can continue to grow without breaching ecological limits—or running out of resources.

It's vital here to distinguish between "relative" and "absolute" decoupling. Relative decoupling refers to a decline in the ecological intensity per unit of economic output; resource impacts decline relative to GDP. The situation in which resource impacts decline in absolute terms is called "absolute decoupling." This is essential if economic activity is to remain within ecological limits. In the case of climate change, for instance, absolute reductions in global carbon emissions of 50–85 percent are required by 2050 in order to meet the IPCC's 450 ppm stabilization target.[19]

The prevailing wisdom suggests that decoupling will allow us to increase economic activity indefinitely and at the same time stay within planetary boundaries. But the evidence is far from convincing. While global primary energy efficiency has increased by a third since 1980 and the carbon intensity of each dollar of economic output has fallen by about the same amount, absolute reductions in impact have been elusive. Global primary energy use, carbon emissions, biodiversity loss, nutrient loadings, deforestation, global fossil water extraction are all still increasing. Carbon dioxide emissions from fossil fuel consumption increased by 40 percent between 1990 and 2009.

Massive investments in new technology and rapid improvements in resource productivity could, in theory, redress this situation. But the sheer scale of the challenge is daunting. In a world with 9 billion people with the level of affluence expected in the OECD nations as argued above, we would need an economy forty times bigger than today's by the end of the century. What on earth does such an economy look like? What does it run on? Does it really offer a credible vision for a shared and lasting prosperity?

Arithmetic is key here. A very simple mathematical identity, put forward almost forty years ago by Paul Ehrlich and John Holdren, governs the relationship between relative and absolute decoupling. The impact (I) of human activity is the product of three factors: the size of the population (P), its level of affluence (A) expressed as income per person, and a technology factor (T), which measures the impact associated with each dollar we spend.

For as long as the (T) factor is going down, we have relative decoupling. But for absolute decoupling we need (I) to go down as well. And that can only happen if (T) goes down fast enough to outrun the pace at which population (P) and income per capita (A) go up.

Over the last five decades both affluence and population have gone up substantially, each being about equally responsible for the overall five-fold growth in the economy. In recent years, the affluence factor has exceeded the population factor in driving growth. But both are clearly important, as Ehrlich himself recognized.[20] And neither has proved particularly tractable to policy. Increasing affluence has been seen as synonymous with improved well-being. Advocating limits to population growth has been seen as contravening basic human liberties.

Ironically, both these preconceptions are wrong. Increasing incomes don't always guarantee well-being and sometimes detract from it. And the fastest population growth has occurred in the developing world—driven not by liberty but by a lack of education and inadequate access to contraception.[21]

Nonetheless, the intractability of addressing both population and income has tended to reinforce the idea that only technology can save us. Knowing that efficiency is key to economic progress, it is tempting to place our faith in the possibility that we can push relative decoupling fast enough that it leads in the end to absolute decoupling. But just how feasible is this?

Carbon intensities have declined on average by 0.7 percent per year since 1990. That's good; but not good enough. Population has increased at a rate of 1.3 percent and average per capita income has increased by 1.4 percent each year (in real terms) over the same period. Efficiency hasn't even compensated for the growth in population, let alone the growth in incomes. Instead, carbon dioxide emissions have grown on average by 2 percent per year, leading over seventeen years to an almost 40 percent increase in emissions.[22]

The IPCC's Fourth Assessment report suggests that achieving a 450 ppm stabilization target means getting global carbon dioxide emissions down to below 4 billion tonnes per annum by 2050 or soon after. This would be equivalent to reducing annual emissions at an average rate of 4.9 percent per year between now and 2050.

But income and global population are going in the opposite direction. According to the UN's mid-range estimate, the world's population is expected to reach 9 billion people by 2050—an average growth of 0.7 percent each year. Under business as usual conditions, the decline in carbon intensity just about balances the growth in population, and carbon dioxide emissions will end up growing at about the same rate as the average income (1.4% a year). It might not sound like much, but by 2050, under these assumptions, carbon dioxide emissions will be 80 percent *higher* than they are today. Not quite what the IPCC had in mind.

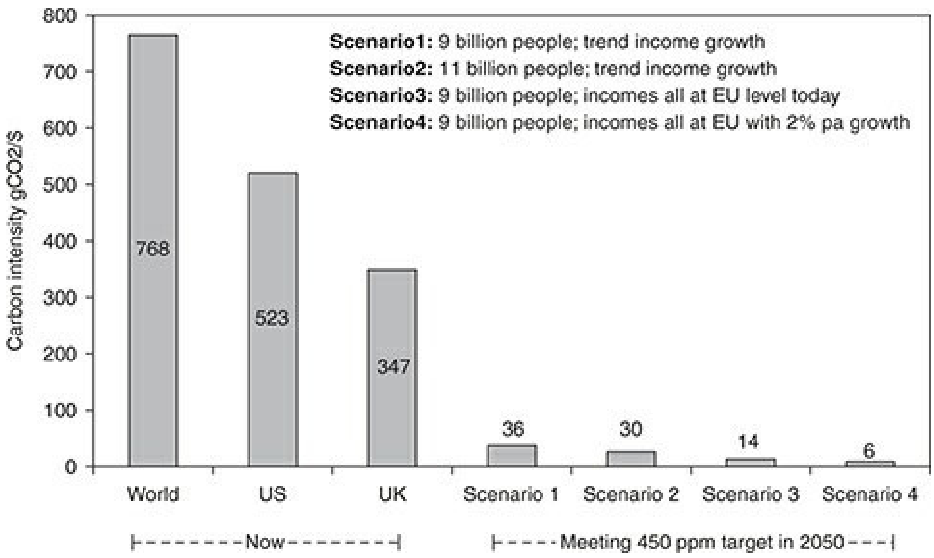
To achieve an average year-on-year reduction in emissions of 4.9 percent with 0.7 percent population growth and 1.4 percent income growth (T) has to improve by approximately 4.9 + 0.7 + 1.4 = 7% each year—almost ten times faster than it is doing right now. By 2050 the average carbon content of economic output would need to be less than 40 g CO_2/$, a twenty-one-fold improvement on the current global average (Figure 2.4, Scenario 1).

Notably, this would still be a deeply unequal world. Business-as-usual income growth is usually taken to mean a steady 2 percent growth rate in the most developed countries, while the rest of the world does its best to catch up—China and India leaping ahead at 5–10 percent per annum at least for a while, with Africa, South America, and parts of Asia languishing in the doldrums for decades to come. In most of these scenarios, both the incomes and the carbon footprints of the developed nations would be more than an order of magnitude higher by 2050 than those in the poorest nations.

If we're really serious about fairness and want the world's 9 billion people all to enjoy an income comparable with EU citizens today, the economy would need to grow six times between now and 2050, with incomes growing at an average rate of 3.6 percent a year. Achieving the IPCC's emission target in this world means pushing down the carbon intensity of output by 9 percent every single year for the next forty or so years.[23] By 2050, the average carbon intensity would need to be fifty-five times lower than it is today at only 14 g CO_2/$ (Figure 2.4, Scenario 3).

And this scenario still hasn't factored in income growth in the developed nations. Imagine a scenario in which incomes everywhere are commensurate with a 2 percent increase per annum in the current EU average income. The global economy grows almost fifteen times in this scenario and carbon intensity must fall by over 11 percent every single year. By 2050 the carbon content of each dollar has to be no more than 6 g CO_2/$. That's almost 130 times lower than the average carbon intensity today (Figure 2.5, Scenario 4).

Figure 2.5. Carbon intensities now and required to meet 450 ppm target



Source: Jackson (2009).

Beyond 2050, if growth is to continue, so must efficiency improvements. With growth at 2 percent a year from 2050 to the end of the century, the economy in 2100 is forty times the size of today's economy. And to all intents and purposes, nothing less than a complete decarbonization of every single dollar will do to achieve carbon targets. Under some more stringent stabilization scenarios, by 2100, we will need to be taking carbon out of the atmosphere. The carbon intensity of each dollar of economic output will have to be less than zero. Or in other words, each $ of global economic activity will on average need to be taking carbon out of the atmosphere rather than adding carbon to it.

This may not be strictly impossible, in purely technical terms. But it clearly implies a transformation well beyond the scale or speed of dematerialization achieved during the history of industrial society. A critical question here is whether this scale of transformation is feasible within the economic and social dynamics of modern society. Does this kind of economy really allow for levels of dematerialization an order of magnitude greater than anything witnessed hitherto? What about the social dynamics of the consumer society? Is this kind of society capable of delivering radical reductions in carbon intensive consumption?

The dynamics of transformation

To rely on heroic beliefs about technological or behavioral change without exploring these questions is to default to a kind of magical thinking about the future. It would be fanciful to suppose that "deep" resource and emission cuts could be achieved without confronting the structure of market economies. It is essential to understand two interrelated issues that together drive the dynamic of modern capitalist economies.

In the first place, the profit motive stimulates a continual search by producers for newer, better, or cheaper products and services. This process of “creative destruction,” according to Schumpeter is a fundamental feature of capitalism, driving economic growth forward.[24] For the individual firm, the ability to adapt and to innovate—to produce cheaper and newer products—is vital. Firms who fail in this process risk their own survival.

But the continual production of novelty would be of little value to firms if there were no market. Understanding the nature of this demand is essential. It is intimately linked to the symbolic role that material goods play in our lives.[25] The “language of goods” allows us to communicate with each other—about social status, identity, social affiliation.

Novelty plays an absolutely central role. It carries important information about status and allows us to explore our aspirations for ourselves and our family, and our dreams of the good life. There is an almost perfect fit between the continual consumption of novelty by households and the continuous production of novelty in firms. The restless desire of the consumer is the perfect complement for the restless innovation of the entrepreneur. The economic system remains viable as long as liquidity is preserved and consumption rises.

An understanding of the social logic of consumerism suggests that it’s mistaken to assume that human motivations are all selfish. Evolution doesn’t preclude moral, social, and altruistic behaviors. On the contrary, social behaviors evolved in humans precisely because they offer selective advantages to the species. All of us are torn to some extent between selfishness and altruism.

The psychologist Shalom Schwartz and his colleagues have formalized this insight into a theory of underlying human values. Using a scale that has now been tested in over fifty countries, Schwartz suggests that our values are structured around two distinct tensions. The tension between selfishness (self-enhancement, in Schwartz’s scheme) and altruism (self-transcendence) and the tension between openness to change and conservation—or in other words between novelty and tradition.[26]

As society evolved in groups, people were caught between the needs of the individual and the needs of the group. And as they struggled for survival in sometimes hostile environments, people were caught between the need to adapt and to innovate and the need for stability. In other words, both individualism and the pursuit of novelty have played an adaptive role in our common survival. But so have altruism and conservation or tradition.

The point is that each society strikes the balance between altruism and selfishness (and also between novelty and tradition), and where this balance is struck depends crucially on social structure. When technologies, infrastructures, institutions, social norms reward self-enhancement and novelty, then selfish sensation-seeking behaviors prevail over more considered, altruistic ones. Where social structures favor altruism and tradition, self-transcending behaviors are rewarded and selfish behavior may even be penalized.[27]

Thus, the searching questions about the balance of the institutions that characterize modern society are: Do they promote competition or cooperation? Do they reward self-serving behavior or people who sacrifice their own gain to serve others? What signals do government, schools, the media, religious and community institutions send out to people? Which behaviors are supported by public investments and infrastructures and which are discouraged?

The institutions of consumer society are designed to favor a particularly materialistic individualism and to encourage the relentless pursuit of consumer novelty because this is exactly what’s needed to keep the economy going.

The erosion of commitment is a structural requirement for growth as well as a structural consequence of affluence. Modern structures of consumerism call on us to be myopic, individualistic, novelty seekers, because that’s exactly what’s needed to perpetuate the economic system.

Simplistic exhortations for people to resist consumerism are destined to failure. Under current conditions, it’s tantamount to asking people to give up key capabilities and freedoms as social beings. Equally, changing the social logic of consumption cannot simply be relegated to the realm of individual choice. It's almost impossible for people to simply *choose* sustainable lifestyles, however much they'd like to. Even highly motivated individuals experience conflict as they attempt to escape consumerism. And the chances of extending this behavior across society are negligible without changes in the social structure.

Conversely, social structures can and do shift people's values and behaviors. Structural changes of two kinds lie at the heart of any strategy to address the social logic of consumerism. First, dismantle or correct the perverse incentives for unsustainable (and unproductive) status competition. Second, establish new structures that provide capabilities for people to flourish, and particularly to participate fully in the life of society, in less materialistic ways.

In practice, this second avenue requires a more detailed exploration than is possible here. It will require policy attention to what flourishing means, particularly when it comes to questions of community, social participation, and psychological flourishing. But these outcomes cannot be delivered in instrumental, *ad hoc* ways. Policy must pay closer attention to the structural causes of social alienation and have the goal of providing capabilities for flourishing at its heart.

This strategy rejects the centrality of material commodities as the basis for profitability. It replaces them with the idea of an economy designed explicitly around delivering the capabilities for human flourishing.

More than this, of course, these capabilities will have to be delivered with considerably less material input. We will need to call on the creativity of the entrepreneur in a different way than in the past. Social innovation is going to be vital in achieving change. But so too is a closer attention to the question of limits.

A key point of influence will lie in the structure of wages. Society now rewards competitive and materialistic outcomes even when these are socially detrimental—as the lessons from the financial crisis made clear. Reducing the existent huge income disparities would send a powerful signal about what is valued in society. Better recognition for those engaged in childcare, care for the elderly or disabled, and volunteer work would shift the balance of incentives away from status competition and toward a more cooperative and potentially more altruistic society.

Increased investment in public goods and social infrastructure is another vital point of influence. A different role for investment is an essential component of an ecological macroeconomics. In addition to its role in ensuring economic resilience, social investment sends a powerful signal about the balance between private interests and the public good.

In summary, we are faced with an unavoidable challenge. A limited form of flourishing through material success has kept our economies going for half a century or more. But it is completely unsustainable and is now undermining the conditions for a shared prosperity. This materialistic vision of prosperity has to be dismantled.

The idea of an economy whose task is to provide capabilities for flourishing within ecological limits offers the most credible vision to put in its place. But this can only happen through changes that support social behaviors and reduce the structural incentives to unproductive status competition.

Steps toward the green economy

The policy demands of this analysis are significant but relatively clear. There is a need for a concerted and committed effort on the part of governments to establish viable and effective policies to initiate the transition to a green economy. They can be grouped under three main themes:

- to establish and impose meaningful resource and environmental limits on economic activity
- to develop and apply a robust macro-economics for sustainability

- to redress the damaging and unsustainable social logic of consumerism

Table 2.1 summarizes specific policy steps that national governments could take.

Table 2.1. Steps toward a sustainable economy

Establish the Limits
Resource use, emissions caps, and reduction targets Fiscal reform for sustainability Promoting technology transfer and ecosystem protection
Redesigning the Economic Model
Developing macroeconomic capability Investing in jobs, assets, and infrastructures Increasing financial and fiscal prudence Improving macroeconomic accounting
Changing the Social Logic of Consumerism
Sharing the work and improving the work-life balance* Tackling systemic inequality Measuring prosperity Strengthening human and social capital Reversing the culture of consumerism

Source: Jackson (2009).

Establishing ecological limits

The material profligacy of consumer society is depleting key natural resources and placing unsustainable burdens on the planet's ecosystems. Establishing clear resource and environmental limits and integrating these limits into both economic structure and social functioning is essential.

This means paying a much closer attention to the ecological limits of economic activity through establishing reduction targets and emission caps. The stabilization targets and emission budgets established for carbon provide an exemplar here.[28]

The conditions of equity and ecological limits, taken together, suggest a key role for the model known as "contraction and convergence" in which equal per capita allowances are established under an ecological cap that converges toward a sustainable level.[29] This approach has been applied, to some extent, for carbon. Similar caps should be established for the extraction of scarce nonrenewable resources, for the emission of wastes (particularly toxic and hazardous wastes), for the drawing down of "fossil" groundwater, and for the rate of harvesting of renewable resources.

Effective mechanisms for achieving targets under these caps need to be set in place. Once established, these limits also need to be integrated into a convincing economic framework.

Ecological macroeconomics

For the richest nations, there's an urgent need to develop a new ecological macroeconomics. A macroeconomy predicated on continual expansion of a debt-driven, materialistic consumerism is ecologically unsustainable, socially divisive, and financially unstable.

A new macroeconomics require changes in the configuration of key macroeconomic variables. Consumption, state spending, investment, employment still matter in a new economy, but the balance between consumption and investment, the role of public, community and private sectors, the nature of productivity growth, the conditions of profitability are likely to shift as ecological and social goals come into play. New macroeconomic variables will need to be brought explicitly into play including limits on carbon, the value of ecosystem services and the stocks of natural capital.

The role of investment is vital. In conventional economics, investment stimulates consumption growth through the continual pursuit of productivity improvement and the expansion of consumer markets. In the new economy, investment must be focused on the long-term protection of the assets on which basic economic services depend. The new targets of investment will be low-carbon technologies and infrastructures, resource productivity improvements, the protection of ecological assets, maintaining public spaces, building and enhancing social capital.

This new portfolio demands a different financial landscape from the one that led to the collapse of 2008. Long-term security has to be prioritized over short-term gain and social and ecological returns must become as important as conventional financial returns. Reforming capital markets and legislating against destabilizing financial practices are an essential foundation for a new sustainable macroeconomy.

The question of productivity is key to resolving the dilemma of growth. The "productivity trap"[30] arises from the relentless pursuit of labor productivity growth. Labor productivity growth appears to offer a means to higher efficiencies in delivering economic output, but it requires continuous growth to maintain full employment. In the language of overanxious politicians, growth equals jobs. And any attempt to stabilize or reduce economic output—as a means of reducing resource throughput or environmental impact, for example—is viewed as a direct threat to people's livelihoods.

There are two avenues through which it might be possible to escape the productivity trap.[31] One is to accept productivity growth in the economy and reap the rewards in terms of reduced hours worked per employee—to share the available work among the workforce to retain equitable employment opportunities. The second strategy is to shift the structural composition of the economy to sectors that have lower labor productivity and lower labor productivity growth. Both these avenues have some precedence in economic thought but need to be integrated into a convincing macroeconomic policy framework.

Finally, a new macroeconomics will need to be ecologically and socially literate, ending the folly of separating economy from society and environment. A first step in achieving this must be an urgent reform of the national accounting system so that what we measure is brought more in line with what really matters. The integration of ecological variables into the national accounts and an end to the "fetishism" of GDP are essential.

Changing the social logic

The social logic that locks people into materialistic consumerism is extremely powerful. But it is also detrimental ecologically and psychologically. An essential prerequisite for a lasting prosperity is to free people from this damaging dynamic and provide opportunities for sustainable and fulfilling lives.

Structural change must lie at the heart of any strategy to address the social logic of consumerism through two avenues: dismantling the perverse incentives for unproductive status competition and establishing new structures that provide capabilities for people to flourish—and particularly to participate meaningfully in the life of society—in less materialistic ways.

Achieving this means finding new ways for meeting the desires and aspirations that are now met through commoditized materialistic consumption. One way to achieve this is through investment in public amenities and spaces that create opportunities for leisure and self-development. An equally important strategy lies in strengthening communities and building strong social ties that enrich human life without enlarging our ecological footprint.

Even more important is developing nonconsumerist ways of being in the world—drawing on a variety of traditions that oppose consumerism.

Consumerism has been a major driver of materialism, and advertising is the most obvious attribute of the consumer society. Although advertising provides information, it is primarily a means of persuasion, one that is particularly pernicious in limiting people's mental and spiritual universe. A nonconsumerist economy will limit advertising and allied forms of manipulating people.

The advantages in terms of prosperity are likely to be substantial. A less materialistic society will increase life satisfaction. A more equal society will lower the importance of status goods. A less consumption-driven economy will improve people's work-life balance. Enhanced investment in public goods will provide lasting returns to national prosperity.

Green economy and sustainable development

A resilient economy in which low-carbon enterprises can thrive and people can find meaningful employment and flourish is a necessary precondition for sustainable development. But the structural drivers of the conventional economy are not sufficient to deliver this. Without structural change it seems unlikely that businesses, individuals, and governments will engage in the necessary transformation to a green economy.

Enterprise is constrained by performance against short-term investment conditions. People are constrained by a powerful social logic that locks them into consumerism. Governments will tend to favor conditions that promote increased consumerism over sustainability for as long as economic stability depends on consumption growth.

But it is possible to identify both general conditions and specific strategies that could transform economies and patterns of consumption. Interestingly, the foundations for such a transition draws from the philosophical foundations for the industrial economy.

The utilitarian roots of modern economies fail to capture the deeper and broader notions of human well-being. The libertarian focus on individual freedoms misses the broader social nature of human beings. Institutional structures of the market, the legal forms of enterprise, the structure of ownership, and profit-making have all tended to focus to narrowly on individual self-interest.

The vision of sustainable development in terms of a strong, healthy, and just society, able to flourish within the ecological limits of a finite planet, calls for a broadening of the social dimensions of human behavior, a strengthening of the institutions that reinforce and encourage social behaviors, and long-term investment in the structures and infrastructures that support these behaviors.

Ultimately, if the green economy is to support sustainable development, it must replace the incomplete vision of self-interested hedonism that haunts conventional economics with something more closely aligned with our broader nature as social beings.

Most crucially, the idea that the pursuit of individual interest can by itself lead to social progress is flawed and useless to the pursuit of sustainable development. The institutions of the green economy must start from our interconnectedness to each other, to our shared past, to our common future, and to the environment on which we depend for life.

[1] OECD (2008).

[2] Utilitarianism was first established as an idea by John Stuart Mill in book of the same name first published in 1863 (Mill 1906). Libertarianism evolved alongside utilitarianism through the writings of John Locke, Edmund Burke, Adam Smith, and others (Hamowy

2008).

[3] Polanyi (1942).

[4] Maddison (2008).

[5] Meadows et al. (1972) and (2004).

[6] Turner (2008).

[7] The G20 group warned of the threat of rising oil prices to global economic stability as early as 2005 (http://www.independent.co.uk/news/business/news/g20-warns-of-oil-price-threat-to-global-economic-stability-511293.html).

[8] On mineral reserves and extraction rates, see Turner et al. (2007), especially Tables 1–3.

[9] McKibben (2007), p. 18. On sources versus sinks, see, for example, Common and Stagl (2006), Marglin and Banuri (2008), Turner et al. (2007).

[10] MEA (2005); TEEB (2008).

[11] On income inequality in developed nations, see OECD (2008); on global disparities, see UNDP (2005). On the effects of income inequality, see Marmot (2005), Wilkinson (2005), Marmot and Wilkinson (2006), and Wilkinson and Pickett (2009).

[12] OECD (2008).

[13] The average annual growth in global GDP in the last fifty years is just over 3 percent per year. If the economy grows at the same rate over the next ninety-one years, it will be $(1.031)^{91} = 16.1$ times bigger than it is today.

[14] This is the UN's mid-range population estimate for 2050 .

[15] Typical EU income in 2007 was $27,000 per capita (in $2000) dollars. At 2 percent average growth per annum, this reaches $63,000 by 2050. For 9 billion people to achieve this income, the global economy must be $573 trillion dollars. In 2007, it was $39 trillion. This means that the economy in 2050 is 570/39 = 14.6 times the size it is today. Assuming that population is stabilized by 2050 and that any further growth is due to income growth at the same 2 percent average rate, then by 2100 the economy is $(1.02)^{50} = 2.7$ times bigger than it is in 2050, that is, around 2.7×15 = 40 times bigger than it is today.

[16] See, for example, Layard (2005), nef (2006), Haidt (2007), Abdallah et al. (2008). On "social recession," see Rutherford (2008), Norman (2010). On well-being and inequality, see Jackson (2008).

[17] For more detail on this underlying model, see Booth (2004), Common and Stagl (2005), Ayres (2008), and Victor (2008).

[18] IFS (2009).

[19] IPCC (2007), Table SPM.6.

[20] See Ehrlich (1968).

[21] See, for example, APPG (2007).

[22] Rates of change for r_a were calculated using world GDP data (at constant 2000 prices, market exchange rates) taken from IMF (2008), available online at: http://www.imf.org/external/pubs/ft/weo/2008/02/weodata/index.aspx.

[23] The rule of thumb here gives: 4.9 + 0.7 + 3.6 = 9.2%, but the error term is slightly larger (0.4%). The actual value is a little over 8.8 percent.

[24] Schumpeter (1934).

[25] Jackson (2009), (2005); Douglas and Isherwood (1996).

[26] Schwartz (2006), (1999).

[27] This finding was first demonstrated formally by the game theorist Robert Axelrod (1984).

[28] CCC (2008); IPCC (2007), for example.

[29] Meyer (2004).

[30] Jackson and Victor (2011).

[31] Jackson and Victor (2011).

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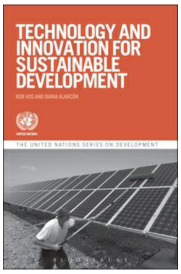

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Chapter 3. Historical Characteristics and Scenario Analysis of Technological Change in the Energy System[1]

Charlie Wilson and Arnulf Grubler

[2]Introduction

Technological change is widely recognized as the main driver of long-term economic growth (Solow, 1957) and of development in general (Freeman and Perez, 1988). Contrasting perspectives persist on the relationship between technological, institutional, and social change. "Technological determinism" depicts technology as the main agent of change. "Social constructivism" depicts the shaping of the technological landscape by social forces. The perspective of this chapter is that these dichotomies cloud complex interdependencies. Technologies and their institutional and social settings coevolve. Change in these different arenas is mutually dependent, mutually enhancing, mutually dampening. Regardless of these particular perspectives, scholars agree on the importance of technological change in historical energy transitions and on future scenarios of energy system transformation (Grubler, 1998; Nakicenovic et al., 2000; Smil, 2003; Halsnæs et al., 2007).

Studies of past energy transitions, as well as technological successes stories, provide many insights relevant to mitigating climate change, providing universal access to modern forms of energy, ensuring secure markets and supply chains, and reducing air pollution and human health impacts (Johansson et al., 2012). These challenges of a future sustainable energy transition will require substantive innovation and technological change across all regions, particularly in developing countries. Historically, the emphasis of energy-related development has begun by addressing energy poverty, then on building up infrastructure as part of industrialization, then on widening access, and finally on tackling the environmental externalities associated with growth in energy use and consumption (Grubler, 1998). The overriding question for developing countries is how to move from this historical pattern to an integrated, concurrent approach dictated by the sheer magnitude of numbers as well as energy access and climate stabilization objectives (Metz et al., 2007). While the difficulties of such an integrated approach are significant, especially in view of capital constraints and often weak institutional capabilities, the benefits of a sustainable energy transition are substantial (Johansson et al., 2012).

Here we review historical evidence on the dynamics and characteristics of technological change and diffusion, focusing on the energy system. Alongside this historical emphasis is an analysis of how technological change is represented in future scenarios. Both sources of evidence are used to draw implications for the ongoing development and diffusion of clean energy technologies. Important differences in context and needs mean global and universal policy prescriptions are inappropriate. Rather, generic policy design criteria are recommended to support effectively functioning clean technology innovation systems.

Historical dynamics of technological change in the energy system

Historical energy transitions

Global energy use has grown by a factor of 25 over the last 200 years. This increase, far in excess of the roughly seven-fold increase in population over the same period, constitutes the first major energy transition: from penury to abundance. The transition in the *quantity* of energy use is closely linked to corresponding transitions in the *quality* of energy used and the *structure* of the energy system. Quantitative and qualitative transitions have been driven to a large extent by technological change but they are far from complete. Some 2 billion people continue to rely on traditional patterns of energy use: noncommercial biomass as the principal source of energy; no access to electricity; and levels of energy use characteristic of preindustrial societies (some 20–50 gigajoule[3] [GJ] primary energy per capita). Indeed, over the entire twentieth century, energy use in industrialized countries has been persistently *above* the levels seen in developing countries despite accounting (currently) for one-seventh of the global population. This situation reversed after 2000. Strong energy demand growth in developing countries, particularly China, coupled with stagnant, even slightly decreasing energy use in industrialized countries linked to the recession, have meant developing countries now account for over half of global energy use, or 276 exajoules (EJ) of a global total of 530 EJ in 2009 (Grubler, 2008; BP, 2010; IEA, 2010). Scenarios suggest that by 2100, developing countries could account for between two-thirds to three-quarters of total global energy use.

Although energy use has increased in industrialized and developing countries over the past 200 years, the underlying driving forces have been radically different. Historically, increasing energy use has been weakly related to population growth. Nearly exponential increases in energy use in industrialized countries contrasts with comparatively modest, linear increases in population. In developing countries, the reverse is true: nearly exponential increases in population yielding—up to 1975—a linear increase in energy use. Since 1975 (and especially since 2000), the increasing *per capita* energy use characteristic of industrialized countries is taking shape in developing countries. These historical differences are explained by the nature of the industrialization process of industrialized countries—income growth, fueled by technological change, leading to affluence and high levels of material (and energy) consumption. The historical record suggests that many developing countries are now at the beginning of a long, decadal development path with increasing levels of energy use as incomes rise. Conversely, in many industrialized countries, per capita energy use since 1975 has remained remarkably flat despite continuing growth in per capita income, suggesting an increasing decoupling of the two variables.

Although the pattern of increasing energy use with economic development is pervasive, there is no unique and universal "law" governing their relationship over time and across countries. There is a persistent difference between development trajectories spanning the extremes of highly energy intensive (e.g. the United States) to highly energy efficient (e.g. Japan). The concept of "path dependency," discussed further below, helps to explain these differences in energy use patterns among countries and regions even at comparable levels of income.

Two major transitions have shaped the *structure* of the global energy system and the *qualitative* dimension to energy use since the onset of the Industrial Revolution (Nakicenovic et al., 1998). The first is characterized by the emergence of steam power relying on coal that helped to overcome the constraints of preindustrial energy systems including the limited availability of mechanical power, low-energy densities, and the lack of ubiquitous and cheap transport systems (see also Landes, 1969). This first energy technology transition took well over a century to unfold: between the late eighteenth century until the 1920s when coal-based steam power was over two-thirds of the global energy system. The second energy technology transition is characterized by the displacement of the previously dominating coal-based steam technology cluster by electricity (drives, light) and petroleum-based technologies (automobiles, aircraft, petrochemicals). This second transition is far from completed: some two billion still lack access to modern energy services provided by electric appliances and end-use devices (Johansson et al., 2012).

These historical energy technology transitions are characterized by various "grand" patterns of technological change, each of which is discussed in the sections that follow:

1. end-use applications drive supply-side transformations;
2. ii. performance dominates cost in the initial market niches;
3. iii. technologies do not change individually, but cluster and "spillover";
4. iv. the time constants of technological change are long, decades not years;
5. experimentation and learning precede "up-scaling" and widespread diffusion;
6. vi. the magnitude and rate of expansions in energy conversion capacity are inversely related;
7. vii. diffusion in late adopter regions is faster than in initial innovator regions, but saturates at a lesser extent.

End-use applications drive supply-side transformations

Neither of the two major energy technology transitions since the Industrial Revolution were driven by resource scarcity or by direct economic signals such as prices, even if these exerted an influence at various times (Grubler, 2008). It was not the scarcity of coal that led to the introduction of more expensive oil. Instead, these historical shifts were, first of all, technological, particularly at the level of energy end-use. The diffusion of steam and gasoline engines and of electric motors and appliances can be considered the ultimate driver, triggering important innovation responses in the energy sector and leading to profound structural changes in the energy supply. The history of past energy transitions thus highlights the critical importance of end-use technologies, consumers, and the demand for energy services such as heating, lighting, mobility, and power.

Stationary steam engines in industry and agriculture and mobile steam engines on ships and locomotives were the dominant markets for this new technology. Small by comparison were the coal mines and the coking and town gas plants that represented the emerging cluster of a coal-supply technology. In the case of electricity, the first innovation leaving Thomas Edison's R&D laboratory in Menlo Park was the incandescent light bulb. In the technology language of today, a demand innovation—the electric light bulb—triggered a host of supply-side innovations—electricity generation, transport, and distribution.

The size of end-use markets and the volume of applications dwarf their supply-side counterparts. Reliable historical records for the United States describe the evolution of energy technologies and illustrate the importance of energy end-use.

By the beginnings of the US steam age in the 1850s, the dominant energy technologies were the simple conversion devices of ovens, furnaces, and boilers, which converted chemical energy in the forms of fuel wood and coal into heat. Horses were the dominant transport technology converting chemical energy (feed) into mechanical energy, with five-fold greater capacity than the first stationary steam engines. By 1900, close to the peak of the coal/steam transition, thermal conversion in boilers and furnaces accounted for 90 percent of the 1,000 GW of installed conversion capacity in the United States. A hundred years later, this total had grown to some 34,000 GW or 120 kW per capita, ten times the level of 1850. This spectacular expansion has been marked by the electrification of homes and industry, and the striking 1,000-fold increase in energy conversion capacity enabling private mobility. Today, car and truck engines comprise nearly three-quarters of all energy conversion capacity in the United States, exceeding the thermal capacity of electric power plants by a factor of around 10.

Performance dominates cost in initial market niches

Initially, new technologies are attractive not cheap. New technologies when introduced are crude, imperfect, and expensive (Rosenberg, 1994). Performance initially dominates economics as the driver of technological change. New energy technologies are attractive for their ability to perform a particular task or deliver a new or improved energy service. This is often circumscribed by a specific set of needs in a particular context: a market "niche." End-users in such niches are generally less sensitive to the effective price of the energy service provided or have a higher willingness to pay for its performance advantages (Fouquet, 2010). Costs will often only start to fall meaningfully after an extended period of commercial testing, learning, efficiency gains, and other incremental improvements. The concurrent establishment and growth of an industrial base drives costs down through standardization, mass production, and economies of scale. Only then are new technologies able to compete with incumbent technologies on a cost basis, driving their widespread diffusion.

Initial steam engines were, by any standards, inefficient and extremely expensive. The first atmospheric steam engines had thermal conversion efficiencies of only 1 percent, consuming some 45 pounds of coal per horsepower delivered (Ayres, 1989). It took a century to boost their thermal efficiency to around 20 percent in a successive stream of innovations. It took another century again to reach the current steam turbine efficiency of 40 percent. The initial costs of steam engines in the mid-eighteenth century amounted to a phenomenal US$12,000 per kW (in 2003$) (Crafts, 2004) in an economy a factor of 130 smaller than today with per capita incomes around US$1,500 (in 2003). Yet despite their high inefficiency and high cost, the modest performance benefits of steam engines in terms of power output and density meant they began substituting for the incumbent power providers—horses and water. After an extended period of experimentation and development, costs of steam engines started to come down during the mid-nineteenth century, 100 years after their introduction. By the beginning of the twentieth century, costs had fallen to below US$3,000 per kW (in 2003).

In spite of initial high costs, a similar pattern in the adoption of new energy technologies is found in the introduction of electricity and electric appliances for light and motive power (Devine, 1983; Smil, 2000). Fouquet (2010) compares the drivers of fourteen energy transitions in the means of providing heat, light, mobility and power in the UK over the past millennium. In the majority of cases, better or different energy services drove the transition: “The steam engine enabled entrepreneurs to boost production, not limited by humans or animals or by the location of flowing water. Electricity radically altered the production process from belts centrally driven by a steam engine to numerous machines . . . potentially controlled by the worker. Railways and cars transformed the provision of transport services, allowing a faster service and a more flexible and private form of transport respectively. Gas lighting was easier to use and less dangerous. Electric lighting was much easier to use.” (Fouquet, 2010, pp. 6591–92).

Major energy transitions are associated with step-changes in both the quality and the quantity of energy services provided through end-use technologies. Though transitions may be catalyzed by innovations that create new, better or qualitatively different energy services, transitions are subsequently driven and sustained by dramatic falls in the effective cost of providing energy services. (Fouquet and Pearson, 2007; Fouquet, 2010). Any efficiency gains are then overwhelmed by increases in energy service demand and a corresponding expansion in the volume and pervasiveness of end-use technologies (Haas et al., 2008).

Technologies do not change individually but cluster and “spillover”

No individual technology is able to transform large and complex energy systems. The importance of single technologies arises in particular through two effects: “clustering,” or combinations of interrelated technologies, and “spillovers,” or applications outside the configuration, use, sector or geography for which a technology was initially devised. In other words, technologies act more effectively as families or “gangs,” not as individuals.

Technology researchers have introduced the concept of “general purpose” technologies to describe the synergies of technologies deployed in a variety of applications promoting knowledge spillovers and market growth, with corresponding economies of scale (Lipsey et al., 2005). Steam is a prominent historical example. Stationary steam engines were first introduced in the eighteenth century for dewatering coal mines. Stationary steam power subsequently spilled over to drive mechanization in manufacturing (e.g. textiles) and agriculture (e.g. threshing) and also to mobile applications such as railways and steamships. Perhaps the exemplar of a general purpose technology whose importance is founded on clustering and spillover effects is electricity, the “greatest engineering achievement of the 20th century” (US_NAE, 2003). Information and communication technologies (ICTs) are the clearest current example of a general purpose technology (Basu and Fernald, 2008). As such ICTs could drive services-led growth while leaving the basic structure of the energy system in tact (Moe, 2010). Others, however, have argued for a more pervasive impact of ICTs on the energy system, exemplified by the smart grid concept of system management based on two-way flows of both information and power.

Clustering is particularly evident in the mutual dependencies between energy conversion technologies and energy supply infrastructure and networks. Each of the major energy transitions in the United Kingdom since the 1300s were characterized by a change in energy source (e.g. horse to steam power, sail to steam ship transportation, candles to kerosene lighting); but each energy transition also involved major changes in the energy supply network, as well as the energy service provided (Fouquet, 2010).

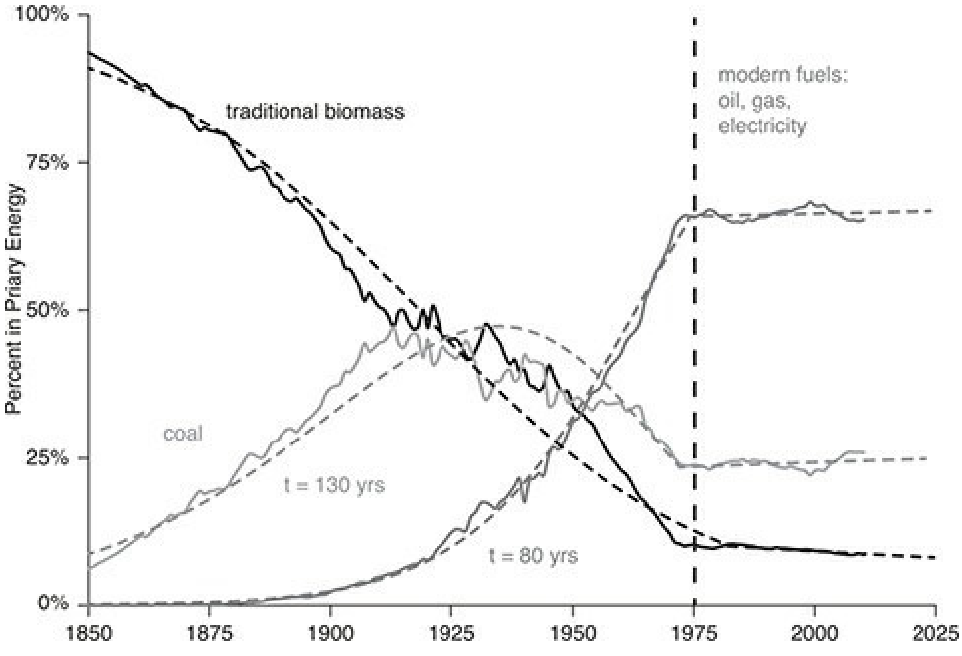
Clustering and spillover effects mean it is difficult to dislodge a dominant technological regime with its component technological systems, high sunk investment costs, and the associated institutions, patterns of social organization, and behavioral routines and practices that support a technological regime (Sovacool, 2009). This is referred to in the technology literature as “lock-in” (e.g. Unruh, 2000) and is described dynamically by the characteristics of “path dependency” (Arthur, 1989). Path dependency helps explain the persistent differences in development trajectories between countries, controlling for the effects of income. Path dependency in energy systems arises from differences in initial conditions (e.g. resource availability and other geographic, climatic, economic, social, and institutional factors) that in turn are perpetuated by differences in policy and tax structures, leading to differences in spatial structures, infrastructures, and consumption patterns (Grubler, 2008). These in turn exert an influence on the levels and types of technologies used by end-users and within the energy supply.

The time constants of technological change are long, decades not years

The turnover of capital stock in the energy system ranges from many decades to well over a century (Grubler et al., 1999). It took steam power in the UK close to 100 years (to the 1860s) to gain a 50 percent market share in total installed horsepower, gradually displacing wind and waterpower (Crafts, 2004). It took some 40 years (to the 1920s) for electric drives to account for 50 percent of all prime movers in US industry (Ausubel and Marchetti, 1996). Substantial capital and labor productivity effects arose only after that threshold was passed (Devine, 1983). In a range of UK energy transitions since the Industrial Revolution, the average time period from first commercialization to market dominance was around fifty years (Fouquet, 2010). Including the period from invention to first commercialization extends this time constant to around 100 years. Energy transition dynamics at the global scale are significantly slower: ranging from 80 to 130 years for new energy technology clusters to achieve market dominance and about twice as long when considering the entire technology life cycle from first introduction to market maturity. These slow rates of change are explained by spillover and clustering effects and the capital intensiveness and longevity of many energy-related plants and infrastructures from end-use applications (e.g. buildings) to conversion technologies (e.g. refineries, power plants) and distribution systems (e.g. railway networks, electricity grids) (Smekens et al., 2003; Worrell and Biermans, 2005).

More generally, the process of technological change, from innovation to widespread diffusion, takes considerable time. Figure 3.1 summarizes the two major energy technology transitions globally in the period 1850–1975: coal/steam replacing traditional biomass, and then modern energy technologies and carriers (oil, gas, and primary electricity from hydropower and nuclear) replacing coal/steam. The y-axis shows market shares as a percentage of total primary energy use for traditional fuels (brown), coal (grey), and modern energy carriers (red). Evident from Figure 3.1 are the long periods of slow and gradual market penetration of end-use and supply technologies alongside the observed substitution of energy sources (Marchetti and Nakicenovic, 1979). The turnover, or displacement times (Δt), of traditional fuels and then coal is around 130 years and 80 years, respectively, at the global level. The significant slowdown and near flatlining of these transition dynamics since 1975 are clearly evident, due largely to the continuing role of coal for electricity generation.

Figure 3.1. Two grand transitions in global energy systems (1850–2008)



Source: Grubler (2008) updated using BP (2010); IEA (2010). Data prior to 1950 are estimates. Dotted lines show fitted logistic substitution models.

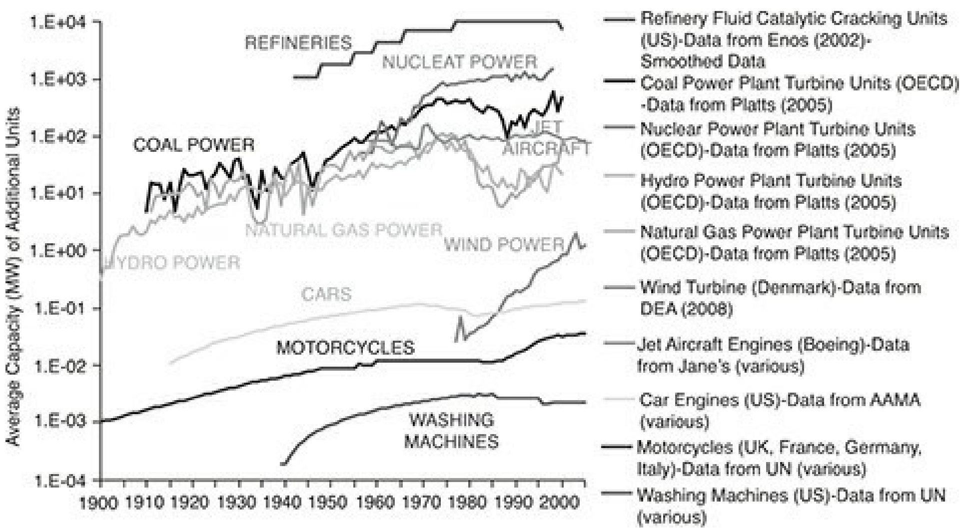
Experimentation and learning precede up-scaling and widespread diffusion

Widespread adoption of a technology follows an often extended period of experimentation during which the technology is tested, refined, and adapted to market conditions. This has been termed the "formative phase" of the technology's life cycle (Jacobsson and Lauber, 2006) and characterizes the early stages of commercial diffusion. The life cycle of some energy technologies—from invention and innovation through to widespread market adoption and eventual saturation—is further characterized by a process of "up-scaling," an increase in the capacity of an individual technological unit to convert energy into a useful service. Up-scaling is often associated with economies of scale, reductions in average unit costs as the size of individual units ("unit" scale economies) or the volume of total production ("manufacturing" scale economies) increases.

Figure 3.2 shows the "up-scaling" dynamic for a range of energy technologies that have diffused over the course of the twentieth century. Each line describes the changes over time of the average capacity in megawatts (MW) of newly installed "units": steam turbine units in coal, gas, and nuclear power plants; wind turbines in wind farms; jet engines in passenger aircraft; internal combustion engines in cars; and compact fluorescent light bulbs in lighting systems.

Historically, the formative and up-scaling phases of energy technologies have tended to progress sequentially. Figure 3.3 shows more detailed data for coal power. The left-hand graph shows the number of steam turbine units built each year, along with their average and maximum unit capacities. These describe growth dynamics at the technological unit level. The right-hand graph shows the total capacity added each year as well as the steady growth over time of cumulative total capacity. These describe growth dynamics at the industry level.

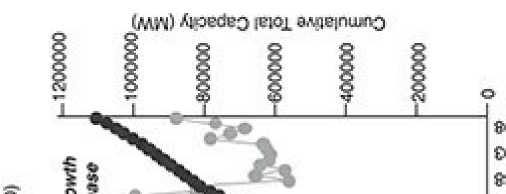
Figure 3.2. Up-scaling of selected energy technologies since 1900

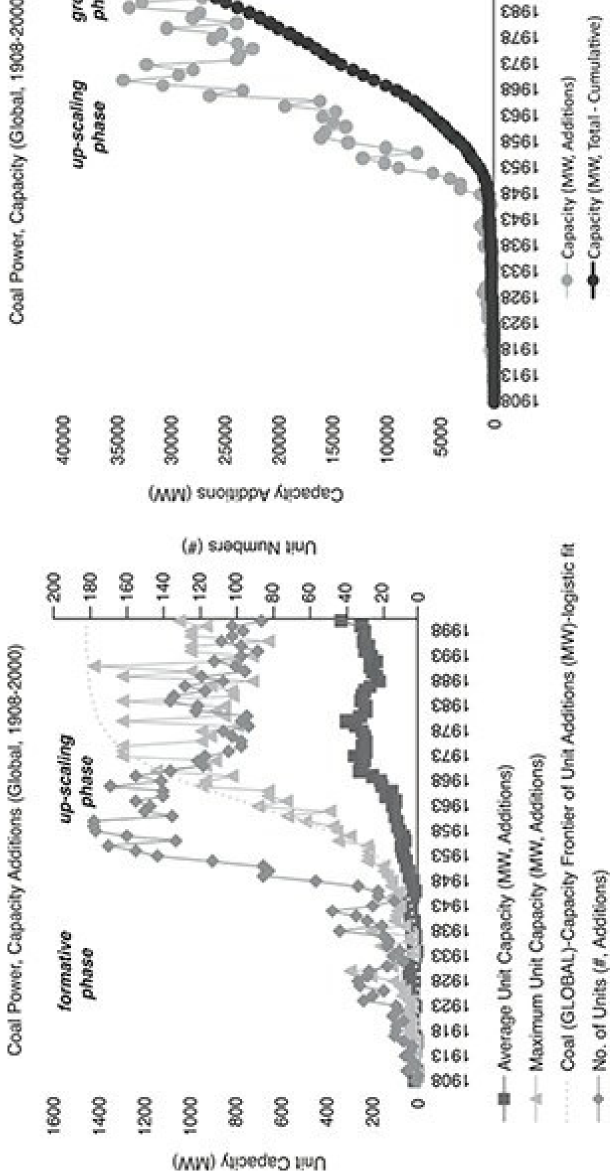


Notes: Lines show average capacity in MW of new units each year on log-scale y-axis.

Source: See graph legend and Wilson (2012); Bento (2013) for details.

Figure 3.3. Growth in coal power capacity globally since 1900





Notes: Left-hand graph shows unit capacities and numbers; right-hand graph shows capacity additions and cumulative total capacity.

Source: Platts (2005); see Wilson (2012) for details.

Figure 3.3 shows a clear overall sequence:

1. i. a *formative phase* of many smaller-scale units with only small increases in unit capacity;

2. ii. an *up-scaling phase* of large increases in unit capacities, particularly at the scale frontier, concurrent with an increase in numbers of units;

3. iii. a *growth phase* of large numbers of units at larger unit capacities.

For the first fifty years, slow growth in cumulative total capacity is driven by increasing numbers of units. Unit capacities remain low, with maximum unit capacities typically in the 10–50 MW range. During the next twenty years, continued growth in cumulative total capacity is increasingly driven by a concentrated period of up-scaling, which is preceded by a dramatic jump in the numbers of units. Maximum unit capacities increase to around 1,000 MW; average unit capacities to around 250 MW. Over the course of the next thirty years, unit capacities vary somewhat around these saturation levels, but sustained growth in cumulative total capacity is driven again by increasing numbers of units.

The sequence of formative, up-scaling, and growth phases observed in the expansion of coal power capacity is broadly consistent across many different energy technologies and in all regions as well as globally (Wilson, 2012). However, the timing and rate of up-scaling varies. In general:

1. Up-scaling occurs more rapidly (and over a shorter timeframe) for technologies with strong unit scale economies: for example, coal power, nuclear power.

2. ii. Up-scaling occurs less rapidly (and over a longer timeframe) for technologies servicing heterogeneous or dispersed markets: for example, natural gas power, jet aircraft.

The potential tension between these two drivers is clear in the case of natural gas power whose scale independence in terms of technical efficiency has meant applications spanning distributed units in the kW range up to centralized combined cycle configurations in the 100s of MW or even GW range (Lee, 1987). The demand context for each technology thus determines the appropriateness of different unit scales. In general, market niches are more heterogeneous for distributed end-use technologies than for centralized supply-side technologies. End-use technologies (e.g. aircraft, light bulbs) supply a particular energy service (e.g. mobility, illumination) in a wide variety of contexts. As an example, the diversity of lighting services requires bulbs ranging in capacity from several watts (LEDs) to over 10kW for specialized exterior lighting (metal halide lamps) (IEA, 2006).

By comparison, energy supply and conversion technologies (e.g. refineries, power plants) produce one or a small number of homogeneous energy carriers (e.g. liquid transportation fuels, electricity). These are subsequently distributed to the point of use. With transmission networks and reasonable proximity to concentrated demand centers, electricity generation has historically been characterized by strong unit scale economies and rapid up-scaling of unit capacities (see Figure 3.2). In the case of US refineries, up-scaling was concentrated during the decades following the Second World War, concurrent with the growth phase of the industry. Increases in unit capacities largely saturated by the 1970s; industry capacity expansion similarly plateaued following the oil shocks. As the largest capacity end-use technology, jet aircraft also exhibited rapid and early up-scaling. First introduced commercially in 1958, up-scaling potential was largely saturated in 1969 with the Boeing 747 (see Figure 3.2).

Experimentation and learning are concentrated during the formative phase

The formative phase of a technology's life cycle describes the critical period between the early development of an innovation and widespread commercial diffusion sustained by positive feedbacks or "cumulative causation" (Jacobsson and Bergek, 2004). During the formative phase, technologies are repeatedly and iteratively tested, modified, improved, reduced in cost, and adapted to market demands. This often takes place in market niches that offer some protection from competitive pressures (Kemp et al., 1998). Well-functioning innovation systems are characterized by entrepreneurialism to conduct "*risky experiments necessary to cope with the large uncertainties that follow from new combinations of technological knowledge, applications and markets*" (Hekkert et al., 2007, p. 422). Dosi (1988) includes experimentation as one of five integral characteristics of innovation, the other four being uncertainty, scientific knowledge, complexity, and accumulation.

Experimentation with many small-scale units through the formative phase contributes to a process of "learning-by-numbers"—or building many before building big. This is illustrated further by Table 3.1, which summarizes data for five energy supply technologies in their initial markets (which vary geographically and in size). The right-hand column shows the length and number of units built during a formative phase, which runs from first commercial application to the point at which new units reach 10 percent of the eventual scale frontier. This formative phase lasts decades and sees the build out of hundreds of units. Nuclear power is the outlier with a relatively short formative phase and relatively few numbers of units built prior to up-scaling. But in fact, this exception supports the generalizable rule. The unit scale frontier of nuclear power increased fivefold in the decade that followed commissioning of the first 50 MW commercial reactor in 1956. Ultimately, these rapid increases in unit size were a contributing factor to the rising complexity that created diseconomies of scale and constrained further growth of the industry in the late 1970s (Lovins et al., 2003; Grubler, 2010).

Table 3.1. Formative phases of energy supply technologies

Technology	Initial Market	First Commercial Capacity Installed	10% of Unit Capacity Frontier Reached	Formative Phase: Number of Years & Number of Units
Natural Gas Power	OECD	1900s	1948	50 years, >400 units
Coal Power	OECD	1900s	1950	50 years, >775 units
Nuclear Power	OECD	1950s	1963	10 years, 25 units
Wind Power	Denmark	1970s (1880s*)	1987	15–100 years, >1,400 units
*Refineries***	*US*	*1860s–1870s*	*(1948–average capacity only)*	*(80–90 years, >100 units?**)*

Source: Wilson (2012).

The knowledge generated and experience accumulated in the formative phase is neither automatic nor autonomous. In many cases, learning is facilitated by relationships between industry actors (supported by public investments in, for example, testing infrastructure) to ensure experiences feed back into subsequent designs (Garud and Karnoe, 2003). When this policy-supported process of collective learning is absent, the development of viable domestic technological capability and industry can fail (Neij and Andersen, 2014).

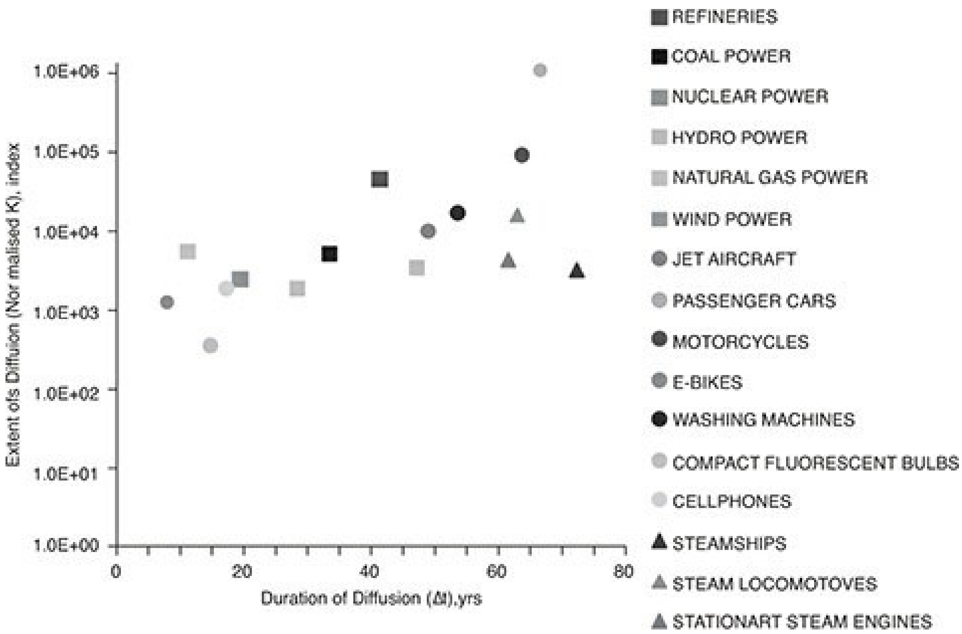
The magnitude and rate of expansions in energy conversion capacity are inversely related

Intuitively, the more pervasive the diffusion of technology, the slower the process (Grubler, 1996). The relationship between the extent and duration of capacity expansion is a useful descriptive measure of the overall growth dynamic of energy technologies.

Figure 3.4 shows a strong positive relationship observed historically between the extent and duration of diffusion for a range of energy technologies. Both axes of Figure 3.4 show parameters from logistic functions fitted to historical time series data of cumulative total capacity in MW. The x-axis is a measure of the *duration* of diffusion. Δt is the period a technology takes to grow from 10 percent to 90 percent of its final saturation level. This saturation level is shown on the y-axis as a measure of the *extent* of diffusion, normalized to account for differences in the overall size of the energy system (i.e. analogous to market share). For details of the methodology and data, see Wilson et al. (2012a) and

Bento (2013).

Figure 3.4. Relationship between extent and duration of capacity growth historically



The consistency of the relationships in Figure 3.4 between the extent and duration of diffusion is surprising as the end-use and energy supply technologies analyzed are of markedly different characteristics (Wilson et al., 2012a). The technology life cycles of refineries, power plants, jet aircraft, cars, and light bulbs are characterized by distinctive cost and efficiency profiles, capital intensiveness, turnover rates, market niches, regulatory contexts, manufacturing bases, and so on. Why should the observed extent–duration relationships be so consistent across technologies? First, this may simply describe the dynamics of demand growth. How rapidly and how extensively demand changes is both driven and constrained by the adaptability of end-user needs and wants. These in turn are embedded in practices, routines, social networks, organizational structures, and so on. The inherent inertia to change in technological systems is similarly found in social systems: indeed, the two are inseparably entwined. Second, consistent extent–duration relationships may signal limits in the capacity of mechanisms shaping innovation to accelerate the time to mass market (Grubler, 1998). Such mechanisms include knowledge generation through R&D, learning and scale effects, knowledge spillovers (and knowledge depreciation), entrepreneurialism, demonstration activities, niche market applications, and so on (Grubler et al., 2012).

In sum, the simple relationship between diffusion extents and durations in Figure 3.4 describes the inherent inertia of a large, complex, interrelated system of technologies, institutions, and end-user needs.

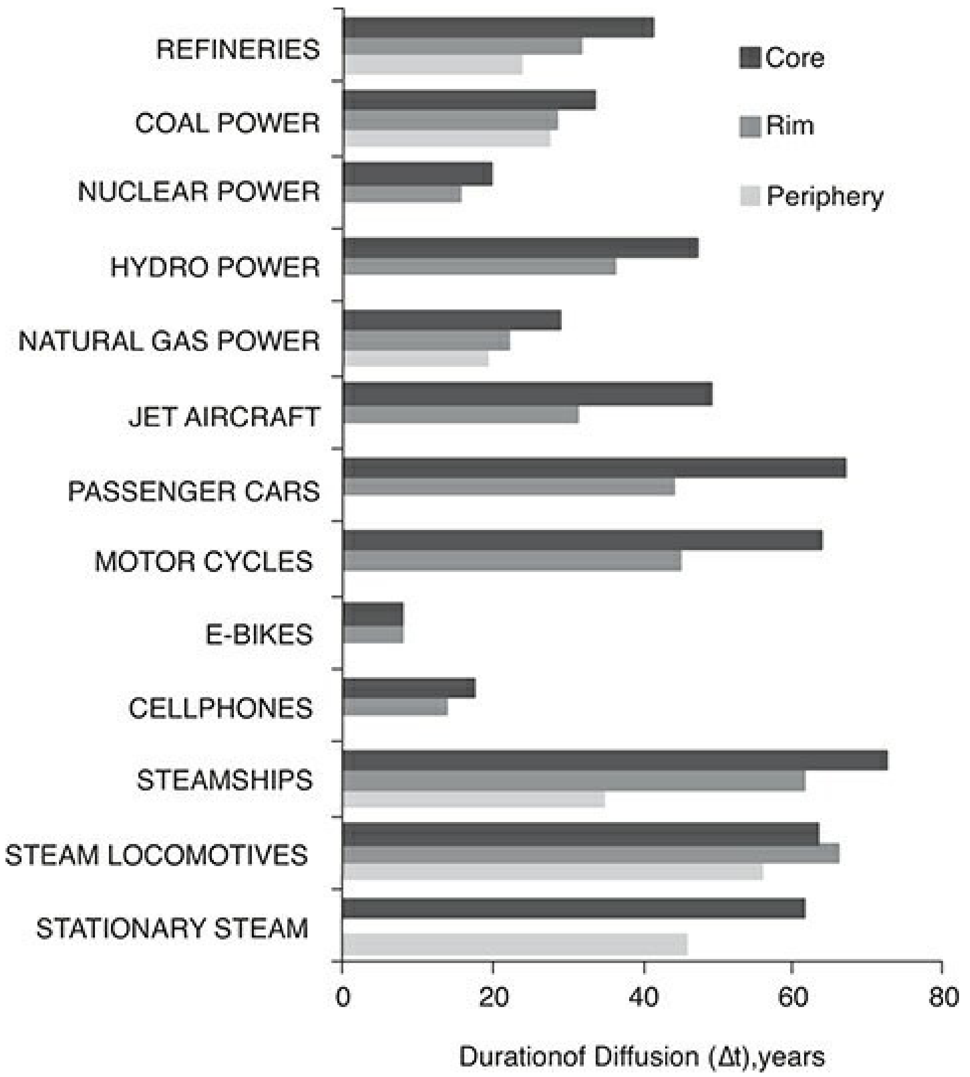
Diffusion in late adopter regions is faster than in initial innovator regions but saturates at a lesser extent

A generalizable *temporal* pattern of technological diffusion sees a slow beginning as technologies are introduced that then—if successful—accelerates into a rapid growth phase before slowing and eventually saturating (Grubler et al., 1999). There is also a generalizable *spatial* pattern to diffusion. In the initial markets or regions where a technology is first commercialized, a technology’s growth tends to be slower but more pervasive (Grubler, 1996). In subsequent markets, growth tends to be more rapid but saturates at a lesser extent (i.e. is less pervasive). Mobile phone densities are 1.2–1.3 per capita in the Scandinavian innovator countries (Finland, Sweden) but only around 0.85 in the United States and Japan (OECD, 2009). The spatial diffusion of cars is another example, albeit a more complex one given the interdependencies of infrastructure, urban form, and petroleum. In the United States as the initial market, car ownership per capita grew from the early 1900s throughout the twentieth century; in Japan, growth began in earnest in the 1950s and was compressed into several decades. But by the 1990s, ownership per capita in Japan was only slightly larger than that of the United States in the 1930s (Grubler, 1990, p. 151; Schipper et al., 1992). Less pervasive diffusion in later adopting markets reflects the long time constants of change in the interrelated systems of technologies, infrastructures, and institutions (including patterns of end-use services and end-user behavior).

More rapid diffusion in later adopting markets signals the “spillover” or transfer of knowledge from the formative phase of technologies in their initial markets (Grubler, 1998). Knowledge spillover can shorten, but not preclude entirely the need for local development of the conditions and institutions that support diffusion and that are gained through cumulative experimentation and learning (Dahlman et al., 1987; Gallagher, 2006).

Figure 3.6 provides further evidence for faster rates of growth in later adopting regions for a range of energy technologies. The bars show the duration of each technology’s growth in terms of cumulative total capacity as it diffuses spatially out of its initial “core” region through subsequent “rim” regions and ultimately into “periphery” regions. The measure of duration is the Δt in years derived from logistic functions fitted to the data. This measure of duration is inversely related to the rate of diffusion, so the longer the bars in Figure 3.5, the more prolonged and the slower the rate of capacity expansion. The duration of diffusion consistently decreases from core to rim to periphery.

Figure 3.5. Spatial diffusion of energy technologies historically



Notes: Bars show durations of diffusion in cumulative total capacity measured as the δt in years (or turnover time). “Core” regions are typically within the OECD; “rim” regions are typically Asian countries; “periphery” regions are typically Africa or Latin

American countries. See Wilson (2012) and Bento (2013) for details and data.

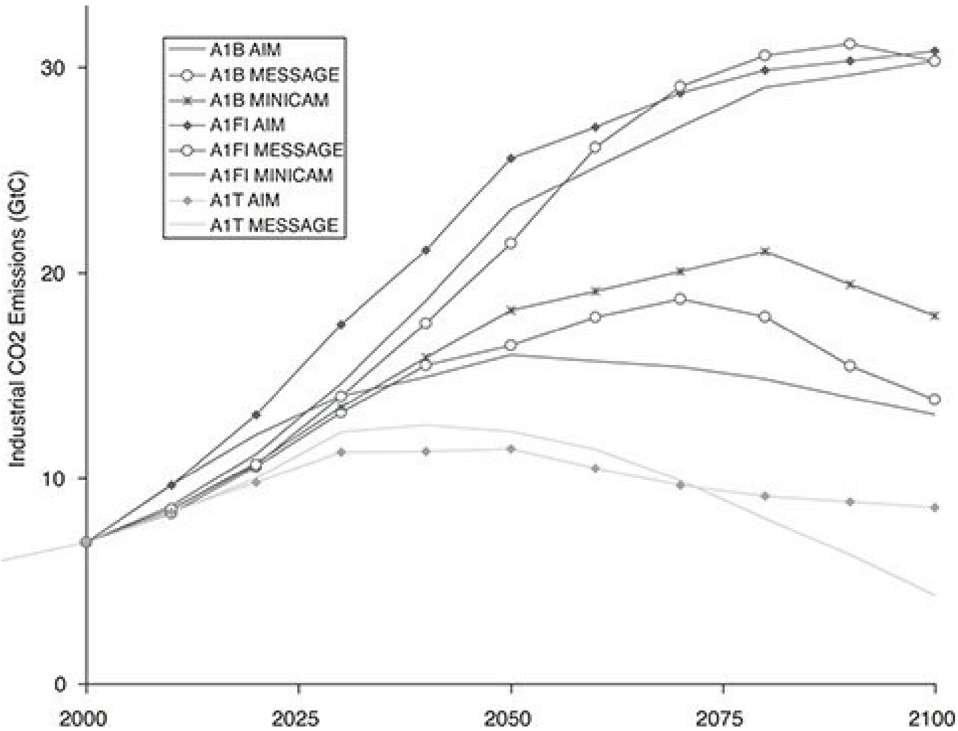
Scenario representations of future technological change

The role of technological change in future energy scenarios and in climate change mitigation has been reviewed comprehensively in the IPCC's Fourth Assessment Report (Fisher et al., 2007; Halsnæs et al., 2007). Here we summarize the levers of technological change for transitioning toward more sustainable energy systems. Growth dynamics in future scenarios are also contrasted with the historical perspective outlined previously.

Path dependency in future technological change

Figure 3.6 shows scenarios of industrial CO_2 emissions in the "high growth," or A1 scenario, family of the IPCC Special Report on Emissions Scenarios ("SRES"), grouped into A1FI (high emissions), A1B (medium emissions), and A1T (low emissions) (Nakicenovic et al., 2000). None of these scenarios explicitly includes the effect of climate policies, yet the vast differences in terms of emission outcomes is striking.

Figure 3.6. Industrial CO_2 emissions in the IPCC's SRES A1 "high growth" scenario family



Source: Nakicenovic et al. (2000).

Comparison of the fossil fuel intensive A1FI scenarios, the low-carbon technology A1T scenarios, and the "balanced" A1B scenarios, illustrate how the dynamics of technological change give rise to consistent and stable technological combinations that crowd out competing alternatives through increasing returns to adoption and consequent creation of path dependency on the dominant technology. Because of the long lifetimes of power plants, refineries, buildings, and other energy infrastructure, these contrasting technology strategies result in emissions diverging only gradually, after several decades or more (Grubler, 2004). But the seeds of subsequent divergence will have been widely sown by then, based on research and development efforts, intervening investments, and technology diffusion strategies (Nakicenovic et al., 1998). These translate into different environmental outcomes only as new technologies gradually replace older technology vintages. As a result, near-term technology and policy decisions are critically important for leveraging long-term change.

While systemic change is strongly path dependent, the growth paths of individual technologies can vary widely. In the scenario projections for solar photovoltaics ("PV"), there is a clear bifurcation of outcomes depending on assumed technology characteristics and investment costs as well as future market deployment environments including the existence and stringency of CO_2 emission constraints. But the temporal dimensions of this technological differentiation in energy systems are extremely long. In the medium-term (2030), only modest, niche-market inroads of solar PV into the global energy system are expected. Only by 2100 have scenarios clustered either around relatively small solar PV markets (0–80 EJ), assuming no or low CO_2 emission constraints and high investment costs, or around relatively large solar PV markets (100–180 EJ), under stringent CO_2 emission constraints and low investment costs. To put these numbers into perspective: current global energy demand amounts to some 530 EJ, and electricity generation to some 60 EJ. The highest growth scenarios suggest that by the end of the twenty-first-century solar PV could generate as much as three times more electricity than is generated at present for all sources and technologies combined.

Marked differences in long-term technology outcomes are the result of complementary (or absent) "market pull" and "technology push" innovation and technology policies. Underlying the alternative projections of solar PV investment costs (which in turn reflect other technology characteristics such as conversion efficiency) are R&D efforts, improved designs, and "debugging" through niche market application and feedbacks. These processes "push" the technology through ever-wider diffusion as CO_2 emission constraints change the relative prices of energy sources and so "pull" solar PV and other low-carbon technologies into the market.

The supply-side emphasis of future energy transitions

Future scenarios tend not to explicitly portray alternative pathways of technological change in energy end-use. This reflects the current state-of-art of modeling technological change in scenarios of energy transitions and climate stabilization rather than any disavowal of end-use technologies on the part of researchers and scenario modeling teams. Even technologically explicit "bottom-up" models contain little detail at the level of energy end-use, instead using aggregate indicators such as sectoral energy intensity (GWh / $ of GDP) (Hanaoka et al., 2009) or exogenously specified indices of efficiency improvements (Azar and Dowlatabadi, 1999; Magne et al., 2010). End-use technology investments are represented endogenously only indirectly through aggregate relationships between demand, energy price, and other factor inputs (capital, labor) (van Vuuren et al., 2009). In other words, unspecified technological change is assumed to occur and is represented in models only in terms of its impact on energy demand; these impacts are then interpreted *ex post* in terms of technological and/or behavioral changes. The energy transitions shown in Figure 3.7 predominantly concern the energy supply. This is in stark contrast to the driving role of changing and novel energy end-use services seen historically.

There are various reasons for the relatively poor model representations of future technological change in end-use technologies. First, there is an extreme paucity of end-use data as end-use technologies are classified under different industrial and consumer goods markets (Nakicenovic and Rogner, 1996). A related, practical data challenge is the increased granularity of end-use technologies: compared to energy supply technologies, they are smaller scale, more decentralized, more heterogeneous, and many more in number.

Second, it is extremely challenging to derive plausible and consistent scenario assumptions on the evolution of a large number of energy end-use applications—from new transport and communication technologies to manufacturing innovations and consumer appliances. This has important implications as it causes scenarios to diverge from historical experience by downplaying the driving role of changing patterns of end-use services and technologies. A major intermodel comparison of stringent climate stabilization targets found that "all models pay considerably less attention to end-use energy efficiency technologies than to supply side technologies, which could create a bias towards favoring [carbon intensity] improvement" (Edenhofer et al., 2010, p. 28). Of the five models compared, the one with the most detailed representation of end-use technologies found "energy efficiency and end-use technologies constitute first rank options to cope with severe climate constraints” (Kitous et al., 2010, p. 58). This includes rapid penetration by mid-century of electric vehicles and low-energy buildings, with the diffusion dynamics of both end-use technologies modeled endogenously.

Implications for clean energy technology and innovation policy

Here we conclude by drawing broad policy implications from the dynamics of technological change observed historically and in future scenarios. The policy-induced technological change in climate change mitigation scenarios is a major point of departure from historical energy transitions. Consequently, past transitions offer insufficient guidance on whether regulation, externality pricing (carbon taxes), and other supporting policies to drive low-carbon technology diffusion will be adequate, and how it will affect rates and extents of growth. The future represented in the scenarios describe a world with more globally integrated markets, pervasive diffusion of information, and communication technologies, stronger regional growth in Asia, and so on. Together with the driving role of policy, these differences in future context imply the potential for more rapid technological change and faster spatial diffusion.

Portfolio diversification helps manage uncertainties

Innovation outcomes are irreducibly uncertain. This helps explain the cautionary wisdom around public policies trying to pick technological winners ex ante. Policies have to support a wide range of technologies. However seductive they may seem, silver bullets do not exist. Innovation policies should use a portfolio approach under a risk hedging or “insurance policy” decision-making strategy. Portfolios recognize that innovation is inherently risky. Failures vastly outnumber successes. Experimentation, often for prolonged periods, is critical to generate the applied knowledge necessary to support the widespread diffusion of innovations and up-scaling to capture available scale economies. History cautions against overly exuberant efforts to compress formation and learning cycles. The diseconomies of scale ultimately revealed in the history of nuclear power were discussed earlier (see also Grubler, 2010). Another salutary example is the US synfuel program, which targeted a ramp-up in production through the 1980s from almost zero to a targeted 2 million barrels a day (some 25% of all US oil imports). The program was cancelled after five years, having spent almost $5 billion (1980) to reach only 10,000 barrels a day (Anadon and Nemet, 2014).

A number of basic criteria define the design of technology portfolios. The whole energy system should be represented, not only particular groups or types of technology. The entire suite of innovation processes should be included, not particular stages or individual mechanisms. Less capital intensive, smaller-scale, that is, *granular* technologies or projects are a lower drain on scarce resources, and failure has lower consequences. Risk aversion and the resulting risk premia or extents to which decision makers are willing to pay to hedge against unexpected outcomes are important influences on optimal technology portfolio design. Unexpected outcomes or risk include anything from cost overruns and delayed market readiness to outright failure or infeasibility. Deterministic models suggest optimal investment should focus on those technologies forecast to have the least cost in the future and ignore the attractiveness of higher cost alternatives in terms of reduced risk. Portfolio theory can be used to capture the benefits from diversification for different degrees of risk aversion. In general terms, risk aversion means higher short-to-medium term investments in advanced, noncommercial technologies and deeper CO_2 emission reductions (Krey and Riahi, 2009).

Diversity in publicly funded portfolios should also help keep potential options open in the face of economic pressures to standardize and up-scale technological “solutions” that offer initial promise. Incumbents naturally favor current technologies, yet a characteristic of leading innovator countries in historical energy transitions has been a political appetite to overcome vested interests (Moe, 2010). In so doing, technology policy should also seek to avoid all innovation risks of novel concepts being transferred wholly onto the public sector.

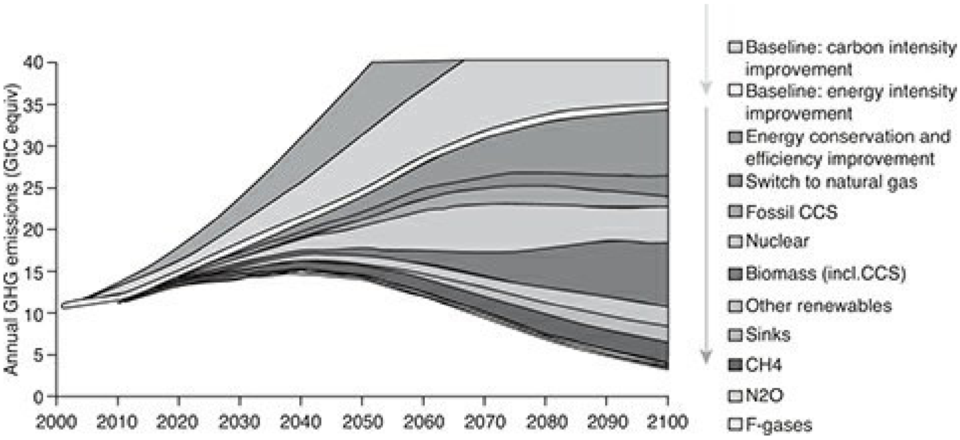
An important, related challenge is to manage the risk of prematurely locking-in to technologies or clusters that may ultimately prove suboptimal (van den Bergh et al., 2007). This creates tension between short- and long-term policy targets if the former rewards deployment of market-ready technologies at the expense of developing technologies with greater transformative potential (Sandén and Azar, 2005). This is illustrated well by "technology-neutral" market pull policies for renewable electricity such as the United Kingdom's Renewable Obligation during the 2000s, which strongly favored the most commercially viable alternative (utility-scale wind farms). These contrast with "technology-banded" policies, which set differential support for technologies depending on their market readiness (e.g. Germany's feed-in tariffs).

Scenario analysis helps identify technological "needs"

Scenarios are an important response to the uncertainty of technological change. Large-scale energy modeling studies described compare the most influential technological and market uncertainties across a set of scenarios (Nakicenovic et al., 1998; Nakicenovic et al., 2000). Scenario analysis can also be used to explore how optimal energy technology portfolios change under different socioeconomic, technological, and climate outcome assumptions. A related question is whether certain portfolios are more robust to these uncertainties than others.

Riahi et al. (2007) explored how portfolios of energy technologies changed as a function of how salient uncertainties were represented. Across twenty-two scenarios, they compared energy demand, resource constraints, the availability and cost of technologies, and also the stringency of greenhouse gas emission constraints. Grubler and Riahi (2010) developed this analysis further by testing the relative contribution of different types of technology across the scenarios, and so the robustness of different technology options. Figure 3.7 illustrates these contributions in GtC per year in the case of a high emissions baseline scenario (A2r) and an emissions constraint resulting in 550 ppmv CO_2-equivalent concentration by 2100. The top two "mitigation wedges" show the annual GtC contributions of carbon intensity (energy supply) and energy intensity improvements (end-use) in the baseline relative to a "frozen" state of technological development in 2000. The remaining wedges show the annual GtC contributions to emission reduction targets of different energy technologies and resource options.

Figure 3.7. Climate change mitigation wedges



The mean GtC contribution of different technology options to emission reductions are summarized in Table 3.2 in rank order. The ranking of these different "mitigation wedges" is quite robust across the scenarios explored, with energy efficiency and conservation the single most important option contributing over 50 percent to cumulative emission reductions over the twenty-first century. This robustness is captured by the dispersion between the minima and maxima for each technology option as proposed by Riahi et al. (2007).

Table 3.2. Comparing technology options: Emission reduction contributions versus

R&D expenditures

	Cumulative Emission Reductions (GtC-Eq., 2000–2100) across All Scenarios Describing Future Uncertainties				*% Cumulative Public R&D in IEA Countries (1974–2008, in 2008$)*
	Minimum	**Mean**	**Maximum**	**Mean %**	
Energy Efficiency	666	1,695	3,008	59	*9*
Renewables	64	520	917	18	*9*
Nuclear	64	243	425	9	*54*
Other	72	229	361	8	*16*
Fossil Fuels	19	177	415	6	*13*
Total	885	2,864	5,126	100	*100*

Source: Grubler and Riahi (2010); R&D data from IEA (2009).

Innovations in end-use technologies are important and underemphasized

While the largest efficiency improvement potentials lie in energy end-use sectors (Grubler and Riahi, 2010), the allocation of public resources is mismatched. On the one hand, public R&D investments are heavily weighted toward supply-side technologies; of an estimated $50 billion global annual investment (in 2005), less than $10 billion were allocated to end-use technologies and energy efficiency. Of the $417 billion spent on R&D in International Energy Agency (IEA) countries cumulatively in the period 1974–2008, less than $40 billion were allocated to energy efficiency (compared to some $56 billion allocated to the commercially unproven technology concept of nuclear fusion). On the other hand, market or diffusion investments are heavily weighted toward end-use technologies (Grubler et al., 2012). IEA estimates of annual investments in supply-side plant and infrastructure are roughly $0.8 trillion (in 2005). A bottom-up estimate of the total annual costs of end-use technologies puts a conservative total somewhere between $1–4 trillion (Wilson and Grubler, 2014). These asymmetries in R&D and market investments in favor of energy supply technologies are found throughout the energy innovation system (Wilson et al., 2012b).

The need for investment to support the widespread diffusion of efficient end-use technologies is also clearly shown in the scenario analysis of climate change mitigation summarized in Table 3.2. This allows a comparison of each technology's contribution to emission reductions with its relative position in public R&D portfolios, at least in the IEA countries for which R&D data are available. The two right-hand columns of Table 3.2 show a clear mismatch between the scenario analysis of robust contributions to future emission reductions and the balance of R&D investments to date. Energy efficiency is greatly underrepresented in R&D portfolios while the reverse is true for nuclear, which has dominated public R&D portfolios. Public innovation expenditure should be rebalanced to include smaller-scale end-use technologies (Wilson et al., 2012b).

Support for such technologies in the past has proven both cost-effective and successful, generating high social returns on investment (Fri, 2003).

Policy can support performance advantages of innovations in niche markets

In historical transitions, cost-insensitive end-users in specific market niches have played a key role in the commercial testing, demonstration, and improvement of energy technology innovations. But in future transitions, there are few evident niches in which end-users may be willing to pay over the odds for environmental public goods. The specific niches that do exist for energy supply technologies are the result of other performance characteristics: no fuel inputs (e.g. solar PV in satellites or remote off-grid applications), quiet operation (e.g. nuclear power in submarines), and storage capacity (e.g. fuel cells for grid back-up). Efficient end-use technologies may offer operational cost savings but may face either design trade-offs against more desirable performance attributes from the end-user's perspective such as size, power and acceleration in vehicles (e.g. Reynolds and Kandlikar, 2007; Nemet, 2014) or carry higher upfront capital requirements as in green buildings (e.g. WBCSD, 2009).

Policies to create and protect market niches are therefore important (Schot and Geels, 2008). Military and space applications are an obvious example of niche creation through direct procurement. By definition or by design, remoteness and reliability can support decentralized energy systems. Switzerland, for example, has mandated 100 percent reliability in the backup systems for its communication networks, creating a price insensitive niche market for off-grid supply. The US$12,000 per kW (in 2003$) of steam engines when first introduced are in the same ballpark as the current costs of fuel cells, which are often classified as prohibitively expensive. Niches shield new technologies from full commercial competition while experience builds, learning improves performance and reduces cost, economies of scale are captured, complementary infrastructure is expanded, and efficiency increases.

These market niche approaches sit in contrast to more conventional "market pull" efforts, which support the widespread diffusion of innovations into densely occupied and cost-competitive market segments. This alternative route for driving down units costs as a function of cumulative experience by subsidizing production ("buying down the learning curve") or underwriting sales with risk or price guarantees, sidelines the evidence from history. Even success stories like that of Brazilian ethanol suggests this route may take many decades rather than years (Meyer et al., 2014).

Innovation policy needs to be stable, credible, aligned, and well-timed

Technological change is described by long-term constants of change and the leverage of near-term decisions over path-dependent futures. Consequently, clear, stable, and consistent expectations about the direction and shape of the innovation system are necessary for innovation actors to commit time, money, and effort with only the uncertain promise of distant returns. To date, policy support for the innovation system has too often been characterized by volatility, changes in emphasis, and a lack of clarity. The debilitating consequences on innovation outcomes of stop-go policies is illustrated well by the wind and solar water heater programs in the United States through the 1980s, as well as the large-scale US efforts to develop alternative liquid fuels (Grubler et al., 2012). In future scenarios, a lack of credibility in international climate policy imposes significant costs on climate stabilization as investment decisions in energy plant and infrastructure become increasingly myopic (Bosetti and Victor, 2011). Managing expectations among the many innovation system actors is important. Ill-timed policies or stop-start policies if short-term objectives are not being met can undermine long-term innovation investments.

Alongside stability and credibility, innovation policy needs to be aligned. Policies to support innovations through early research and development can be undermined by an absence of support for their demonstration to potential investors and their subsequent deployment in potential markets. Thus technology policies need to adopt an integrated approach, stimulating both the development as well as the adoption of energy technologies. R&D initiatives without simultaneously incentivizing users to adopt the outcomes of innovation efforts (e.g. promoting energy efficient building designs without strengthened building codes, or CCS development without a price on carbon) risk not only being ineffective but also preclude the market feedbacks and learning that are critical for continued improvements in the technologies. Incentives can also be perverse. Static innovation incentives can undermine continual improvement. By comparison, dynamic technology standards can spur a continuous innovation "recharge," as illustrated by the Japanese "Top Runner Program" for energy efficient appliances (Kimura 2014).

Aligned policies are also systemic policies. The innovation system comprises not just technologies and infrastructures but also actors, networks, and institutions. The creation of a viable and successful Brazilian ethanol industry through consistent policy support over several decades ranging from agricultural R&D, guaranteed ethanol purchase prices, fuel distribution infrastructures, as well as vehicle manufacturing (initially ethanol only and more recently multi-fuel "flex fuel" vehicles) is a good example of a stable, aligned, and systemic technology framework (Meyer et al., 2014).

Technology policies supporting market deployment can support a build out of numbers of units, or an up-scaling of unit capacity, or both. Policies to support growth in numbers of units might diversify market niches, promote modularity, or advance flexibility and adaptability to different contexts. Policies to support up-scaling might cofund demonstration projects and field trials, streamline the licensing process for retrofits (or support leasing business models for process technologies), or provide testing infrastructure. Timing, however, is important. The importance historically of a formative phase of building out large numbers of units over an often extended period strikes a cautionary note for policies acting too early in a technology's commercial life cycle to support up-scaling.

Conclusions

Table 3.3 illustrates how different policy mechanisms may generate innovation and diffusion outcomes over different timescales. The potential suggested by Table 3.3 for inducing a low-carbon technological future needs tempering by the lessons of historical transitions. The current dominance of fossil fuels relates to their relative cost and performance advantages over low-carbon technologies (Smil, 2003). Initially, performance advantages dominated in historical energy transitions. End-users in specific market niches were willing to pay handsomely for flexibility, convenience, safety, versatility, substitutability, or cleanliness (at the point of use). Other than in some specific contexts, there are no such obvious performance advantages for low-carbon technologies, and in terms of power density and intermittency, renewable energy technologies are unattractive (Smil, 2008). Neither do low-carbon technologies offer cost advantages under current institutional arrangements. Here, fossil fuel resource constraints may work alongside externality pricing to make renewables more cost-competitive, yet resource availability (competing land uses) may also act as constraints for the deployment of renewables at scale.

The fossil fuel present arrived through a centennial process of incrementally innovating and—borrowing from Newton—"standing on the shoulders of giants" (Acemoglu et al., 2009). The magnitude of decarbonization required in the future affords no such gradualism. Moreover, a transition away from the energy infrastructures and institutions that have coevolved with fossil fuels over the last century carries its own costs and inertias (Unruh, 2000). Policy-induced up-scaling and deployment without lengthy formative periods of experimentation and testing implies additional risks (Wilson, 2012).

Political efforts to overcome vested interests will be important together with strong public investment in infrastructure development. Government regulation with civil society support to create and protect niche markets will be critical (Schot and Geels, 2008). But it is otherwise unclear whether a policy-*driven* rather than policy-*enabled* energy transition in the coming decades will be institutionally similar to the historical transitions driven by better, and then cheaper, energy services (Fouquet, 2010).

Table 3.3. Illustrative technology innovation and diffusion policy approaches matched to realistic timescales of outcomes

Timescale of Policy Outcome	Examples of Policy Approaches
Short-term (e.g. to 2020) capital stock additions (some)	• create, stimulate, and protect market niches around performance advantages of new technologies • deploy market-ready clean technologies through credible and stable incentive mechanisms • develop long-term technology innovation and market deployment strategies in a consultative process, creating "joint expectations" • reduce/eliminate direct or indirect subsidies for technologies not aligned to long-term technology strategy and portfolios • use "sunset" clauses for planned retirement of depreciated inefficient or polluting capital vintages
Medium-term (e.g. to 2050) capital stock additions (all), capital stock turnover (some)	• expand public and private R&D investments stably in diversified portfolios designed to manage risks and corresponding with end-use needs • underwrite many, granular and multifarious technology demonstration and learning cycles • support disclosure, interaction, and feedback between innovation system actors • engage in multiple international collaborative projects to further knowledge dissemination and technology spillovers • align innovation and market deployment incentives (e.g. recycling externality pricing revenues back to R&D and market deployment incentives)
Long-term (e.g. to 2100) capital stock additions (all), capital stock turnover (all)	• set long-term targets with appropriate monitoring and enforcement mechanisms to sustain shared technology expectations • maintain portfolio diversity to prevent premature lock-in or standardization • set technology standards for the gradual phase out of "bridging" technologies
Throughout (present–2100)	• create and nurture formal and informal institutional settings for technology assessment, evaluation, portfolio design, and knowledge sharing

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[1] Tyndall Centre for Climate Change Research, University of East Anglia (Norwich, UK).

[2] International Institute for Applied Systems Analysis (Laxenburg, Austria); School of Forestry, Yale University (New Haven, Connecticut, United States).

[2] International Institute for Applied Systems Analysis (Laxenburg, Austria); School of Forestry, Yale University (New Haven, Connecticut, United States).

[3] The joule is a derived unit of energy in the International System of Units. The gigajoule (GJ) is equivalent to 1 billion (10^9) joules and the potential energy generated by 160 liters of oil when burned is estimated at 6 GJ.

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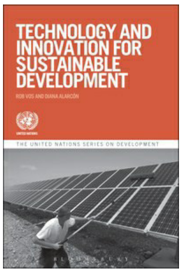

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Chapter 4. Clean Energy for Sustainable Development*

Richard Alexander Roehrl

A major technological transformation in energy is needed for sustainable development

Modern civilizations are largely dependent on fossil fuel energy technologies, which make high-density urban settlements possible. While technological progress has eliminated many problems, it has also added new and often unexpected ones (Grübler, 1998; Diamond, 2005). Emissions of greenhouse gases (GHG) arising from the combustion of fossil fuels are the main cause of anthropogenic global warming. All energy technologies, whether they are fossil-based or not, consume resources, use land, and pollute air, water, and the atmosphere. Energy use has reached a scale at which planetary boundaries are being breached for a range of essential Earth-system processes, including in terms of global warming and biodiversity loss, which is likely to lead to catastrophic environmental change (Rockström et al., 2009). At the same time, there is urgent need to expand access to modern sources of energy to meet the needs of a large proportion of people in some of the poorest countries, who depend on traditional energy sources to the detriment of their health from air pollution.

Climate change

Despite two decades of climate change policies, thousands of programs, initiatives, regulations, market-based instruments, and international agreements and the disbursement of hundreds of billions of dollars in subsidies, funds, research and development (R&D) efforts, and development aid, the declared goal of establishing a renewable low-carbon energy system on a global scale remains elusive. In 2012 fossil fuels accounted for 81.7 percent of the global primary energy mix, while low-carbon nuclear power accounted for 4.8 percent, hydroelectricity for 2.4 percent, and biomass for 10 percent. Modern renewables jointly accounted for only 1.1 percent. (International Energy Agency, 2014).

Mainly as a result of the current energy matrix, global CO_2 emissions have increased at an annual rate of more than 3 percent, considerably faster than in previous decades (van Vuuren, Detlef, and Riahi, 2008). The past decade was the first in two centuries with increasing CO_2 emissions intensities, owing to a "coal revival," in contrast with the rapid conversion to natural gas in the 1990s. In 2012, the global share of coal reached an estimated 29 percent, which, in relative terms, was higher than and, in absolute terms, about twice as large as the time of the first oil crisis in 1973. In the 2000s, China alone added more coal power capacity *each year* than the total installed capacity in the United Kingdom of Great Britain and Northern Ireland (International Energy Agency, 2010, p. 202). Most recently, global CO_2, emissions have grown at a slower pace, namely 1.4 percent in 2011 and 1.1 percent in 2012 and thus decisively below the 2.9 percent average since 2000. The recent short-term trend was driven mainly by absolute decreases of emissions in the EU and the United States as well as a below-trend increase in China, which was primarily due to the lingering economic effects of the global financial crisis. However, the last years have also seen a number of important shifts, such as the rise in shale gas production, especially in the United States, the decrease in nuclear energy after Fukushima, as well as a slight increase in modern renewable energy (PBL Netherlands Environmental Assessment Agency, 2013).

GHG emissions keep on increasing. This trend is diametrically opposed to declared goals and targets, according to which *global* emissions would need to be *reduced* by 50–80 percent by 2050 and turn *negative* (through carbon capture) in the second half of this century, in order to stabilize CO_2 concentrations at about 450 parts per million by volume (ppmv), a target recommended by the Intergovernmental Panel on Climate Change (IPCC) and agreed upon at the sixteenth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change,[1][1] held in Cancun, Mexico, in 2010. Essentially, this would require making the power and transport sector carbon-free *worldwide* by mid-century, in view of the limitations associated with replacing industrial processes based on fossil fuels. Today's CO_2 emitting devices and infrastructures alone imply cumulative emissions of about 496 gigatons (Gt) of CO_2 from 2010 and 2060, leading to atmospheric concentrations of about 430 ppmv (Davis, Caldeira, and Matthews, 2010). In other words, only an immediate *global stop* to building new fossil-fired capacities would lead close to the envisaged global target of 450 ppmv by mid-century. This puts into perspective the enormous ambition of the global target, given the long-lived capital stock and rapidly rising demand for energy.

Energy poverty

At the same time, about one-fifth of humanity, or nearly 1.3 billion people, continues to live without access to electricity, mainly in South Asia and Sub-Saharan Africa. Many more, especially in urban areas, have access but cannot afford to make full use of it. In addition, about 49 percent of humanity, or 2.6 billion people, continue to rely on traditional biomass, such as wood, dung, and charcoal. (International Energy Agency, 2013). The benefits of electrification are clear. For poor households in developing countries, having household lighting has been estimated to add between $5 and $16 per month in income gains. The added benefits of access to electricity in general would be in the order of $20–30 per household per month through enhanced entertainment, time savings, education, and home productivity (World Bank, Independent Evaluation Group, 2008). These benefits outweigh by far the $2–$5 per month that poor households typically pay for the cost of electricity. Whereas energy efficiencies of kerosene, candles, and batteries are very low (i.e. $3 per kilowatt-hour [kWh] for kerosene), lighting with solar electricity costs around $2.2 per kW, $0.5–$1.5 per kWh with diesel generators and micro-utilities and less than $0.3 per kWh for centralized traditional utilities. However, for traditional utilities, providing services to poor households becomes economically interesting only at demand levels higher than 25 kWh per month, whereas poor households already derive great benefits per unit of cost in the range of 1–4 kWh per month.

For the poorest people in developing countries, cooking (and space heating in particularly cold climates) can account for 90 percent or more of the total volume of energy consumed (World Energy Council and Food and Agriculture Organization of the United Nations, 1999).

Relatively simple and inexpensive improved stoves can reduce by as much as 30 percent the amount of fuel needed for cooking (Global Energy Assessment, 2012). Access to modern energy could also deliver significant gains in health: air pollution from inefficient stoves leads to an estimated 1.5 million premature deaths per year, more than from malaria, tuberculosis, or HIV.

Before this background, the Sustainable Energy for All Initiative has made universal access to modern energy services one of its key objectives to be achieved in 2030. It is important to note that bringing universal access to modern energy services to almost 3 billion people would require only about 3 percent higher electricity generation, less than 1 percent more demand for oil, and less than 1 percent more CO_2 by 2030 (International Energy Agency, United Nations Development Programme and United Nations Industrial Development Organization, 2010). Thus, the development aspirations of the world's poor are not in conflict with efforts to solve the climate problem. The 500 million richest people, who constitute only 7 percent of the world population, are responsible for half of all greenhouse emissions. They live in every country of the world and earn more than the average citizen of the United States of America. In contrast, the poorest 3.1 billion people are responsible for only 5–10 percent of total emissions (Pacala, 2007; Chakravarty et al., 2009). The global energy challenge is immense, as evidenced by the multiple global objectives explored by the Global Energy Assessment (GEA) (Riahi et al., 2012): (a) to ensure universal access to electricity and modern cooking fuels by 2030; (b) to reduce premature deaths due to air pollution by 50 percent by 2030; (c) to limit global average temperature change to 2° C above preindustrial levels by 2100 (with a probability of greater than 50 percent); and (d) to establish energy security, for example, to limit energy trading and increase diversity and resilience of energy supply by 2050. Meeting GEA objectives requires a complete transformation of the global energy technology system in the course of one generation, which is a considerably shorter time frame than was the case for historical energy transitions (see Chapter 3 in this book). Governments have called for concerted actions to accelerate the introduction of technology change toward cleaner energy and to rationalize the use of energy; Chapter 5 in this book reviews the cost and policy options available. The next section assesses current efforts and their limitations to meet agreed targets on GHG emissions. The last section distills a set of recommendations.

Are current efforts in the right direction? Are they enough?

International efforts to fight climate change

A complex system of organizations and institutions has emerged at the international level to promote energy technology cooperation and provide both financial resources for clean energy investments and price signals to favor low-carbon energy technologies.

The International Energy Agency (IEA) maintains forty multilateral technology initiatives, also known as implementing agreements, covering the full range of energy technologies, including programs with voluntary participation designed to accelerate the deployment of clean energy technologies and cost-effective technologies for carbon capture and storage (CCS). Thus far, however, these international efforts have had a relatively small effect on the global energy transition.

The Clean Development Mechanism (CDM) under the Kyoto Protocol to the United Nations Framework Convention on Climate Change[2] was expected to greatly stimulate clean energy technology transfer to developing countries and significantly reduce costs for developed countries. The market value of CDM transactions had reached US$ 6.5 billion in 2008, but dropped thereafter by about 60 percent as a result of the financial crisis and uncertainty about the future climate policy regime. In 2012, almost 3,300 projects were registered, which if fully implemented would produce reductions of 2.8 Gt of emissions, almost three-quarters of which are for projects in the energy industry. CDM investments have been concentrated, however, in a handful of large emerging economies, such as China, Brazil, and India (United Nations Framework Convention on Climate Change, 2013).

From 1991 to 2009, the Global Environment Facility (GEF), which serves as a financial mechanism for the United Nations Framework Convention on Climate Change, allocated more than $2.7 billion to climate mitigation activities while leveraging an additional $17 billion in financing. In 2008, the World Bank also established the Climate Investment Funds, which represent a collaborative effort among the multilateral development banks to address climate finance gaps. By 2010, contributors had pledged $6.4 billion in new funds. One component, the Clean Technology Fund finances the scaling up of demonstration, deployment and transfer of clean technologies and focuses on countries with significant mitigation potential. The first round of investment plans encompasses thirteen countries, energy efficiency projects, bus rapid transit, concentrating solar power, and wind power.

The transfer of environmentally sound technologies is recognized under the United Nations Framework Convention on Climate Change, but action on the ground has progressed relatively slowly. The Conference of the Parties at its sixteenth session (COP16), agreed to establish a Climate Technology Centre and Network, which aim to support technology transfer and local technology innovation capacity. The Climate Technology Center and Network had its first board meeting in October 2014. In 2012, the Rio+20 outcome document requested the UN Secretary General to identify options for a technology transfer facilitation mechanism, which have been discussed in the UN General Assembly from 2013 to 2014.

National plans for clean energy technology

An increasing number of governments—notably, those of China, Japan, and the Republic of Korea—and the European Union (EU) have adopted or followed some kind of national energy technology innovation strategy. Such strategies provide a framework for coherent packages of policies and programs that encompass all stages of the technology life cycle. Japan has long focused on the promotion of performance targets and is now the world leader in energy efficiency. Recent efforts in developed economies to support clean energy technology have typically focused on economic instruments for creating niche markets and promoting the commercial diffusion of new technologies.

Efforts of emerging and other developing economies to support clean energy technology have typically focused on the creation of domestic research, development, manufacturing, and export capacities. China's Twelfth Five-Year Plan, endorsed in March 2011, encompasses a green growth strategy geared toward building technology leadership, through special efforts to develop and deploy wind, solar, hydro, nuclear, energy efficiency, electric cars, "smart grids," infrastructure, and high-speed rail.[3] South Africa aims to slow down the growth of GHG emissions and effectively reduce them after 2030, through increased energy efficiency, feed-in tariffs for renewables, development of carbon capture and storage for coal-fired power plants and coal-to-liquid plants, a levy on coal-fired power and the introduction of a carbon tax. The Republic of Korea is implementing a green growth strategy and five-year action plan that aim for a 46 percent reduction in energy intensity by 2030 and for an 11 percent share of renewable energy. The national energy plan for 2008–30 foresees investments in low-carbon transport, hybrid vehicles, renewable energy technologies and the construction of ten nuclear power plants. Mexico has set an indicative target of reduction of its GHG emissions by 50 percent from 2000 to 2050, and its Special Climate Change Program makes provisions for wind power, cogeneration, efficient household appliances and lighting, promoting rail freight, and 600,000 efficient cooking stoves.

Energy plans of the poorest and most vulnerable economies have aimed to find a balance between governments' immediate priorities and the priorities of aid donors in order to leverage development assistance. For example, energy plans and policies for a number of small island development states aim to address their special vulnerabilities and promote renewable energy. Maldives announced its goal of achieving a carbon-neutral energy sector by 2020; Tuvalu aims to achieve 100 percent renewable energy utilization by 2020; there have been positive experiences with thermal solar water heating in Barbados, Mauritius, and Palau; hybrid solar-diesel power generation is being piloted in Maldives and Tuvalu; and geothermal energy is in the early phases of exploration in Saint Kitts and Nevis and Saint Lucia. Despite such commitments, however, fossil-fuel use has continued to increase faster than renewable-energy use in most small island development States (United Nations, 2010).

Initiatives to extend access to modern energy

From 1970 to 1990, more than 1 billion people had been provided with electricity access, half of whom were in China alone and almost 2 billion additional people secured electricity access in 1990–2008 (Global Energy Assessment, 2012). Historically, the evolution of the energy system has taken several decades (see Chapter 3 for the history of energy system transformations), and the time needed to achieve universal access to electricity has ranged from about twenty years in Thailand and forty years in China to ninety years in Mexico. The

United Kingdom and the United States needed about fifty years to achieve universal access around 1950. Among the emerging economies, Mexico, China, Brazil, Thailand, and Mauritius achieved universal access in the 1990s. India and South Africa, however, still have some way to go, as do all the least developed countries. Countries with low population densities or those consisting of dispersed islands face special challenges. Electrification in remote islands remains limited owing to high capital costs, despite special efforts made by Small Island Developing States. For example, Fiji completed about 900 rural electrification community projects between 2005 and 2009 in order to be able to provide universal electricity access by 2016 (United Nations General Assembly, 2010).

The Global Energy Assessment (2012) reviewed fifty-one programs, conducted since 1980 in eight Asian, twelve African, and nine Latin American countries, whose aim has been to distribute clean cooking stoves to poor households. The review highlighted the wide range of cooking-stove models tailored to local needs, fuel supply, available technical skills, and affordability. Energy efficiencies ranged from 15 percent for simple mud stoves running on straw and twigs (several thousands of which were constructed by trained artisans in Vietnam at a cost of $1.80) to as high as 40 percent in the case of a program in China involving 300,000 clay stoves running on coal briquettes and constructed in local workshops. Programs in Latin America tended to be smaller in size, but were mostly subsidized to varying degrees. Noteworthy are the large-scale programs designed to distribute since the 1990s more than 5 million Chulha stoves, running on a range of fuelwood, straw, dung, and agricultural waste, with efficiencies between 20 and 28 percent, and delivered at costs of only $1.80–$4.60, depending on the subsidy levels (which ranged from 0 to 78% of the cost). Manufactured metal stoves in India, Zimbabwe, Rwanda, Mali, the Niger, Burkina Faso, and Guatemala, were about ten times more expensive than Chulha stoves, but typically achieved higher efficiencies—close to 30 percent.

Investments over the innovation life cycle

Table 4.1 provides global estimates of public and private investments in energy innovation, market formation, and diffusion (Wilson and Grübler, 2010; Grübler et al., 2012). In 2010, investments in commercial diffusion amounted to between $1 trillion and $5 trillion, substantially more than the $150–$180 billion invested in market formation and the $50 billion for research, development, and deployment (RD&D). RD&D and government-driven market formation investments focused on power and fuel supply, whereas the majority of private sector diffusion investments were for end-use and efficiency.

Table 4.1. Global estimates of public and private investments in energy innovation, market formation, and diffusion, 2010 (billions of 2005 USdollars)

	Innovation (RD&D)	**Market formation**	**Diffusion**
End-use and efficiency	>>8	5	300–3,500
Fossil fuel supply	>12	>>2	200–550
Nuclear	>10	0	3–8
Renewables	>12	˜20–60	>20
Electricity generation, transmission, and distribution	>>1	˜100	450–520
Other and unspecified	>>4	<15	n.a.
Total	**>50**	**<150–180**	**1,000–5,000**

Source: Gallagher et al. (2011).

Investment in RD&D

Only one-fifth of the $50 billion in public and private RD&D investments was for end-use technologies and energy efficiency in 2010. The RD&D intensity of the energy supply industry was comparable with that of the textile industry, but much lower than that of manufacturing. Public investment in energy-related RD&D continues to be low in developed countries, amounting to 5 percent of total public RD&D. It had increased rapidly in response to the oil crises of the 1970s, but collapsed in the mid-1980s in line with falling oil prices and privatization, only to recover from 2000 in response to concerns about global warming.

Over the last twenty years, emerging economies have become leaders in terms of public RD&D expenditures. They are also emerging as leaders in terms of renewable energy patents. Energy RD&D in Brazil, the Russian Federation, India, Mexico, China, and South Africa was about $19 billion (in PPP terms), which is more than the total public energy RD&D budget of all IEA countries combined (estimated at $12.7 billion in PPP terms). This challenges the conventional wisdom that new energy technologies are developed in Organisation for Economic Co-operation and Development (OECD) countries and transferred to developing countries. Energy RD&D investments in emerging economies were focused on fossil fuel and nuclear energy, with renewables and energy efficiency underrepresented (Table 4.2).

Table 4.2. Public and private spending on energy-related RD&D in selected emerging economies and the United States of America, 2004–8 (millions of 2008 US dollars at PPP)

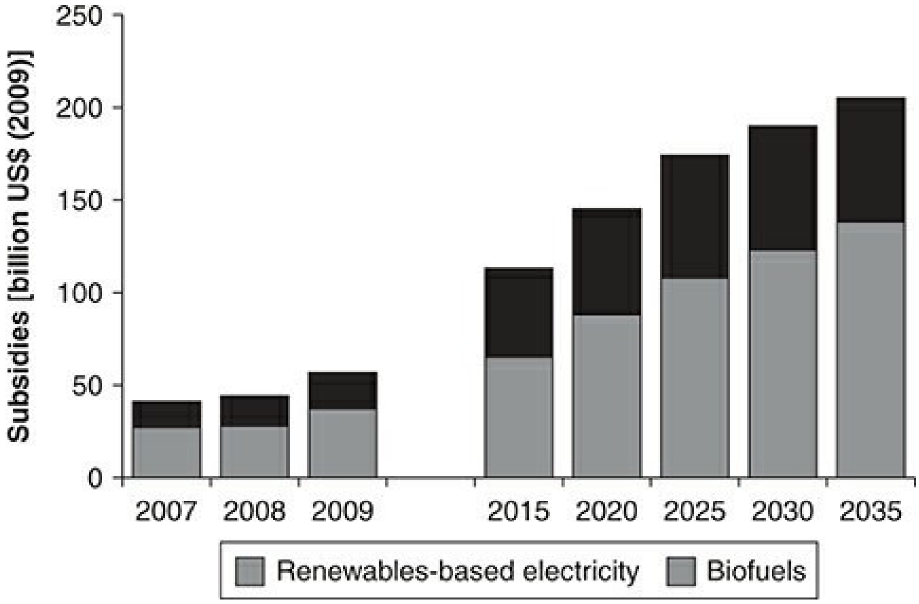
	Fossil (including CCS)	**Nuclear (including fusion)**	**Electricity, transmission, distribution and storage**	**Renewable energy sources**	**Energy efficiency**	**Energy technologie (unspecifie**
China	7,044	19	n.a.	n.a.	161	5,885
Brazil	1,246	8	122	46	46	196
Russian Federation	430	n.a.	22	14	25	553
India	800	965	35	57	n.a.	n.a.
Mexico	140	32	79	n.a.	263	19
South Africa	164	164	26	7	n.a.	9
Subtotal	*9,824*	*>1,187*	*>285*	*>124*	*>497*	*>6,662*
USA	1,821	804	319	699	525	2,510

Source: Gallagher et al. (2011).

Investment in market-formation

Market-formation investments (including public and private) in the early stages of technological diffusion are sometimes referred to as "niche market" investments. These include public procurement and government subsidies for certain technologies, as well as private investments involving renewable performance standards, carbon taxes, and feed-in tariffs. About $100 billion out of the total of $150–$180 billion in global investments for market formation was for electricity generation, transmission, and distribution, $20–$60 billion for renewables, and about $5 billion for end-use and efficiency. The niche market investments for renewables are expected to increase rapidly in the coming years, in view of current government plans in developed and developing countries alike. The International Energy Agency (2010) has estimated that government support for renewables will rise from $57 billion in 2009 to $205 billion in 2035 (Figure 4.1). By comparison, fossil-fuel consumption subsidies amounted to $312 billion in 2009 (IEA, 2010). These numbers do nonetheless indicate that governments favor renewables, since, excluding grid investments, government subsidies for modern renewables amounted to $9.7/GJ compared with $0.8/GJ for fossil fuels.

Figure 4.1. Annual global support for renewables in the IEA New Policies Scenario, 2007–35



Note: The IEA New Policies Scenario assumes cautious implementation of recently announced commitments and plans, even if not yet officially adopted.

Source: International Energy Agency (2010).

Investments in diffusion

Global supply-side energy investment was about $740 billion in 2010, with $70 billion for renewables. These investments were dominated by electricity generation, transmission, and distribution (51%) as well as upstream investments in fossil fuel supply (46%), including the oil exploration and production component and the gas exploration and production component, which accounted for 19 and 13 percent, respectively. The most important renewables investments were in large-scale hydropower (annual capacity additions of 25–30 gigawatts [GW]) and biofuels ($20 billion, of which $8 billion was for Brazil's ethanol). Global investment in energy end-use technologies was more than double the supply-side investments, and reached an estimated $1.7 trillion in 2005 of which almost $1.2 trillion was for road vehicles (Grübler and others, 2012).

Public-private partnerships in energy investments have become increasingly popular, accounting for almost $40 billion in the first semester of 2009 despite the global financial crisis. Other private sector investments in energy technology include investment by angel investors, companies' internal investments, debt instruments, project finance, mergers and acquisitions, and investments in publicly listed energy technology firms. Energy-related venture capital investments boomed in EU and North America in recent years, reaching $15.5 billion, or 10 percent of all private investments in energy technology diffusion in 2008 (IEA, 2009). Most of these investments were for solar, biofuels, biomass, battery technologies, smart metering, software, and high-efficiency engines.

Country experiences with the introduction of clean energy technology

Ethanol in Brazil, the United States, and Mauritius

Brazil was the first country to launch a program to promote the use of ethanol in 1975, with producer subsidies and user incentives aimed at a rapid shift toward dedicated engines running on ethanol. In response to low gasoline prices in the mid-1980s, a national research program was started that achieved a reduction in production costs from $35/GJ (in 2004 US$) to less than $10/GJ in 2009. In Brazil, ethanol derived from sugar cane has a high energy return of 8.3 times the energy input and high yields of about 5,500 liters per hectare. In addition, the introduction of flexible fuel engines allowed users to choose the desired mix of ethanol and gasoline. The cumulative subsidy aimed at making up for the difference between the higher ethanol production cost and world oil prices between 1975 and 2004 amounted to an estimated $50 billion. Rising oil prices in recent years meant that ethanol production costs became cheaper than world oil prices after 2004. Flexible fuel engines have been highly successful, already reaching 81 percent of the light-vehicle registrations by 2008 (Brazil, Associação Nacional dos Fabricantes de Veiculos Automotores, 2008).

In the United States, commercial production of fuel ethanol from corn had started in 1980, reaching 35 billion liters in 2008. In 2007, the US Congress passed a bill that mandated the production of 140 billion liters of corn ethanol by 2022, which would be equal to about 13 percent of US gasoline demand. If this goal were to be achieved domestically, it would require using the entire US corn harvest.

Many developing countries in tropical zones have tried to learn from Brazil's experience with ethanol and experimented with various local crops. An interesting case is that of Mauritius, which created a local sugar cane and biofuel research institute. Lower sugar cane yields and a smaller scale of operation led to ethanol prices that were about twice as high as those of Brazil. Moreover, even if all tropical countries attained sugar cane yields as high as Brazil's and all of the world's sugar cane production (19 million hectares in 2005) were shifted to ethanol production, the resulting yield would meet only about 6 percent of the world's gasoline demand.

Coal-based synthetic fuels in the United States

In response to the second oil crisis, the United States embarked on a large-scale program to produce synthetic fuels from coal. In 1980, it had established the Synthetic Fuels Corporation, which was to improve technologies and produce 2 million barrels of liquid fuel per day by 1992 at a cost of $60 per barrel in order to replace about 25 percent of US oil imports. Against the backdrop of the collapse of oil prices, the program was cancelled after five years, with production having reached only 10,000 barrels per day and incurred costs amounting to $5 billion (at 1980 prices) (Gaskins and Stram, 1991).

Hydrogen production in the United States

In contrast with the large diffusion investments in ethanol and synthetic fuels, support for hydrogen production has been small-scale and limited to R&D. However, hydrogen has found a performance niche in certain industrial processes. Annual production in the United States from 1971 to 2003 increased more than tenfold, and production costs were reduced by a factor of five, without any subsidies and despite the material challenges associated with handling hydrogen (Ausubel, 2007).

Nuclear power in the United States

Experience with nuclear power offers a prime example of an ambitious "big push" experiment, which governments have carried out in order to accelerate development, deployment, and diffusion of a new energy technology. More than half of all cumulative energy-related public RD&D support in IEA countries since 1974 has been for nuclear power technologies. In the beginning of the 1970s, the International Atomic Energy Agency (IAEA) had expected global installed nuclear power to reach at least 2.5 terawatts (TW) by 2000, as compared with what was in fact the actual total of 351 GW. The first nuclear power plant started operating in the UK in 1956. In the United States, as many as 65 plants were ordered between 1965 and 1969, and by the end of 1970, the country had 107 units online, under construction, or purchased. No new plant has been ordered in the United States since 1978 due to low oil prices (for much of the 1980s and 1990s) and increasing costs associated with safety regulation. By 1978, an average of 1.3 new regulations was being added *every day* in the United States.

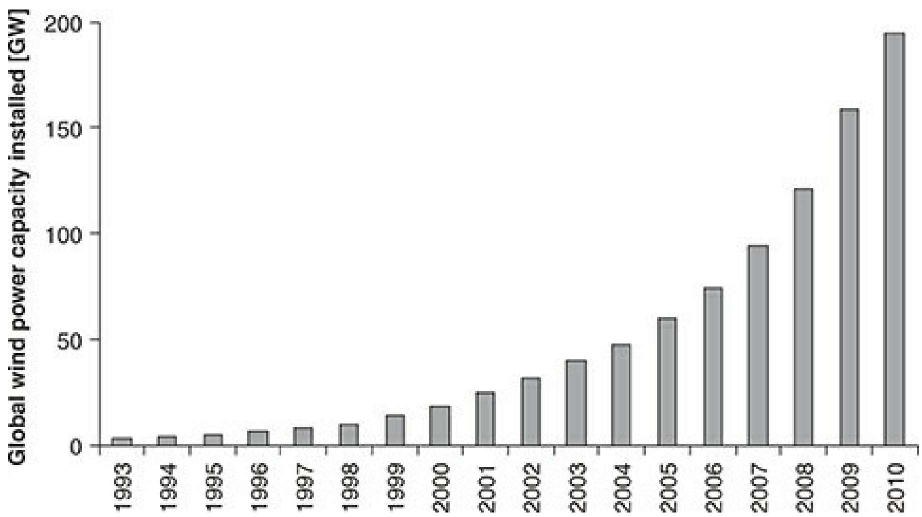
Wind power in Germany, Denmark, United States, the Netherlands, China, and India

Denmark, the United States, Germany, the UK, Sweden, and the Netherlands were early movers in wind energy innovation from the 1970s on, but followed different approaches. In the 1970s and 1980s, Germany and Sweden had focused on public R&D support but provided only limited support for market formation. Denmark, the Netherlands, and the United States focused on R&D and deployment of smaller-scale and simpler wind turbines in niche markets. Denmark established a test station for wind turbines in 1978, issued type approvals from 1979, and introduced investment and production subsidies in 1979 (Grübler et al., 2012). The result was sustained growth of the industry, the entry of new actors (farmers and municipalities), and very high reliability (98% in 1985) (Heymann, 1998). While the Netherlands had also established a test field in 1981, it focused on competition rather than cooperation among manufacturers, which led to a much slower rate of progress and to lower reliability. In the United States, a number of subsidy schemes were introduced that led to a boom in wind power so that, by 1986, California had installed 1.2 GW of wind power, which, at the time, constituted 90 percent of the world total. However, "subsidy harvesting" by the private sector spurred hasty development and inadequate operational testing. By 1985, only 38 percent of wind-power plants in the United States were operating properly, and the industry collapsed in 1986 when government subsidies were reduced.

From the 1990s, many increasingly large wind power projects were undertaken in Denmark, Germany, and Spain. The cost per kWh of wind power was halved between 1980 and 2000, and reliability, efficiency, level of turbine noise, and grid stability greatly improved. Germany introduced feed-in tariffs, and average wind farm and turbine prices declined by 30 percent from 1991 to 1996 with export prices at about half the average domestic price (Junginger, Faaij, and Turkenburg, 2005). Germany's feed-in tariffs effectively cross-subsidized technology transfer and the development of wind power industries in other countries, including China and India. From 1996 onward, prices began to increase in Germany, owing to rapidly expanding demand both domestically and for exports to emerging economies.

China and India have used industrial policy, including legal provisions, duties, taxes, and subsidies, to support domestic wind power research and the wind power industry since the 1990s. Further, China mandated domestically produced components and, along with India, instituted domestic technology certification programs. As in the case of Europe, wind power plants were not necessarily built in the most suitably windy locations: the local policy environment was a much more important factor. For example, in India in 2004, 57 percent of wind power capacity was installed in Tamil Nadu, which only has 7 percent of the wind resources. By the end of 2010, 194 GW of wind power capacity had been installed worldwide (Figure 4.2), of which 84 GW were in EU, 40 GW in the United States, 42 GW in China and 13 GW in India. In 2010, 35.7 GW of new capacity were installed, which was 6 percent less capacity than in 2009. More than half of this new capacity was installed in China (16.5 GW) and India (2.1 GW), compared with 9.8 GW in EU and 5.1 GW in the United States (Eurobserver, 2011). By the end of 2012, 319 GW of wind power had been installed worldwide.

Figure 4.2. Global installed wind power capacity, 1993–2010 (Gigawatts)



Source: Eurobserver (2011).

Photovoltaics in Germany, the United States, Japan, China, and Kenya

Solar photovoltaics (PV) was invented in the United States but was not deployed there on a large scale. For several decades, through its R&D, and its "Sunshine Programme" from 1994 to 2004, Japan refined the technology and successfully reduced the costs of a 3kW roof system from 6 million to 2 million yen. The Sunshine Programme was remarkable in that it phased out its solar PV subsidies (which peaked at about $250 million in 2001) over the duration of the program.

Despite its low insolation levels, today Germany is by far the largest solar PV market in the world, owing to its generous feed-in tariffs. China produces and exports the majority of solar panels, most of which are sold in Germany, which remains the producer of machines needed in the manufacturing plants. Most recently, off-grid solar PV has become increasingly popular in poor areas without access to electricity, in view of the prevailing high electricity prices and low demand levels.

Solar water heaters in the United States and China

Research in US national laboratories and universities had improved solar water heater technology in the 1970s. A key breakthrough was the production of selective coatings that would absorb more sunlight. Driven by US federal and state subsidies and expectations of high future energy prices, the solar water heater industry boomed from the late 1970s, and a $1 billion industry was created. In the 1980s, there was rampant abuse of generous subsidies (subsidy harvesting), which resulted in poorly installed systems. Within a couple of years, about half the systems were no longer functioning (Taylor, 2008). In 1984, tax credits for new installations expired, and the solar water heater industry in the United States collapsed, with the technology being by and large abandoned for two decades. The technology is currently cost-effective, especially in large installations with high demand for hot water. While the quality of the technology has improved since 1976, unit costs have not been reduced significantly and, instead, have been determined mainly by the price of steel and glass (Taylor et al., 2007). In contrast, solar water heaters have been rapidly adopted in China, which now accounts for most of the 100 GW installed capacity today.

Concentrated solar power in the United States, Germany, Spain, and North Africa

The United States, Germany, and Spain have led long-standing research programs in solar thermal electricity, which included experimentation with a variety of designs.[4] The first modern concentrating solar power (CSP) plant with 1 megawatt (MW) capacity had been built in Italy in 1968. The parabolic trough design of a 354 MW plant built in California in 1984 became dominant. Overall deployment remains much lower than that of wind power, owing to higher cost and water conflicts of use in desert areas. In the United States, costs of producing CSP are about 12–18 cents per kWh compared with 2 cents for nuclear power, although costs as low as 5 cents might be achievable in the future with heliostat mirrors and gas turbine technology.

An industrial consortium, consisting mainly of German companies, has recently been formed with the goal of constructing a country-size CSP facility in North Africa and linking it to the EU power grid with high-voltage alternating current (HVAC) lines. The initiative is commonly known as DESERTEC. The consortium has plans for a €400 billion CSP facility together with solar PV and wind power over an area of 17,000 square kilometers (km^2) in the Sahara, which might deliver as much as 15 percent of Europe’s power by 2050. Besides the costs, the main obstacle to the realization of the DESERTEC goal continues to be geopolitical in nature.

Micro-hydroelectricity in China

China has the largest hydroelectricity potential in the world. During the “Great Leap Forward” (which started in 1958), there had been plans to build 2.5 GW of micro-sized hydroelectricity plants by 1967, but only about 0.5 GW were completed (Carin, 1969). In a new wave of construction from 1970 to 1979, their number increased from 26,000 to 90,000, with mean size doubling to only 70 kW. Much larger hydroplants in the MW and GW ranges have been built since the 1980s. Many technical and maintenance problems (silting, drought, leaks) with hastily built micro-plants meant low load factors and relatively high costs (Smil, 2010a). In 2006, China completed the world’s largest hydropower plant, with a capacity of 18.2 GW.

Biogas in China

From the early 1970s, China had promoted micro-scale biodigesters running on animal dung, human feces, garbage, and waste water. A 10 cubic meter (m^3) biodigester was deemed sufficient to provide biogas for a family’s cooking and lighting needs. Some 30,000 were completed by 1973 and 400,000 by 1975. China’s official target for 1985 was 20 million units, but in reality their numbers fell to less than 4 million by 1984, as millions of the units were abandoned owing to lack of the necessary skills for maintenance (Smil, 2010a).

Country experiences in improving energy efficiency

Top Runner Program on end-use efficiency in Japan

Japan has maintained mandatory energy efficiency standards for appliances and automobiles since 1980, which were not very successful, however, as they were largely based on negotiations with industry. In 1998, Japan initiated the Top Runner Program to improve energy efficiency of end-use products, as a cornerstone of its climate change policy. The idea is that the most energy-efficient product on the market during the standard-setting process establishes the “Top Runner standard,” which all corresponding product manufacturers will aim to achieve in the next stage.[5] Energy efficiency standards are discussed and determined by the Ministry of Economy, Trade, and Industry and its advisory committees comprising representatives from academia, industry, consumer groups, local governments, and mass media. The scope of the program is being reviewed every two to three years. It started with nine products and has been expanded to twenty-one products by 2009 (Grübler et al., 2012) The targeted products account for more than 70 percent of residential electricity use. To date, all targets set by the program have been achieved or overachieved. For example, the energy efficiency of room air conditioners improved by 68 percent, refrigerators by 55 percent, TV receivers by 26 percent, computers by 99 percent, fluorescent lights by 78 percent, vending machines by 37 percent, and gasoline passenger cars by 23 percent (Japan, Energy Conservation Center, 2008), representing a level of enormous technical improvements, already above one of the highest levels of energy efficiency in the world. Yet, it is not clear whether the program can be replicated successfully outside Japan. Specific success factors that were noted include a limited number of domestic producers with high technological capacity, which were willing to comply with the standards even without sanctions.

Car fuel efficiency standards in the United States

The typical efficiency of US cars in the early 1970s had been the same as in the 1930s—13 miles per gallon (mpg), which meant 85 percent of the gasoline was wasted (Smil, 2010a). The Corporate Average Fuel Economy (CAFE) standards, which were introduced in 1975, doubled the average efficiency of United States passenger cars to 27.7 mpg by 1985, but no further improvements were made until CAFE standards were revised in 2007. In fact, the popularity of sport utility vehicles (SUV), vans, and pickup trucks depressed United States vehicle fleet efficiency, which reached only 22 mpg by 2006. The 2007 revision of CAFE no longer exempts light trucks classified as SUVs or passenger vans (unless they exceed a 4.5 t gross vehicle weight rating), and the aim is to increase fleet efficiency to 35 mpg by 2020. For comparison, the Model T Ford, from 1913, which was the world’s first mass-produced automobile, averaged 25 mpg. All new cars in New Zealand currently rate between 34 and 62 mpg. The EU corporate vehicle standard of 130 g CO_2/km, to be achieved by 2012, is equivalent to 47 mpg (or 5l liters (l)/100 km) for a gasoline-fueled car.

The experience from market-based measures

Oil price spikes, high gasoline taxes, subsidies, and permit trading schemes are “natural” experiments, which provide insight into the impact of market measures, such as energy or carbon taxes.

Carbon price signals and emissions trading

The social cost of carbon (SCC) captures the scale of the externality of a unit of carbon emitted over its lifetime in the atmosphere. Under an optimal climate policy, the emission reduction target should be set so that the cost of reducing emissions (marginal abatement cost) is equal to the SCC. SCC estimates vary ranging from $41 to $124 per ton of CO_2 substantially lower prices. Recently, the market price of allowances in the EU Emissions Trading Scheme (ETS) has fluctuated around $20 per ton of CO_2. With respect to individual behavior, calculations done by MacKay (2008) suggest that only with very high carbon prices would there be a noticeable impact on activities like driving and flying. For instance, he concluded that at $150 per ton, domestic users of gas would notice the cost of carbon in their heating bills; a price of $250 per ton would increase the effective cost of a barrel of oil by $100; at $370, carbon pollution would cost enough to significantly reduce people’s inclination to fly; and at $900, driving habits might be significantly changed. The prevailing allowance prices appear too low to foster “market pull” of low-carbon technologies, and the volatility of emissions trading schemes holds back investment in low-carbon infrastructure.

Gasoline taxes update

In November 2012, gasoline retail prices in different countries ranged from about 2.3 cents to 254 cents per liter, with the wide range due to massive government intervention in the form of gasoline subsidies and taxes. Nineteen countries (mainly oil producers) had “very high subsidies,” with retail prices ranging from 1 to 69 cents per liter, which was below the world crude oil price of $110 per barrel at the time. Ten countries granted subsidies with retail prices ranging from $0.69 to $0.96 per liter. The majority of developing countries and notably the United States had retail prices ranging from $0.96 to $1.64 per liter. A fourth group of countries, mostly affluent countries implemented "very high taxation" leading to gasoline prices higher than $1.64 per liter (Deutsche Gesellschaft für Internationale Zusammenarbeit, 2013). High gasoline prices have not halted the growth of vehicle miles in affluent countries, but they have created a preference for smaller and more fuel-efficient vehicles. Nonetheless, absent regulations, income has been the main driver of transport energy demand, regardless of the level of gasoline retail prices.

These cases illustrate the limitations of a policy approach based on price incentives; only command-and-control measures (such as those of the Top Runner Programme in Japan) have had significant impacts on fuel efficiency and emissions of road vehicles.

Feed-in tariffs

Feed-in tariffs (FITs) guarantee suppliers of renewable electricity a price that covers their costs with a profit, even though the price is higher than that paid for the fossil fuel-based alternative. The FIT consists in either fixed prices based on generation cost, independent of the market (as in Germany), or a fixed premium on top of the market price for electricity (as in Spain). FIT policies have been adopted in some 75 national and subnational (State/provincial) jurisdictions worldwide (REN21, 2010). A study of support policies for electricity from renewable sources in OECD and selected developing countries concludes that jurisdictions with FITs had the highest market growth for renewables and that payments per kWh tend to be lower under FITs than under renewable portfolio standard schemes (International Energy Agency, 2008). However, as with any subsidy instrument, careful design and periodic recalibration are necessary to ensure that the objectives are achieved at the lowest cost to society, and this requires strong government capacity.

The limitations of current approaches to the energy transformation challenge

In response to the energy challenges from the oil crises and climate change, massive government and private sector responses have been implemented to promote clean energy technology research, development, and deployment. Changes in the technology for clean energy however have slowed considerably at the level of the global fuel mix since the 1970s. Despite impressive growth rates for the diffusion of renewable energy technologies since 2000, it is clear that the current trajectory is nowhere near a realistic path toward complete decarbonization of the global energy system by 2050. This indicates a variety of challenges and outright limits that need to be taken into account when devising energy policy.

Plans need to add up on a global level

At the most basic level, initiatives need to add up (in arithmetic terms) to the declared ambitions at the national and global levels. IEA (2010) presented a "New policies scenario," which assumes (cautious) implementation of recently announced commitments and plans. In this scenario, demand for all types of energy increases in non-OECD countries, while in OECD, demand for coal and oil declines. Global emissions would continue to rise, but at a decreasing pace, reaching 35 Gt in 2035 (which is 21% higher than the 2008 level). Developing countries would account for essentially all the increase, whereas developed countries' emissions would peak before 2015 and then fall. This would lead to stabilizing GHG (equivalent) concentrations at over 650 ppmv, resulting in a likely temperature rise of more than 3.5° C in the long term. In other words, national plans announced across the world plus what was agreed at the Cancun session of the Conference of the Parties in 2010 do not add up to action sufficient to achieve the global targets for emission reductions. More generally, at the international level, the growth of global emissions and resource use is originated in both developed and populous emerging developing economies. Without participation and actions by today's developing countries, no realistic solution is possible to the global environmental problems.

The need for a systemic approach

To the extent that energy technologies are part of a complex interdependent system, plans also need to add up in terms of the requirements of the energy system and the overall progress toward global eco-efficiency.

First, plans need to add up in terms of the global energy-economy-environment system. For example, satisfying about 20 percent of today's demand for gasoline, diesel, and kerosene with modern biofuels is possible in technical and economic terms from the perspective of the energy system alone. However, this would likely have enormous impacts on agriculture, food prices, ecosystems, water availability, the nitrogen cycle, energy demand and prices, and, most importantly, the livelihoods of the poor in rural and urban areas alike (see also Chapter 7 in this volume).

Second, plans also need to add up in terms of the *national* E3 system. One phenomenon to consider in this regard is the "rebound effect" (the Jevons paradox), that is, the effect of increased energy use resulting from increased energy efficiency. While the rebound effect may be small at the local level, it is typically large at the level of the national or of the global economy. Thus, an increase in energy efficiency of a manufacturing plant, while highly desirable from an eco-efficiency perspective at the corporate level, may be partially or wholly offset through reduced energy prices and increased real incomes. Additional measures and regulations are needed to prevent or at least limit the rebound effect.

Third, plans need to add up at the level of the *energy systems* themselves. For example, at present, there are no good substitutes for fossil fuels as industrial feedstocks. Coke made from coal is needed as a reduction agent for smelting iron from ore. The historical alternative of charcoal cannot be used in modern blast furnaces, and even if it could be used in some form, about 3.5 Gt of dry wood per year would be needed for pig iron smelting alone, which requires plantations that are about two-thirds the size of the forests of Brazil. Similarly, there are no plant-based substitutes for hydrocarbon feedstocks (about 100 giga cubic meters [Gm^3] of natural gas per year) used in making plastics and synthesizing ammonia for fertilizer production. As a result, any proposal to phase out fossil fuels requires targeted research into alternative industrial processes.

Fourth, plans need to add up at the level of *power systems.* For example, owing to its intermittency and need for backup capacity, the potential reduction in GHG emissions that can be achieved by wind power depends almost entirely upon the existing power system to which it is added. In fact, the installation of a wind farm does not necessarily lead to a reduction in emissions, in particular when backup capacity is provided by coal power. Ambitious plans for deployment of intermittent renewables need to be based on plans for the development of smart grids.

Staying within limits

Adoption of alternative sources of clean energy need to take account of the various factors that would limit implementation in terms of *biophysical limits*; *scientific-technical limits*; *economic limits*; and *sociopolitical limits*.

Biophysical limits refer to what is possible within planetary limits. For example, the potential for solar radiation absorbed by land is 790 zettajoules (ZJ), which was about 2,000 times the figure for fossil fuel extraction in 2010. Leaving aside unsuitable locations constituting about half of the world's land area (those characterized by weak insolation or inaccessibility) about 470 ZJ are available.

Technical limits refer to what is technically doable and are essentially based on spatial power densities of the technologies, their conversion efficiencies, and their deployment potential. For example, solar power reaches spatial power densities that are two orders of magnitude higher than for wind and three orders of magnitude higher than for photosynthesis. Solar power can in principle reach power densities commensurate with demand densities in houses and some smaller cities. However, industry, high-rise buildings, and megacities require even higher power densities made available by fossil fuels and nuclear power, which exhibit higher power densities (Smil, 2010a). In contrast, wind power or biomass, with power densities less than 0.5 W/m2, require very large areas of land and power infrastructure to provide power to urban areas.

Economic limits refer to what is affordable, especially the relative costs of different types of energy. However, although modern renewables continue to be significantly more expensive aside from hydro (high quality, but low potential) and wind (which provides low-quality power), economic limits are ultimately a lesser constraint, as they can be overcome with political will and special efforts.

Sociopolitical limits refer to what is acceptable socially and politically. For example, in pluralistic democracies, the “not-in-my-backyard” (NIMBY) attitude is a powerful factor. There are civil movements against pipelines, coal power plants, wind and solar power plants, and, especially, nuclear power installation. Italy phased out nuclear power in the past, and Sweden, Belgium, and most recently Germany and Japan have taken phase-out decisions at some point in time. An extreme example involves the licensing of the Konrad radioactive waste depository in Germany, which took twenty-five years and included public consultations with 289,387 people who formally raised more than 1,000 issues. In poorer countries, higher energy prices typically mean higher food prices and potentially lead to increased poverty, social conflict, and even revolts.

When proponents and adversaries of energy technologies make opposing statements about their potentials, the differences are often a reflection of the different types of limits that are being considered (MacKay, 2008).

Smil (2010b, p. 110) notes that “direct solar radiation is the only form of renewable energy whose total terrestrial flux far surpasses not only today’s demand for fossil fuels but also any level of global energy demand realistically imaginable in the twenty-first century.” However, it would be technically possible to harness only a small fraction of this, and even less would be economically or politically acceptable. For example, the very ambitious Global Energy Assessment efficiency scenarios assume a techno-economic potential for solar PV, solar thermal and solar water heating of 2.6 ZJ.

MacKay (2008) provides per capita estimates of technical potentials for harnessing renewable energies for Europe, the United Kingdom, the United States, and the world. He provides a low-carbon energy plan for the world and estimates the global potential for nonsolar renewable energy to be about 83 GJ per capita. In other words, without tapping at least some form of solar energy, it is technically impossible to provide for the level of energy use prevailing in Western Europe today. One billion people in Europe and North Africa could be sustained by country-size solar power facilities in deserts near the Mediterranean; and half a billion in North America could be sustained by Arizona-size facilities in the deserts of the United States and Mexico (Smil, 2010b). The impacts of such a global energy plan on socioeconomic and ecological systems would be enormous. For example, the harnessing of 284 EJ of biofuels would require using all of the world’s arable or cropland of about 27 million km^2 for biofuels, which is clearly infeasible. For comparison, the land requirements of today’s global fossil fuel infrastructure are less than 30,000 km^2, which is about the size of Belgium (Smil, 2010b). MacKay’s (2008) order-of-magnitude estimates provide an illustration of the existing technical limits and what, in principle, could technically be achieved with extraordinary political and financial commitments.

Limits to improving energy efficiency

As discussed above, energy-efficiency improvements when combined with limits on energy consumption have great potential to help achieve global targets. However, it is clear that there are a number of barriers to deployment and adoption of more efficient energy converters, as well as techno-economic limits to be considered. Solutions to overcoming the known barriers exist, but they require long-term commitment and a stable systemic approach by decision makers.

Technical limits to energy efficiency improvements must be taken into account. In 2005, the overall efficiency of global energy conversion (from primary energy to services) was about 11 percent (Cullen and Allwood, 2010b). In other words, global primary energy demand could be reduced to only one-ninth, while the same energy services were provided, if all energy conversion devices were operated at their theoretical maximum efficiency.

In 2005, primary-to-final exergy conversion efficiency was as high as 67 percent (fuel losses, generation, and distribution losses) but final-to-useful exergy conversion efficiency was only about 25 percent (conversion loss). Thus, 509 EJ primary exergy provided only about 86 EJ of useful exergy (in the form of motion, heat, cool/light/sound and other non-energy forms), while 128 EJ were lost in combustion, 173 EJ in heat transfer and 123 EJ through electric resistance, friction, fission, and other fuel-related phenomena. In addition, a system loss is incurred in converting useful energy into final services (“service efficiency”).[6]

It is important to consider compounding of energy efficiencies across the chain. For example, if the conversion loss of each device in the chain had been reduced by only 1 percent (and commensurate limits applied so as to avoid invoking the Jevons paradox), about 33 EJ, or 7 percent of world primary energy of 475 EJ, could have been saved—an amount almost equal to the energy demand of China at the time. In this example, upstream (fuel transformation and electricity generation) efficiency gains would save only 5 EJ, whereas downstream (end-use conversion devices) efficiency gains would be much larger, at savings of 28 EJ (Cullen and Allwood, 2010).

Moving forward

Energy technology innovation matters. It concerns everyone and is often highly politicized. Energy technology policy needs to be comprehensive and supported by industrial policy. Most importantly, global and national energy policy is also development policy and thus must demonstrate special consideration of the poor. Governments need to devise institutional designs that ensure a science-based reality check of energy technology policies, taking into account the challenges described above.

A wide range of policy instruments are available, including economic instruments, regulatory measures, and cooperation. Optimal policy packages depend strongly on a country's institutions, development stage, resource endowments, and sociopolitical preferences and will change over time.

Comprehensive, strategic, and system approaches are needed

Despite the need for tailoring policy to national circumstances, insights from past experience suggest broad guiding principles and performance targets which should guide the analysis (Wilson and Grübler, 2010; Grübler et al., 2012).

Ignoring the systemic characteristics of technological change often leads to a partial view and fragmented or even contradictory policies. Policies must take into account the systemic features of national and global E-3 systems, energy systems, and power systems. Special focus needs to be put on regulations to address the rebound effect, smart grids, and the introduction of alternative industrial processes. The cobenefits of comprehensive approaches can be substantial. For example, the costs of halving premature deaths due to air pollution by 2030 and of ensuring energy security could be reduced to one-fourth, if these goals were pursued jointly with ambitious GHG reduction measures. Bringing universal access to electricity and modern cooking fuels by 2030 would not be in conflict with the other objectives (Riahi et al., 2012).

Historically, performance and quality advantages of new energy technologies compared with the lower energy quality (intermittency and low-power density) of modern renewable energy technologies, led to their early adoption among price-insensitive consumers. Policies designed to create market niches based on superior-quality technologies should be prioritized in order to shield them from full commercial competition during the initial development stages when experience is gained (Schot and Geels, 2008).

Policy-induced scaling up and deployment of new technologies without lengthy formative periods of experimentation and testing could lead to additional risks and might lock in inferior technologies (Wilson and Grubler, 2010). Sufficient time and resources need to be committed for experimentation before scaling up, so as to prevent any premature locking in of suboptimal technologies and clusters (van den Bergh et al., 2007). Picking technological winners ex ante should be avoided, while developing broad technology portfolios should be promoted. Technology portfolios should represent the whole energy system and consider all innovation stages, so as to keep options open, but should avoid large-scale transfer of technology risks to the public sector. In this context, a careful balancing of technology-neutral policies (for example, carbon taxes) and technology-banded ones (e.g. feed-in tariffs), as well as short- and long-term policy targets, should be considered (Sandén and Azar, 2005). It should also be noted that less capital-intensive, smaller-scale (e.g. granular) technologies tend to be associated with lower overall risk. Scenario analysis can be used for risk hedging through identification of "robust" technology portfolios.

Stable and consistent expectations about the direction and shape of the innovation system, in contrast with existing practices that are mostly characterized by stop-go policies, are necessary if innovation actors are to commit resources (Bosetti and Victor, 2011). Innovation policies need to be aligned, which requires coherent support throughout the technology life cycle, but misalignment appears to be the norm in most countries.[7] It is important to choose realistic goals for technology programs and to manage the expectations of innovation system actors, since programs have often been discredited in the past simply because they did not achieve their irrationally exuberant goals.

Public innovation expenditures for highly energy efficient end-use technologies need to be increased. Much greater emphasis needs to be put globally on improving end-use energy efficiency, complemented by behavioral change and limits imposed on energy, land, water, and materials use.

A global frontrunner program and regulation of primary energy demand

A global program that follows the rationale of Japan's Top Runner Program should be considered. Such a program would promote cooperation among countries, communities, and individuals so as to achieve lower primary energy use and lower GHG emissions. Those with the best performance in groups with similar characteristics would successively set the standard for the next phase, which laggards will aim to achieve. For example, Japan might be the top runner that sets the standards and targets to be achieved by other technologically advanced economies in terms of end-use energy efficiency. Other examples might include business people responsible for highly energy-intensive patterns of consumption of transport services, or high-income homeowners. Furthermore, the program might also strive to achieve individual primary energy use and GHG emissions targets.

Given the variety of difficulties associated with fast-tracking the sustainable energy transformation, per capita caps on energy use and emissions may be needed to ease the challenge. A limit of *70 GJ per capita* would seem a reasonable long-term target to be achieved by 2050. This limit would be similar to the figure for the present per capita primary energy use in China and that for the world average. It should be noted, however, that the suggestion is for a limit on primary energy (not final energy), which is most relevant for the environmental impact. In fact, a reasonable primary energy use limit could provide powerful incentives to increase energy efficiency and could ensure the continued provision of more and better energy end-use services despite lower primary energy use.

Higher energy efficiency and lower primary energy use would take much of the pressure imposed by the imperative of rapid decarbonization of highly energy-intensive economies. In environmentally conscious Western European societies, such as that of Denmark, primary energy use is at about 150 GJ per capita, which could be brought down to the 70 GJ target with increased energy efficiency combined with measures to minimize the rebound effect. This would be much more of a challenge for the United States, which currently uses 340 GJ per capita. However, such a limit would still allow ample space for energy demand growth in poor countries, such as India, with a per capita use of only 15 GJ. The target of 70 GJ per capita primary energy use would ideally be applied as averages not to countries, but to individuals, in line with the principle of individual fairness. Energy use within countries is highly uneven, with the world's richest 500 million people (7% of the world population)—who live in both developed and developing countries—using more than half of all primary energy (Pacala, 2007). Burden-sharing among countries based on the principle of individual fairness would differ significantly from sharing based on countries' averages, except for the poorest countries, which would have almost no commitment either way. Indeed, there is ample evidence to show it might be impossible to achieve the desired pace of global energy transition toward low-carbon and renewable energy without limits on primary energy use. A recent study on how to achieve a 100 percent renewable energy system in Denmark by 2050 concluded that such an envisioned outcome was realistically achievable only if primary energy use was halved to 70 GJ per capita (Lund and Mathiesen, 2009). Among major global scenarios, the Global Energy Assessment mix scenario appears to be roughly in line with the focus and targets proposed here. The scenario foresees cumulative global energy-related investments of $65 trillion between 2010 and 2050, or about $1.6 trillion per year. About $23 trillion of this amount would be needed for improving efficiencies, $12 trillion for smart grids (transmission and distribution), $8 trillion for renewable electricity and a combined amount of $4 trillion for fossil-fired and nuclear power plants. An amount of $13 trillion would be needed for fossil fuel extraction and $2 trillion for biomass-related technology deployment (Riahi et al., 2011).

Conclusion

Grounded in comprehensive analysis, this chapter has called for a major worldwide transformation of the energy system to meet the dual challenge of climate change and energy poverty. By drawing upon and critically assessing historical experiences and current efforts on the national and international level as well as market-based measures, the chapter has found that despite manifold initiatives, current efforts do not add up to the enormous challenges confronting the international community to make the transition toward sustainability of the energy system.

Three weaknesses in current efforts are of greatest concern. First, current efforts often fail to adopt a systemic approach. The initiatives reviewed in this chapter often fail to consider the complex interactions between energy innovation and other areas within the E3-system, such as the interdependencies with agriculture, food prices, ecosystems, water availability, and the nitrogen cycle. Second, current efforts are also failing to adopt an energy systems' perspective to ensure technology and innovation for clean energy run parallel to the introduction of alternative industrial processes to move them away from fossil fuels. Third, current efforts also fail to take a power systems' perspective to make sure the deployment of renewable energy is accompanied by the development of smart grids to guarantee reliable energy services. It has further been argued that current efforts are often oversimplified and fail to take into account the biophysical, scientific-technical, economic, and sociopolitical limitations of an agenda to transform the energy systems. International cooperation is understood to be crucial, both between advanced and emerging economies as well as the need for a special focus on energy poverty. Most importantly, the chapter has also argued that the goals of resolving energy poverty and climate change are not contradictory, but despite manifold initiatives international cooperation is still insufficient.

Before this background, there is urgent need to accelerate the transformation of the current energy system toward sustainability, if we are to provide access to modern energy for billions and prevent dangerous levels of GHGs that would trigger irreversible climate change. There is a rich experience, both at country and international levels, with a variety of clean energy technology and policy options to guide such transformation. The adoption of a technology portfolio approach to keep all options open with enough time for experimentation and learning will be critical for success. In this complex transition keeping a careful balance between technology neutral and technology banded policies and between the short and long term in relation to policy targets will also be essential.

The chapter has shown that reliance on market forces alone will be insufficient and called for governments and the global community to adopt a strategic vision for both the improvement of efficiency of the energy system and accelerate the introduction of clean sources of energy. Making the transition toward sustainability will require the use of a variety of tools, regulatory measures, and cooperation of multiple stakeholders refocusing efforts on the energy demand side, especially through tipping into the high potential associated with increased end-use efficiency and individual caps on primary energy use.

[2] United Nations, *Treaty Series*, vol. 2303, No. 30822.

[3] Chapter 6 in this book reviews the experience of China and other emerging countries in building capacities to engage in R&D for the transformation of their energy system.

[4] Designs include the parabolic trough, the dish stirling, the concentrating linear Fresnel reflector, and the solar power tower.

[5] The Top Runners set the standard, with consideration given to technological potential. Differentiated standards are set based on various parameters. Compliance with the standard is evaluated by corporate average.

[6] Global energy-related services provided included passenger transport, freight transport, structure, thermal comfort, sustenance, hygiene, communication, and illumination (Cullen and Allwood, 2010).

[7] For example, support for low-carbon technologies is undermined by fossil fuel subsidies and efficiency improvements in transport are swamped by higher demand.

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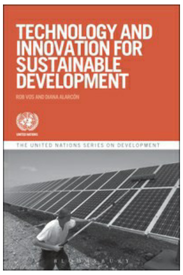

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Chapter 5. Achieving Sustainable Development:

Investment and Macroeconomic Challenges[1]

Marco V. Sánchez and Eduardo Zepeda

> *You are probably reading this on a piece of an ex-tree. Felled by a petrol-guzzling chainsaw, it was carted to a paper mill in a diesel-powered truck. Or perhaps these sentences are on a tablet, with plastic components that started life as crude oil, and metal smelted with coke produced from the tar sands of Canada. Either way the words are probably lit with electricity from coal-fired power station. Maybe you are even sipping wine, grown with fertiliser made using natural gas, in a glass created in an oil-fired furnace . . . Weaning ourselves off this stuff is not going to be easy.*
>
> LePage, 2014.

Introduction

There is an emerging consensus holding that sustainable development requires the implementation of policies to pursue, simultaneously, along with development goals in various domains. Sustainable development requires the adoption of strategies to expand people's choices in developed and developing countries, to protect the environment, and to preserve peace and security (United Nations, 2012). Notwithstanding the multiple dimensions of sustainability, its attainment hinges upon the capacity of civilization to avert a rise in world's temperature that could trigger events of catastrophic consequences. Key to the goal of averting undue increases in the world's temperature is the transformation of the energy system away from its heavy reliance on fossil fuels and toward alternative sources, notably renewables.[2] Transforming the world energy system calls for strong leadership, carefully designed policies, behavioral changes, and large investments in developed and developing countries. While it is difficult to come up with an exact estimate of the additional investment required to build a global sustainable energy system, an often-cited estimate hovers around 0.7 trillion dollars per year between 2011 and 2030; this is around 1 percent of the world's GDP.[3]

Achieving energy sustainability at the cost of 1 percent of the world's GDP in additional investments would not be especially burdensome. In reality, however, the investment effort required to secure sustainable energy systems will be several times that figure. Along with a change in energy supply, additional investments will need to be made to adapt existing devices to the new sources of energy. Changing the energy matrix will not only require investments in dams, solar panels, wind mills, nuclear, hydrogen, and other energy sources but it will also need investments to adapt car engines, boilers for heating systems, compressors, and a large number of other appliances to the new sources of energy (see GEA, 2012; Grubler et al., 2012; Yeager et al., 2012). Moreover, changing the energy matrix will also require additional investments to foster innovation, diffusion, and adaptation to specific national and regional conditions, particularly in developing countries. Beyond these investments in the energy system, governments will have to bear the costs of introducing new regulations and incentives to promote changes in consumption habits and the spreading of cleaner energy technologies across industries and services. Once account is taken of investments in all these areas, estimates about the volume of resources required to support the transformation of energy systems toward sustainability could be as high as 3 percent of global GDP and even run into double digit figures (GEA, 2012). Not all these investments, however, are additional outlays. These estimates include investments that would have to be made in a business as usual scenario and would still be needed in a new sustainability framework. Bringing them into consideration allows for a better sense of the overall size of investments required going forward.

The adoption of sustainable development paths extends beyond the energy system even if broadly conceived. Sustainable development requires the adoption of transformative policies in the economic, social, and environmental dimensions of development. How countries undertake desired transformative changes depends on a variety of factors, but it importantly hinges on their level of development. Developed countries will have to manage the technological transition of the energy matrix and the introduction of sustainable consumption and waste management in a context where their energy policies will be mainly concerned with maintaining and renovating their energy infrastructure still within a mostly fossil-fuel base. Developing countries will confront the more demanding challenge of simultaneously building their basic infrastructure to support a more competitive economic structure, supporting faster economic growth, providing all their citizens with access to modern energy, extending their social infrastructure, deepening human development, advancing technological capabilities, and making the transition toward sustainable consumption and production. The challenge of articulating policies in all these domains is significant.

The transformation of the energy system and the achievement of inclusive development throughout the world represent a global challenge that nevertheless calls for different efforts across nations. The mapping of the global sustainable investments by regions and countries results in varying investment estimates depending on the current reliance of countries on fossil fuels, their resource endowments and their level of development. Measured as a percentage of GDP, the amount of resources that developing countries currently allocate to energy represents a significantly bigger economic effort, compared to that of developed countries. Several regions will need to undertake investments representing several percent points of GDP.

The achievement of other economic and human development goals magnifies the challenges, particularly for developing countries. The Millennium Declaration set the task of achieving a number of goals, the Millennium Development Goals (MDGs). These have inspired and influenced policies in developing countries in varying degrees. They provide a useful framework for assessing the magnitude of effort needed to make progress in human development. In the context of these goals, estimates of the additional public spending countries have to allocate above a business-as-usual path to achieve the Millennium Development Goals (MDG) targets in education, health, and water and sanitation range from a fraction of 1 percent of GDP to several percentage points of GDP, depending on country conditions.

This chapter attempts to offer a broad discussion of sustainable development drawing from two interlinked strains of work to estimate the investment needed for sustainable development in the areas of energy, infrastructure, and human development. The next section looks at the role of policy and technological options in determining the size of energy investments needed by regions of the world. The chapter then proceeds to analyze policy options to expand public investment to attain infrastructure, including energy, and human development targets. The analysis draws upon results generated by an economy-wide framework designed to assess human development policies, a tool well suited to analyze the impact of policies that have widespread consequences in the economy. The chapter closes with some concluding remarks.

Policy, technology, and energy investments for sustainability

This section focuses on the energy investment challenge for sustainable development. Drawing from the results of the Global Energy Assessment systems dynamic modeling (GEA, 2012), hereafter GEA, it draws a picture of the order of magnitude of the investment effort that will be needed globally and regionally, to achieve energy sustainability. The discussion highlights interregional differences and underscores the importance of policy decisions in determining the size of additional investment requirements.

Unsustainable energy trends

Energy investments early in this century represent about 2 percent of global GDP. The GEA exercise includes projections of the energy system that assume no change in the policies and technologies available in 2005 through the rest of the century. Thus, the demand for energy services would be basically met through an extension of current energy supply technology and availability of fossil fuels. The demand for energy is assumed to increase in tandem with a 2 percent annual economic growth in the global economy, mainly driven by developing countries, and continued population growth to reach a plateau of 9 billion people in the second half of the century. This scenario is identified as the *counterfactual scenario* or *path scenario* in the GEA narrative. It is a useful point of reference to illustrate the problems derived from a continuation of current policies and in the absence of additional investments in alternative technologies. This counterfactual scenario results in unsustainable increases in greenhouse gas (GHG) emissions. But, to the extent that it is based on current technology, this is an "inexpensive" route to meet the growing world energy demand; in this *path scenario,* global energy investments decrease from 1.9 percent of global GDP in 2005 to 1.7 percent of GDP in 2050.

Given the differences in development, economic specialization, and population size, it is only expected that investment requirements vary widely across countries. In 2005, they vary across regions from 0.7 percent of GDP (Pacific Asia OECD) to 11.6 percent of GDP (Former Soviet Union countries). In between, the Western European Union would require an investment equivalent to 0.8 percent of GDP, the North America region would have to invest 1.3 percent of GDP, Central and South America and the South Asia regions would need about 2.2 percent of GDP, and Sub-Sahara Africa would require additional investments in the order of 4.4 percent of GDP. Even if countries are grouped in two large categories, differences are significant: 1.4 percent of GDP for developed countries and 3.8 percent of GDP for developing countries.[4] Large differences in the estimates for energy investments will continue well into the end of the century, as income and population continue to grow rapidly in the developing world. But differences will tend to narrow down as population growth rates in developing countries slow down.

Energy investment requirements in this unsustainable path will have different rates of growth across regions. Changes will reflect the convergence in the pace of economic growth and population dynamics, as well as the effects of economic specialization and the availability of energy sources. The main change is a notorious decline in energy investments in the Former Soviet Union group of countries, the countries in North Africa and the Middle East, and in the Sub-Saharan Africa region. Investments in other regions will not change much (few tenths of a percentage point of GDP).

Pathways to energy sustainability

The continuation of current policies has been widely recognized as unsustainable, incapable of slowing the rise in world temperature enough to reduce the probability of facing disastrous consequences for millions of people.[5] While halting the increase in global temperature is an imperative that cannot be stressed enough, it is also true that success in controlling the increase in temperature is not enough to bring sustainability to the development process. A more comprehensive framework that encompasses the economic, social, and environmental dimensions of development will be needed to bring a simultaneous improvement in living conditions and sustainable use of natural resources (United Nations, 2012). Echoing this vision, the GEA exercise asks what kind of policies, technologies, and investments need to take place to transform the current energy configuration into a sustainable energy system, that is, one that keeps the increase in temperature within safe limits, promotes growth, protects the environment, and deepens social inclusion. The task is daunting; keeping it manageable and maintaining the focus on energy, the GEA proposes a fourfold definition of sustainability. An energy system is deemed sustainable if it meets the following criteria: (a) attains almost universal access to electricity and clean cooking fuels by 2030; (b) ensures that the majority of the world's population live in areas that meet the air quality guidelines of the World Health Organization; (c) limits CO_2 concentrations to levels compatible with average temperature increases of less than 2° C; and (d) limits energy trade while increasing the diversity and resilience of the energy supply within each country.[6]

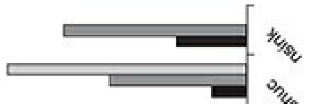
The GEA organizes the discussion about the kind of policies, technologies, and investments that would meet this four-fold definition of sustainability. It defines three types of policies, two modalities of transport characterized by the type of fuel they use, and ten technology portfolios. The combination of these policies and conditions results in 60 energy scenarios or paths. The three energy policy paths that combine supply and demand policies to ensure that supply meets final energy demand are the following.[7] The *supply path* emphasizes policies to meet the increasing demand for energy in the world by scaling-up all supply-side options. It assumes a trend in energy intensity similar to the historical long-term pattern. In this case a large up-scaling of R&D and large investments in new infrastructure and fuels will be needed, including in hydrogen and electricity for transportation (see GEA, 2012, p. 73). The *efficiency path* emphasizes demand energy policies. It simulates a doubling improvement in the long-term historical pace of energy intensity. This path assumes the implementation of policies to ensure a fast adoption of best-available technology throughout the energy system in order to enhance recycling, improve life cycle product design, and extensive retrofitting of existing plants, among other measures. It is worth noting that while supply and efficiency paths feature similar volumes of renewable energy, the share of renewables in efficiency paths is significantly higher because energy demand is much lower. The third policy path, the *mix path,* combines features of the first two alternatives. Each of these policy paths branches out into two transportation modalities: one assuming continued reliance on conventional technologies and fuels (mainly liquid); the other adopting advanced technologies and fuels (hydrogen and electricity). From each of the six policy-transport paths, the analysis branches out into ten technology portfolios defined by different technology combinations, one of them characterized by access to all technologies, the full portfolio, while the other nine feature limited or null access to alternative technologies, including renewables, bioenergy, nuclear, carbon sinks, carbon sequestration, and bioenergy carbon sequestration.[8]

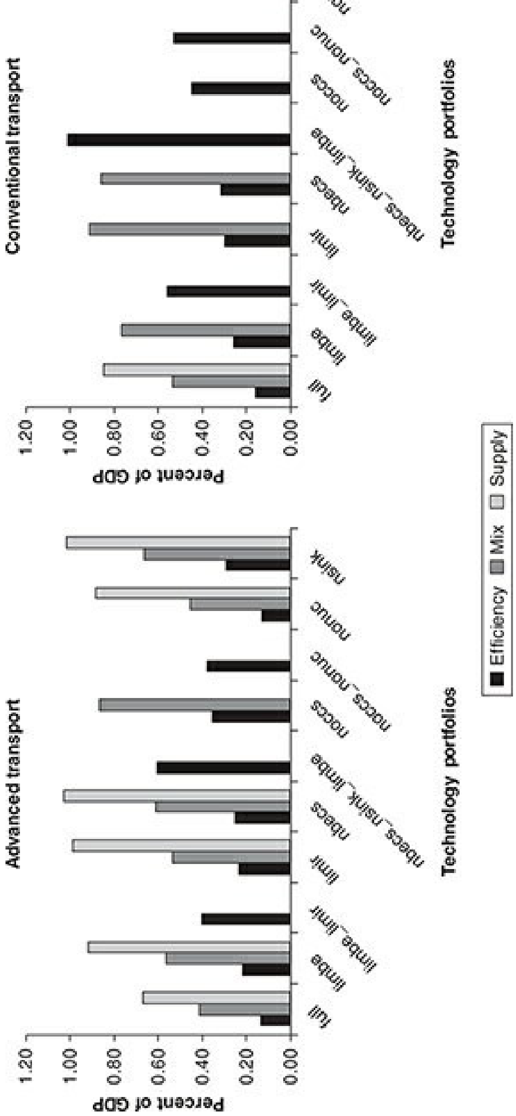
These policies, including the promotion of R&D and the diffusion of technology and innovation, define different technology options and various prices and costs of the energy system. The various options are run through the use of two system dynamic models.[9] The majority of scenarios meet the sustainability criteria. A quick glance at successful scenarios provides a useful approximation to the role of policies, transport modalities, and technologies in shaping sustainable development paths. On the whole, the sustainability test underscores the widely held view that the adoption of energy efficiency policies is a powerful driver toward sustainability. All efficiency policy scenarios meet the sustainability criteria. Efficiency policy paths assume a decline of energy intensity that is twice as large as the historical pace so far; it further assumes that incentives, regulations, and technological innovations will be in place in such a way that there will be a significant reduction in the use of energy to satisfy future demand for energy services. This finding shows that as long as the growth in the demand for energy is met through improved efficiency, the world can afford the use of all energy supply side technologies available.

A different picture emerges from supply policy paths that are not accompanied by improved efficiency on the demand side. Less than half of the paths meet the sustainability criteria. Furthermore, the ability to meet sustainability critically depends on the development of technologies that support the use of hydrogen and electricity for transport services. The majority of supply paths meeting the sustainability criteria feature advanced transport modes fueled by hydrogen and electricity. As expected, the mix policy paths offer intermediate possibilities and a little over half of them succeed in meeting the sustainability criteria.[10]

The combination of policies, technologies, and transport modes not only determines the feasibility of reaching sustainability but it will also influence the size of required investments. Different scenarios yield world energy investment requirements in the range of 1.5 to 2.9 percent of GDP between 2020 and 2050. That is, sustainable paths open the opportunity to reduce energy investments, if the right policies are chosen, although they can also be more costly when compared with the 1.7 percent of GDP investment of the counterfactual scenario.[11] Several patterns emerge within the wide range of investment needs in energy sustainable paths. Efficiency paths will generally require lower investments than mix paths and supply policies. Sustainable paths featuring advanced transport modes will call for additional investments when compared to paths based on conventional transport modes, albeit differences in this case are small (Figure 5.1). The role of technology is more nuanced. The two smallest investment requirements, after taking into account policy and transport mode, correspond to the option where the full technology portfolio is available and the portfolio excluding nuclear energy, as nuclear usually necessitates large investments over a number of years. Portfolios that exclude—or make limited use—of two or more technologies have the highest investment requirements. The different combinations of policy, technology, and modes of transportation entertained in the scenarios built by the study of GEA, confirm the idea that sustainability is affordable.

Figure 5.1. Global additional energy investments in sustainable energy paths, 2011–50 (annual average as percent of GDP)



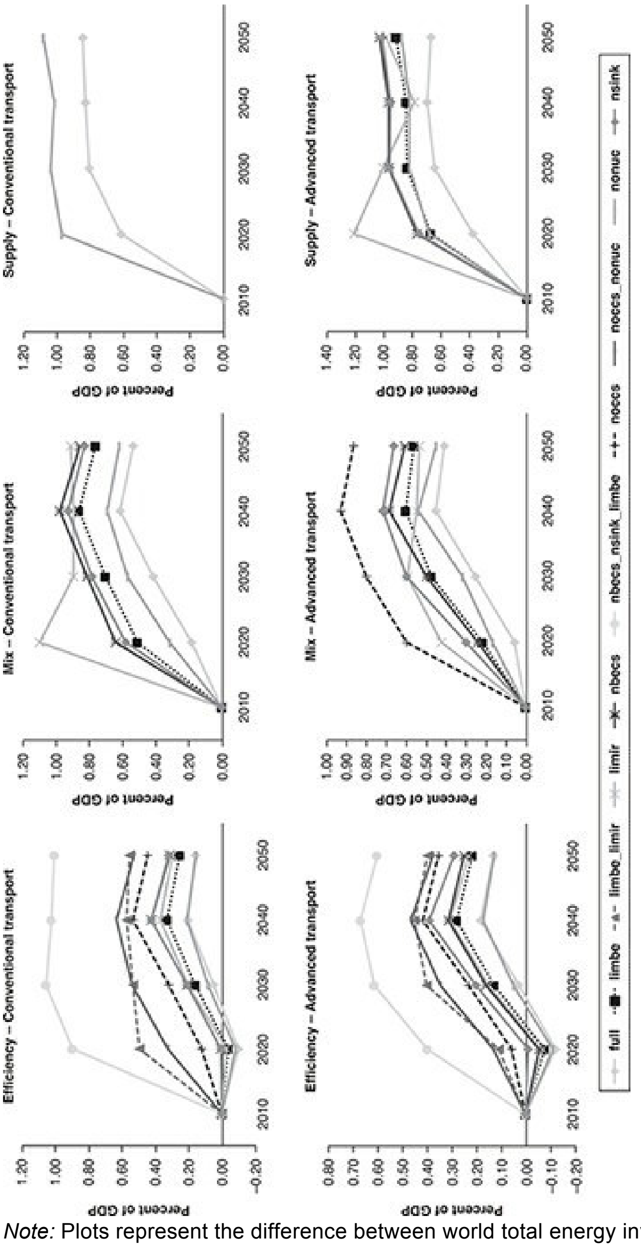


Note: Plots represent the difference between world total energy investment in sustainable paths and world total energy investment in the counterfactual scenario (keeping 2005 policies and technologies unchanged) over GDP estimated at market prices. GDP is the same in all scenarios. In this and in subsequent figures, the technology portfolios are defined as follows:

Figure 5.1 continued	
full:	No carbon (dioxide) capture and storage
limbe:	No nuclear and no carbon (dioxide) capture and storage
limbe_limir:	Full portfolio (all options)
Limir:	Limited biomass and renewables
nbecs:	No nuclear
nbecs_nsink_limbe:	Limited renewables
noccs:	No bioenergy carbon capture and storage
noccs_nonuc:	Limited biomass
nonuc:	No sinks
nsink:	Limited biomass, no bioenergy carbon capture and storage, no sinks
Source: Authors' construction based on GEA database (http://www.globalenergyassessment.org).	

The GEA exercise also confirms the widely held view that sustainability needs substantial frontloading of investments. Additional global energy investments needed to support sustainable paths will generally increase rapidly during the first thirty years, both in absolute terms and in relation to GDP. But even in these early years, the adoption of the right policies can reduce the "cost" of sustainable paths to affordable levels. Simulation results suggest that if the right policies are adopted, the additional investment requirement to achieve energy sustainability would not be larger than few tenths of one percent of global GDP (Figure 5.2). Moreover, in a few specific cases, sustainable paths would actually claim fewer investments in energy than those projected under the counterfactual scenario. On the contrary, supply policies that place the emphasis on fossil fuels will require an investment envelope equivalent to about one percentage point of GDP, which represents an increase of about 50 percent over current trends in energy investment.[12]

Figure 5.2. Global additional energy investments in sustainable energy paths, 2010–50 (annual average as percent of GDP)



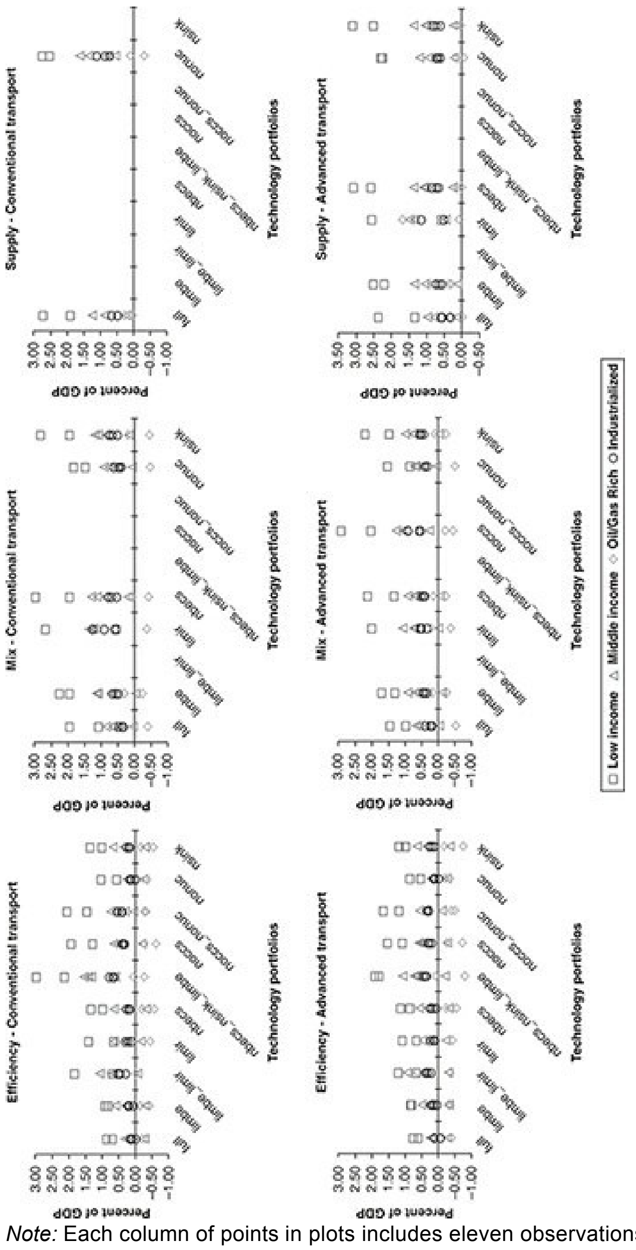
Note: Plots represent the difference between world total energy investment in sustainable paths and world total energy investment in the counterfactual scenario (keeping 2005 policies and technologies unchanged) over GDP estimated at market prices. GDP is the same in all scenarios. Technology portfolios are defined in Figure 5.1.

Source: Authors' construction based on GEA database (http://www.globalenergyassessment.org).

Regional perspective of sustainable investments

As in current trend patterns, energy investments for sustainable development are higher in developing countries when compared to developed. In general, not only do developing countries need to commit a larger proportion of their GDP to energy investments to fulfill their sustainable development aspirations, as illustrated by the counterfactual scenario, but the transition to sustainable energy paths also tends to command a stronger investment effort. Breaking estimates down to eleven regions shows that sustainable energy investments tend to be high in low-income regions, moderate in middle-income regions, and low in industrialized regions (Figure 5.3). Results support the view that on top of traditional development support, developing countries, and particularly low-income countries, will need additional resources to pursue policies to build a sustainable energy system. Detailed results also confirm that the adoption of efficiency policies will contribute to reduce the size of sustainability investments across regions. Moreover, in a number of countries investments in energy may be lower than in a business-as-usual scenario, particularly in early decades. This is the case in countries grouped as Former Soviet Union (FSU) and those in the Middle East and North Africa (MENA). Lower investment requirements in these regions result from the fall in the demand for fossil fuels in other countries that are using more renewable and nonfossil energy.

Figure 5.3. Additional energy investment is sustainable paths by country group, 2011–50 (annual average as percent of GDP)



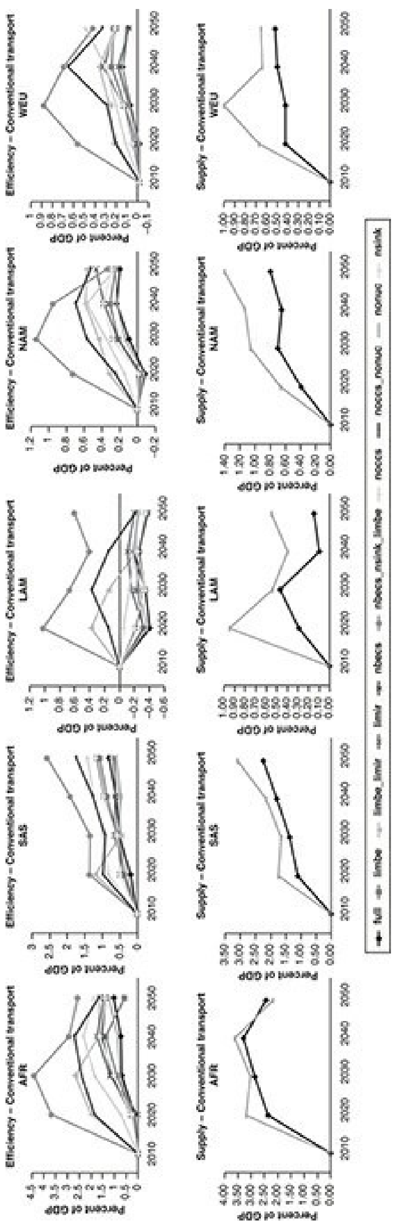
Note: Each column of points in plots includes eleven observations corresponding to the regional disaggregation of the model. Each panel represents a different combination of policies and choice of technology; for example, investment requirements of a scenario that uses conventional technology but improves energy efficiency are shown in the efficiency/conventional panel. Points represent the difference between total energy investment in sustainable paths and total energy investment in the counterfactual scenario (keeping 2005 policies and technologies unchanged). Gross domestic product is the same in all scenarios and is estimated at market prices. Technology portfolios are defined in Figure 5.1. Regions are classified in four groups: Low Income: AFR and SAS; Middle Income: CPA, EEU, PAS, and LAM; Oil/Gas Rich: MEA and FSU; Industrialized: NAM, WEU, and PAO.

Source: Authors' construction based on GEA database (http://www.globalenergyassessment.org).

To gain insights on how policies, level of development, and the frontloading of investments interact, we discuss results in five regions: Sub-Saharan Africa (AFR), South Asia (SAS), Central and South America (LAM), North America (NAM), and Western European Union (WEU). Sustainability investments in Sub-Saharan Africa, the region with the lowest income, record the largest additional sustainability investments, followed by South Asia, the region with the second lowest income. The notable increases in energy investment in the Sub-Saharan Africa region up to 2030 are consistent with the breath of actions needed to reach almost universal access to modern energy in a region with large energy deficits and low population density.[13] For this region additional energy investments for sustainability can escalate to well above 3 percent of GDP as early as 2020. Results also suggest that in low-income regions, notably Sub-Saharan Africa, investments for sustainable energy will vary significantly depending on the technology portfolio adopted. These insights suggest that these countries will require international support to afford the frontloading of large investment requirements and to gain access to the most appropriate technological options at low cost. The two high-income regions show low-investment requirements across policies and over time, fluctuating between 0 and 1 percent of GDP. However, under some supply policy paths, the North American region might require investments well above 4 percent of GDP, signaling the importance of adopting energy efficiency policies in this region. Sustainable investments in Central and South America are comparable to those of high-income regions and in some instances are actually negative. This is explained by the strong fossil-fuel export positions of some countries in the region but also by the region's intensive use of hydroenergy and proportionally small use of coal.

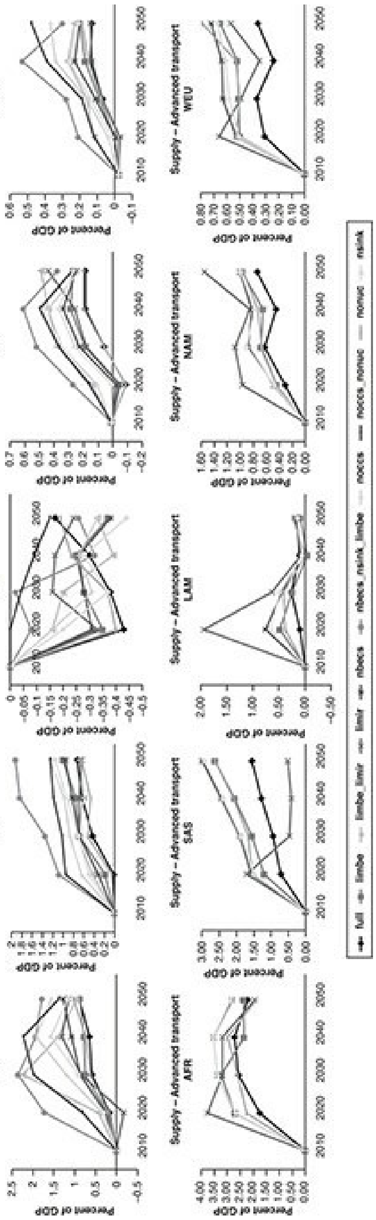
Focusing on energy efficiency

Figure 5.4. Additional energy investment in sustainable paths by region, 2010–50 (annual average as percent of GDP)



Note: Each panel represents a different combination of policies and choice of technology by region; for example, investment requirements of a scenario that uses a supply policy path with conventional technology in Sub-Saharan Africa are shown in the supply-conventional/AFR panel. Plots show the difference between total energy investment in sustainable paths and total energy investment in the counterfactual scenario (keeping 2005 policies and technologies unchanged). GDP is the same in all scenarios and is estimated at market prices. Technology portfolios are defined in Figure 5.1. For simplicity, mix policy sustainable paths are omitted.

Source: Authors' construction based on GEA database (http://www.globalenergyassessment.org).



Investments to make efficient use of energy are very important for sustainability. Paths with strong efficiency policies expand the technology options and reduce the size of needed investments, as observed above. Efficiency investments include, among others, outlays to enhance recycling, improvements to the life cycle product design, and expansions in retrofitting of existing plants. Arguably, the technological advantage of developed countries in this type of investments is particularly strong. It is thus of particular interest to compare how these investments play out in GEA simulated sustainable paths. To simplify the discussion, we limit attention to sustainable paths assuming access to the full portfolio of technologies. For sustainable development, the accent is placed on efficiency; thus, between 2010 and 2040, investments to improve energy efficiency in the world would be twice as large when compared with supply paths.[14] Investments by region suggest that efficiency investments will be relatively higher in lower income regions. In the Sub-Saharan Africa region, for example, demand-side efficient energy investments alone might add up to 1 percent of GDP. In Central, South, and North America, efficiency investments might be slightly lower, clearly less than 1 percent of GDP. Notably, investments in the Western European Union are significantly low (few tenths of a percentage point of GDP), reflecting the relatively high-energy efficiency already achieved in the region.[15] These results underscore the importance of international cooperation in ensuring that countries with less resources and technological capacities have access to the best technological options to build their own sustainable paths.

In recent years investments in renewable technologies have increased rapidly; yet, investment levels still fall short of what might be needed to achieve sustainability (IPCC, 2011; IEA, 2014a). It is interesting to look at the effect that limited access to renewable energy technologies would have on required investment to reach sustainability. When we assume limited access to renewables, the GEA simulations indicate that additional investment required for sustainability, particularly in early years, will be higher in Sub-Saharan Africa, and in the Americas (Central, South and North America).[16] Investment requirements are similar, yet smaller, in the South Asia and Western European Union regions. The financial and technology implications of these findings point again to the need to strengthen international cooperation to ensure low-income regions have a fair chance to build a sustainable energy system. Even if there are leapfrogging opportunities to speed up the transition toward sustainable development, developing countries, and particularly low-income countries, will still need to scale up energy investments. The successful adoption of sustainable development policies will thus require adequate financial resources to support investments. Even when financial requirements are not large on a global scale they do represent a significant effort in the context of developing countries.

Public policies for development

The discussion so far points to the need to undertake significant investments to set energy systems in a sustainable path in developing countries. These investments are well above the sizeable energy investments needed for growth and development, already amounting to several percentage points of GDP in some regions. Such large investments will have to come through a unified effort from private and public sources. But given current market uncertainties and the strong inertia to continue businesses as usual, public policies will need to lead the way toward sustainability. Governments will need to allocate large resources to transform the energy system and achieve other economic and social development aspirations simultaneously. They will need to design a coherent strategy to jump-start the private-public investments needed for sustainability. This raises a number of questions. First, how can governments finance those sizeable investments, at least initially until private investors see the potential and are ready to join the efforts? There is an additional policy challenge in generating crowding-in effects that could lead to virtuous cycles of investment and growth within a sustainable pathway (United Nations, 2009). While asserting the general feasibility of using public funds to jump-start transformative energy investments is a very important step, not all countries have the same potential to create virtuous cycles of public-private investments. Most likely, there will be a significant variation across countries in terms of the size of investments that can be handled without disturbing macroeconomic balances. The second question then is: what are the macroeconomic trade-offs and synergies that such additional investments could bring about? Stepping up public investment immediately poses the question of how to finance them; all potential funding sources involve costs that need to be closely scrutinized, including their impact on private investment and consumption, on the cost of public debt, and on exchange rates.

Additional investment effort and macroeconomic trade-offs

The experience of policies aiming to achieve the MDGs provides a useful reference to answer the questions above. The MDGs were formulated to pursue social development, one of the three pillars of sustainable development. But human development investments, particularly in education and health, are also known to bear fruit in terms of increased productivity and economic growth—the other pillar of sustainable development. Several studies have analyzed the economy-wide effects of stepping up public spending to achieve the MDGs. The range of investments varies significantly across countries, reflecting different initial conditions and efficiency of public social spending. These observations are supported by country studies documented in Sánchez and Vos (2013) for nine countries in Africa, Asia, and the Middle East, and Sánchez et al. (2010) for eighteen Latin American and Caribbean countries. These studies estimate that additional public spending requirements to meet a number of MDG targets related to primary education, health, and water and sanitation. Additional investments range from less than 1 percent of GDP to a high 10 percent of GDP.[17]

The same studies suggest that, in response to public spending, there are a series of macroeconomic, labor, sectorial, poverty, and distributional effects whose size and direction depend on country conditions. For example, in some cases, GDP growth declines, while in others it actually benefits. But even in countries where GDP is stimulated, the competitiveness of the economy over the long term could be undermined by changes in the real exchange rate induced by an increase in the demand for nontradables. These studies also underscore the importance of adequately choosing the funding sources to finance an increase in government expenditures. In general, findings suggest that external sources have a better impact on the economy when compared to domestic sources. Within domestic sources, tapping into taxes generally brings about less adverse trade-offs than domestic borrowing. Among external sources foreign grants are preferable over debt, as there is no debt servicing involved, although due to absorptive capacity limitations, both types of foreign exchange inflows may result in a real exchange rate appreciation with potential to undermine competitiveness. While negative impacts are generally small, investing in human development might also have undesired income distribution effects. This is particularly true in the context of small developing countries where such investments generally increase the demand for skilled workers (e.g. teachers, nurses and doctors, engineers) with a corresponding increase in their incomes as these workers tend to be in limited supply. Rather than an argument against increasing investments in human development such findings highlight the need to recognize and properly account for inescapable trade-offs when designing and implementing sustainable development policies.

Tax and spend

In their quest to mobilize additional resources for sustainable development, policy makers may eventually need to consider resorting to fiscal revenue. Reliance on foreign resources to finance long-term investments may not be a feasible option for many developing countries in view of debt sustainability considerations, unless foreign aid commitments by international donors are effectively delivered. Furthermore, even if foreign aid inflows increased significantly, they have been unpredictable and may be difficult to absorb without unfavorable macroeconomic consequences. Access to these inflows may also come with unfavorable conditionality and their administration is often costly thus diminishing the amount of resources effectively available for investment. Against this backdrop, countries will eventually have to rely on domestic resource mobilization. Even in low-income countries, social service delivery and poverty reduction programs are largely financed through domestic resource mobilization. Domestic borrowing is unlikely to become a significant financing source for development; most developing countries have shallow capital markets and severe constraints in domestic savings. By contrast, most developing countries still have scope to increase tax revenues as tax burdens tend to be low due to the prevalence of a large (informal) economy that remains untaxed. Even within the formal sector, tax collection is ineffective in some countries, and there is room to reduce tax evasion and loopholes.[18]

There is already experience with policies that raise fiscal revenue at the same time that they help reorient the economy toward a sustainable path.[19] A tax imposed on activities according to their carbon emissions—explicitly as carbon tax or implicitly as tax on gasoline, diesel, and energy—is a potentially important tool for sustainability. Several developed countries, notably in the Nordic region, have used this instrument over several years; more recently, some developing countries have also introduced it. A notable example is Costa Rica, who introduced a tax as early as 1997 and has maintained it since then. A tax on carbon emissions fulfills two objectives. First, it helps to raise revenues to fund low-emission programs or, more generally, sustainable development policies. Second, it helps to correct prices and internalize some of the environmental costs of fossil fuels. In practice, however, carbon taxes have been set at such low levels that the price correction benefits have been small, leaving the revenue collection to fund sustainable policies as their most important contribution. Carbon taxes generate revenues that range from few tenths to 1 percent of GDP in different countries.

In spite of the appealing features of a carbon tax, however, the impact of this policy instrument needs to be carefully evaluated. The imposition of the carbon tax itself and the allocation of revenue to specific investments affects the economy as a whole, triggering a number of macroeconomic effects and trade-offs. Assessing the desirability and feasibility of these policies is very important for sustainable development. Full assessment of these effects requires the use of an economy-wide framework that allows for a simultaneous view of the impact of policy shocks into economic growth, budget issues, sector impacts, employment outcomes, and consumption consequences. A brief summary of these types of effects follows.

Assessment of economy-wide effects

The impact of imposing an implicit carbon tax is evaluated in this section using the economy-wide framework known as *Maquette* for MDG Simulations (MAMS). This model belongs to the family of dynamic-recursive computable general equilibrium (CGE) models. The choice of this particular model rests on the fact that, in addition to being a full fledged dynamic CGE model, it incorporates a module that specifies a number of human development indicators (see Lofgren et al., 2013). Its application involves, inter alia, detailed (country specific) microeconomic analyses of the determinants of human development indicators and the drivers of productivity growth, including the stock of public infrastructure and the existence of highly educated workers.

Our analysis is based on the application of MAMS in three developing countries—Bolivia, Costa Rica, and Uganda—representative of the variety of conditions prevailing across developing countries.[20] While these countries share as a common feature their reliance on oil imports for production, the degree by which they are affected by an increase in oil prices (e.g. one that is triggered by a carbon tax) will be different. Not only is their degree of dependence on oil imports different, but Bolivia and Costa Rica can more easily substitute oil with other sources of (more sustainable) energy.[21]

A baseline scenario was generated for each of the three countries in order to formulate a benchmark against which different policy scenarios would be compared. This reference scenario replicates actual economic performance under policies implemented around 2005–13, including spending and tax policies. This performance is subsequently projected until 2030—a reasonably long timeline for a dynamic-recursive economy-wide model analysis. Because the baseline assumes no external shock derails the economy and public spending policies, human development indicators show marked improvement under the scenario constructed.

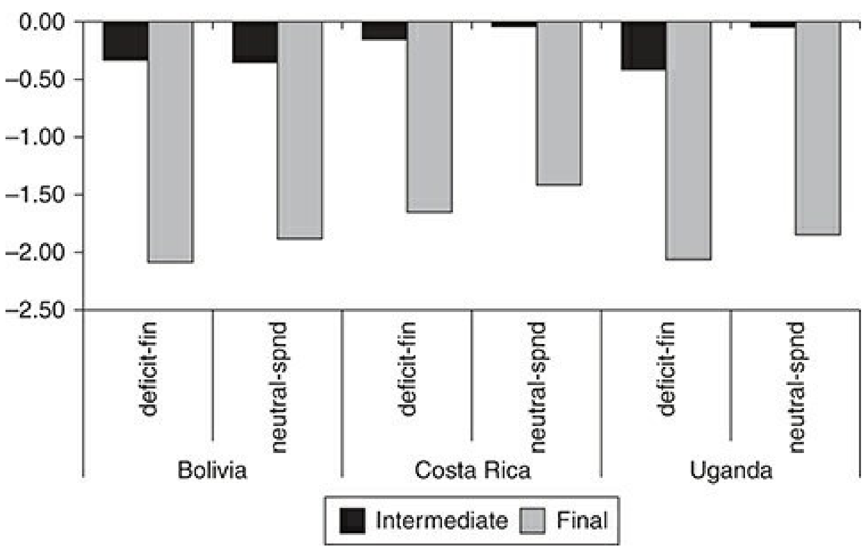
A total of six policy scenarios were generated and compared with the baseline. The common feature of these policy scenarios is that in all of them tax revenues in the period 2016–30 are 2 percent of GDP higher than in the baseline. This difference in tax revenues is driven by a simulated increase in taxes on imports and domestic consumption of fuel oil, which rise gradually over time to make the simulated policy more realistic. The magnitude of change in tax revenues is similar to the additional investment needed to transform the energy system according to some of the GEA sustainable paths noted in the previous section. Each policy scenario is different with regard to the way in which the newly collected revenue is used or spent. In the first policy scenario, for example, the new revenue is used for budget deficit financing (deficit-fin). In all other policy simulations, the deficit is left unchanged while the new revenue is fully used to increase public expenditures in three different ways: (i) preserving the expenditure structure of the baseline scenario (neutral-spnd); (ii) stepping up new public infrastructure (i.e. roads, bridges and electricity networks) (infra-inv); and, (iii) raising current and capital expenditures for education (educ-spnd). Two additional variations of the third option were generated whereby expenditures are allocated to primary education only (educp-spnd) or tertiary education only (educt-spnd). The public infrastructure scenario, in particular, underscores the goal of enhancing growth and development, while the third option underscores the importance of education (in different modalities) for human development. Spending in primary education is essential to enroll more boys and girls in the formal school system at the right age with important consequences for poverty reduction and increased productivity in labor intensive sectors, particularly in the medium- to long-run. Alternatively, increasing spending in tertiary education can help improve the international competitiveness of the country and its capacity to accelerate adaptation and eventually development of new technology to enhance productivity and economic growth.

There are several studies that assess the introduction of policy options to neutralize the impact of a carbon tax on consumers' welfare, on international competitiveness, or to neutralize negative impacts on employment.[22] The focus of the exercise presented here is different. Our aim is to evaluate ways in which carbon taxes can make a contribution to financing human development in particular and sustainable development in general. The discussion focuses on the effects of investing in human development and economic infrastructure.[23]

Macroeconomic effects

Imposing a tax on oil leads to an increase in its domestic price in a context where this product is imported in all three countries. As a result, there is a reduction in fuel consumption among business and households—that is essentially reflected as a reduction in total private consumption. Taxing fuel consumption has a stronger effect on final consumption when compared to the use of oil as an intermediate good, suggesting producers have more opportunities to substitute oil for nonoil sources. These changes are apparent in Figure 5.5, represented by the difference in the average growth of oil consumption (final and intermediate) between the first two policy shocks and the baseline scenario. The changes are much larger in Uganda, confirming that substitution toward nonoil sources are more restricted in that country when compared to Bolivia and Costa Rica. On the whole, the results confirm the view that imposing a tax on fuel has the desired effect of reducing its consumption, which will likely contribute to curb emissions of GHG and pollutants.

Figure 5.5. Change in real consumption of oil in the two first policy scenarios relative to baseline scenario, 2016–30 (difference in annual average growth rate, percent)

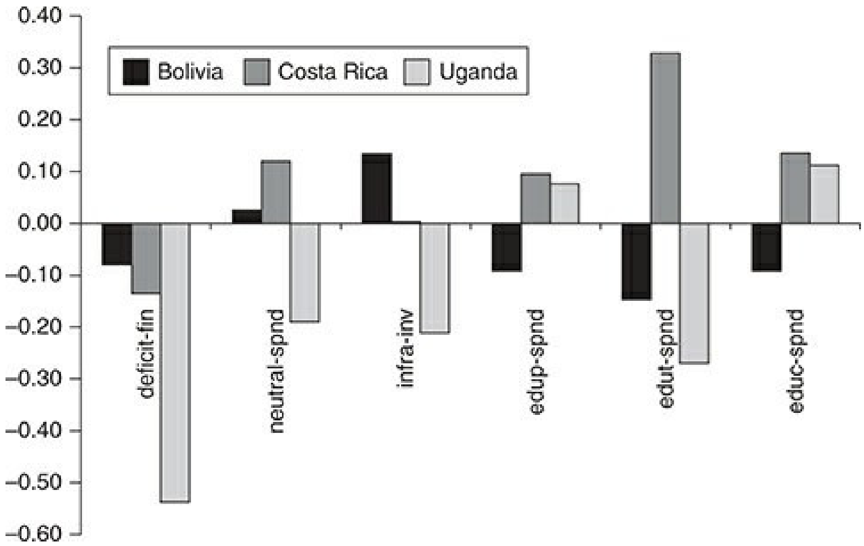


Note: The first two policy scenarios refer to allocating revenues to reduce the budget deficit (*deficit-fin*) or fully spend all new revenue across the board while preserving the expenditure structure of the baseline scenario (*neutral-spnd*).

Source: Authors, based on application of MAMS with data for Bolivia, Costa Rica, and Uganda.

While the simulated policy achieves the goal of discouraging the consumption of oil, it is also important to consider its economy-wide effects. When there is no accompanying hike in spending (as in scenario deficit-fin) the policy induces a fall in the growth rate of GDP in all three countries, well in conformity with the expected consequences of running an austere fiscal policy. The cuts are small for Bolivia and Costa Rica but large for Uganda, where they amount to half of a percentage point in the average growth rate of GDP (Figure 5.6). In contrast, the introduction of the tax in a neutral budget policy context results in an increase of the growth rate of GDP in Bolivia and Costa Rica, but not in Uganda. As noted above, the impact on oil consumption is largest in Uganda, and it is not fully offset by the increase in public spending across all sectors.

Figure 5.6. Changes in real GDP growth in selected policy scenarios with respect to the baseline scenario, 2016–30 (difference in annual average growth rate, percent)



Note: Policy scenarios refer to alternative ways of spending the newly raised fuel-tax revenue as follows: to reduce the budget deficit (*deficit-fin*); to proportionally increase public expenditure preserving the baseline structure (*neutral-spnd*); to step up public infrastructure (i.e. roads, bridges, and electricity networks) (*infra-inv*); and to proportionally expand current and capital expenditures in education proportionally across all levels (*educp-spnd*), only in the primary level (*educp-spnd*), or only in the tertiary level (*educt-spnd*).

Source: Authors, based on application of MAMS with data for Bolivia, Costa Rica, and Uganda.

The specific use of the newly raised revenue is a critical determinant of the impact on growth. One could initially expect that investing in infrastructure will have the strongest positive effects on GDP, on the presumption that building and improving roads, bridges, and electricity networks improve productivity and reduce businesses costs and consumer prices. Beyond this, it is difficult to say with some certainty which of the other spending scenarios will have the next strongest effect on growth. One could argue that spending on education should have a strong impact on growth. However, education spending tends to have a long lag before today's improvements in education enhance productivity in the future. Furthermore, the impact of increased investments in education depends on the capacity of countries to fully absorb the human capital they built over time.[24] In addition, the question of what level of education bears the highest payoffs (whether primary, secondary, or tertiary) is not easy to assess a priori; countries' contexts matter.

Results for Bolivia indicate that channeling resources for public infrastructure has the strongest positive impact on GDP growth (see Figure 5.6). The allocation of additional tax-revenues to a simple proportional expansion in spending across the board has the next strongest positive effect on GDP growth. Contrary to expectations, channeling resources to education, particularly to the tertiary level, actually depresses growth. This result suggests that the Bolivian economy is constrained to fully absorb an educated labor force, especially when all spending is channeled to higher education. Furthermore, skilled teachers and other qualified workers are in limited supply, hence demanding them more leads to increasing wages rather than an increase in employment. The resulting increase in labor income and subsequent private spending cannot fully offset the initial reduction of oil consumption, thus the contraction in economic growth.

In the case of Costa Rica, where completion rates in both primary and secondary education are already high for developing country standards, investing the oil-tax revenue on tertiary education (educt-spnd) has the strongest positive impact on GDP—compared with all other simulations. Spending in lower levels of education also results in gains on GDP growth. Contrary to expectations, the use of newly added taxes to fund infrastructure investments results in a negligible increase in the rate of growth of GDP. Infrastructure in Costa Rica is in better shape than in the other two countries, which means that additional investments will have, ceteris paribus, low returns. There are potential areas of infrastructure that require upgrading (e.g. roads, bridges, ports), but attending these would necessitate a much larger effort than that simulated here.

The use of the new oil-tax revenues for infrastructure building in Uganda does not fully conform to the expected result. Investing in infrastructure only partially offsets the initial negative effect of the tax on GDP growth. A similar result is obtained when spending is scaled up in tertiary education. There are explanations for these counterintuitive results. First of all, the infrastructure sector associated to construction in Uganda is weakly linked, forward and backward, with other sectors of the economy. Therefore, investing two extra percentage points of GDP in infrastructure does not boost capital accumulation in a significant way. In the case of Uganda, productivity and economic growth are more responsive to investments in other type of infrastructure, such as irrigation in agriculture.[25] In the case of investing in tertiary education, Uganda faces similar constraints to those discussed above for Bolivia. A limited supply of skilled teachers and other qualified workers and the limitations to fully absorb better-educated workers actually lead to unemployment. As a result, the initial reduction in private consumption affecting GDP growth cannot be offset. In comparison, spending on primary and secondary education in Uganda does not face such strong labor constraints. The expansion of public expenditures in primary education or in both primary and secondary education show a small but significant increase in GDP growth.

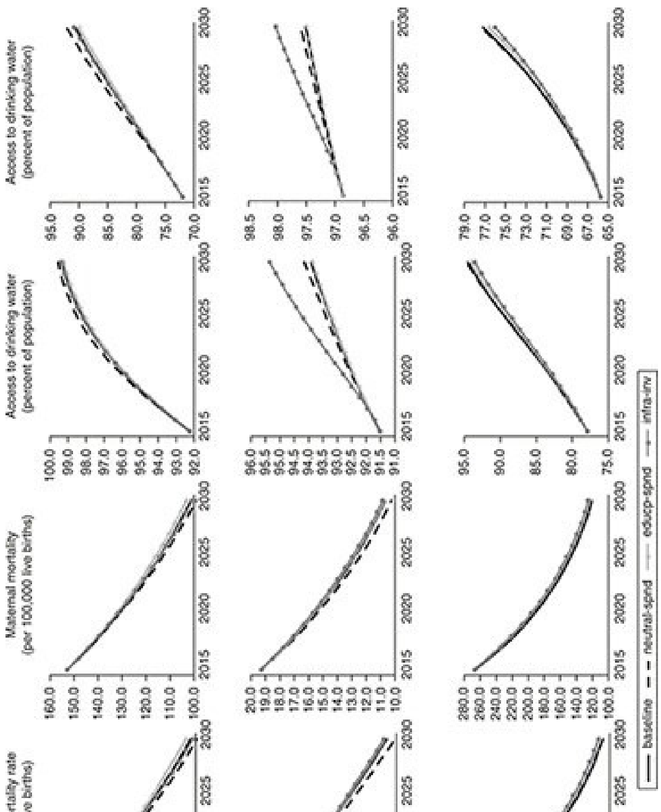
Impact on human development

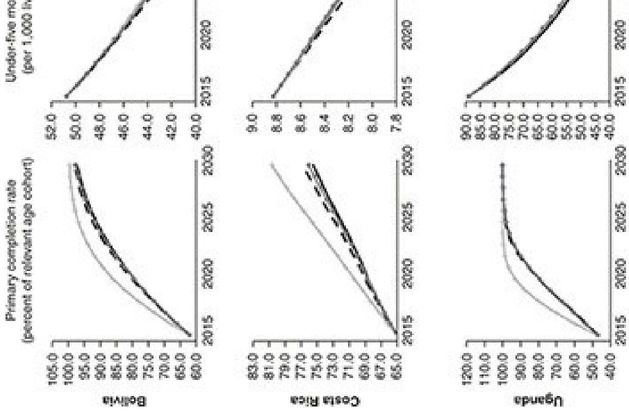
Assessing the impact of policies that raise public revenues to finance social sectors and/or infrastructure extends beyond macroeconomic variables. The modeling framework allows us to probe into the impact of policy options on a number of human development indicators. Improvements in these indicators depend on various factors, including the performance of the economy, household income, public spending in health and education, and the extension of public infrastructure.

Because in the first policy scenario of fiscal austerity the economy performs worst compared with the baseline situation, human development indicators show a modest deterioration (not shown here). On the contrary, using the newly generated tax revenue to spend in one or more public sectors offsets the potential adverse impact of the oil tax on human development. In the budget neutral scenario, the additional revenue (2% of GDP) is proportionally allocated across all government sectors. In this case, all human development indicators improve relative to the baseline in the three countries (Figure 5.7). Only in the case of Uganda do mortality rates not show a clear improvement because these indicators are less responsive to total expenditures in the presence of service inefficiency. The primary completion rate increases relative to all other scenarios in all three countries, in the scenario directing the newly added tax revenue fully to primary education—but also, to a lower extent, when resources are allocated to the education sector as a whole (not shown in Figure 5.7). Noneducation indicators essentially continue to perform as in the fiscal austerity scenario or improve somewhat.[26]

These results suggest that allocating newly added public revenues to social sectors can improve human development and can also accelerate growth, as in the case of Costa Rica, or can improve human development even if it causes some loss in economic growth, as in the cases of Bolivia and Uganda. Stepping up service delivery in education only does not fully offset the adverse effects of the oil tax on noneducation social indicators, even if the economy as a whole grows faster than before. The sectoral allocation of resources therefore determines the wins and losses of the tax policy.

Figure 5.7. Human development indicators in the baseline and selected policy scenarios, 2015–30





Source: Authors, based on application of MAMS with data for Bolivia, Costa Rica, and Uganda.

But there are also synergies to take advantage of, even if the newly generated revenue is not primarily spent in social sectors. In all cases, for instance, allocating the additional revenue to public infrastructure improves all social indicators, although only mildly in most cases—the exception is Costa Rica where the gains in the coverage of drinking water and sanitation is fairly large (Figure 5.7). This result is because improving public infrastructure (such as roads, bridges, and electricity networks) facilitates access to and functioning of education centers, clinics, hospitals, and so on. Human development indicators are then expected to show improvements, although these improvements can vary from country to country and from indicator to indicator. The response of human development indicators to stepping up of public infrastructure is in fact nil in some cases. For example, mortality rates in Costa Rica and Uganda and access to drinking water and basic sanitation in Uganda cannot match their baseline values. This calls for a careful evaluation of alternative policy options and the variety of impact they induce, when investing in infrastructure and the social sectors. Each particular context may generate very different results. On the whole, it is safe to say that human development indicators can be enhanced by an expansive yet responsible macroeconomic fiscal policy that increases investment in infrastructure or combines this intervention with additional social spending.

Trade-offs

In spite of the synergies described above the results of different spending scenarios suggests that win-win situations with simultaneous positive impacts in GDP growth and human development are difficult to find (see Figures 5.6 and 5.7). Decision makers often confront difficult trade-offs when defining policies and strategies for sustainable development.

Examples of such trade-offs, in our results include the following. Bolivia and Costa Rica find a win-win scenario in the policy of proportionally scaling up spending across all government sectors. In this case, GDP growth and human development indicators level off above their baseline levels. Bolivia also has a similar win-win situation if it allocates the oil tax to the expansion of public infrastructure. However, there is still a decision to be made between faster human development progress at the cost of slower economic growth (as in the balanced budget scenario) versus faster GDP growth and slower human development progress (as in the infrastructure scenario).

For Costa Rica, aside from the balanced budget expansion, all other scenarios involve trade-offs.[27] According to our results, if the government channels the oil tax revenue to primary education, primary completion rates and the pace of economic growth will improve but at the cost of slowing down progress in maternal mortality rates. If, instead, oil taxes are devoted to tertiary education, economic growth and net enrollment to higher education will accelerate, but primary completion and mortality rates will not gain much (not shown in Figure 5.7).

The exercise suggests that none of the scenarios simulated result in a win-win situation for Uganda. All the scenarios involve difficult trade-offs. For example, the decision to allocate oil taxes to expand the budget proportionally helps to improve all human development indicators but at the cost of a slowdown in economic growth. Similarly, the allocation of oil taxes to primary education improves GDP growth and primary completion, but it does so at the cost of slowing down progress in sanitation, drinking water, and mortality rates.

Conclusion

Sustainable development urgently needs policies and investments that can truly generate transformative change in all countries. This chapter reviewed estimates of the energy and human development investments required for sustainable development in an effort to highlight the interplay between policy choices and their impact on economic performance and human development. The realm of choices reviewed is wide, even if brief. The chapter looked at the effects of supply and demand energy policies on required energy investments for sustainability. It discussed the impact of policy choices on the type of fuels used in transport systems and the choice of technology, including the promotion of R&D and technology diffusion. It also looked at the economic and social inclusion effects of policies that step up public investment in all or in a few specific areas, including investment in infrastructure and education.

The analysis of the energy policy choices suggests that energy investments will need to increase significantly in many cases if we are to succeed in transforming the energy system along the needs of sustainable development. In a good number of potential sustainable paths, energy investments might need to increase by 1 percent of GDP, which nearly amounts to a 50 percent hike relative to current trends. But the evidence reviewed also suggests that the world can be spared such a strong effort. Sustainable paths featuring strong efficiency policies and appropriate technology portfolios demonstrate that sustainable energy is affordable, for additional energy investments will be in the order of tenths of 1 percent of GDP; moreover, some sustainable paths may even allow for "savings" in the form of reductions in investments in energy.

Results analyzed in the chapter reinforce the view that sustainable development necessitates a scaling-up of international cooperation to finance investment and facilitate the transfer of technology, particularly in low-income countries. Improving the capacity of countries to innovate and accelerate technology diffusion will be essential for the transition to clean energy. The evidence reviewed suggests that sustainable energy investments tend to be higher among low-income countries and lower in developed countries. It also suggests sustainable investments in low-income countries, notably in Sub-Saharan Africa, require easier access to technology and rapidly increasing investments in energy, especially in the area of energy efficiency.

The analysis focusing on the implementation of public policies in three developing countries (Bolivia, Costa Rica, and Uganda) supports the view that there is scope to scale-up public investment to accelerate sustainable development in its three key dimensions (economic, social, and environmental), but the effectiveness of these policies varies from one country to another. The analysis suggests that increasing public investment in the order of 2 percent of GDP do not pose serious macroeconomic problems, at least in the three countries analyzed. However, important trade-offs in the form of, for example, improving human development indicators (and reducing consumption of fossil fuels) at the cost of GDP growth or vice-versa, needs to be considered. Raising revenue to finance public investment is always a sensitive matter. The chapter looks at raising public revenue by imposing an implicit carbon tax, which is one form of revenue generation that has the added benefit of signaling a policy shift toward sustainable development by increasing the price of fossil fuels. The analysis of this revenue collection experiment in the three countries produces encouraging results, in the sense that this policy tool discourages fuel consumption without much disruption in the economy. The impact of the overall sustainable development policy intervention, however, will critically depend on the way increased tax revenues are allocated across sectors. From the analysis in this chapter, it is clear that there is no standard results; allocating revenues for a simple expansion of the budget as opposed to fully investing the additional resources in infrastructure or in education, results in changes in economic growth and other economic variables that are country specific. In some countries the strongest (positive or negative) impact on economic growth comes from the simple expansion of the budget, in others, it is explained by increased investments in infrastructure, or more spending in primary or in tertiary education. Specific country conditions will determine the final outcome. Moreover, the same public spending policies can generate varying effects on human development indicators such as primary completion rates, maternal and infant mortality rates, access to drinking water, and sanitation. It is important to note that only in a few cases, simulations rendered win-win situations, that is to say, cases in which economic growth, reduced consumption of fossil fuels, and human development improve in unison. In the majority of cases, choices have to be made between economic growth—that is less intensive in the use of fossil fuels—and performance in one or two human development indicators.

The overall message of the chapter is that a major transformation toward sustainable development is feasible but it poses two important challenges. First of all, investments in energy and human development will have to be scaled-up, and in contexts of some countries, the amount of resources needed to provide modern energy to people are significant. Second, in stepping up such efforts, policy makers will have to stay within a coherent policy framework that requires careful evaluation of the trade-offs and synergies that multiple policy pathways generate in concrete country contexts.

[1] The views expressed in this chapter are those of the authors and do not represent the views of the organization where they work.

[2] See, for example, IEA (2014a and 2014b), OECD (2011a, 2011b, 2012a, 2012b), United Nations (2009, 2011, 2013), UNDP (2011), UNEP (2010a, 2010b, 2011, 2012, 2013), and World Bank (2010, 2012a, 2012b).

[3] See World Economic Forum (2013), United Nations (2013), UNTT (2014), and Zepeda and Alarcon (2014).

[4] Such disparity in investment roughly corresponds to the large discrepancies in access to energy. In 2005, energy access ranged from above 200 GJ of final energy per capita in the North America region to little more than 20 GJ per capita in Sub-Saharan Africa. See http://www.globalenergyassessment.org/.

[5] See, for example, AR5, IPCC (2013).

[6] See Riahi et al. (2012, pp. 1214–16) and Riahi, McCollum, and Krey (2012, p. 15).

[7] Supply policies are those aiming to ensure that there is enough energy to satisfy the demand for final energy. Demand policies are those seeking to make a more efficient use of energy so that the same energy services can be met with a lower quantity of final energy.

[8] See Riahi, McCollum, and Krey (2012, p. 15).

[9] The simulations are carried using the IMAGE and MESSAGE models and assuming the same GDP and population projections than the counterfactual scenario (i.e. GDP grows at an annual average rate of 2 percent and population reaches a plateau of 9 billion people around the middle of the century). These simulations, as most climate change modeling exercises, do not take into account the effect of climate change on economic growth or energy investments.

[10] The number of sustainable paths by branching is as follows. Total: 41 out of 60. Efficiency: all 20. Supply: 6 and 2 for advanced and conventional transport, respectively. Mix: 7 and 5 for advanced and conventional transport, respectively. Note the special case of nuclear technology, whose phasing out is consistent with sustainability under all combinations of policy and transport mode. See Riahi et al. (2012a, pp. 1212–20).

[11] See IEA (2014a) for alternative estimates of energy investments in sustainable scenarios. See also OECD (2012a) and UNEP (2011).

[12] To simplify the discussion, we present the investment needed to bring the energy system toward sustainability as the difference between the total energy investment in sustainable paths and that of the counterfactual scenario.

[13] See Riahi et al. (2012, pp. 1269–67) and IEA (2014a) for more detailed discussion of energy in Africa.

[14] Between 2020 and 2050 efficiency investments represent on average about 25 percent of total energy investments. Demand side or efficiency investments range between 0.7 to 1 percent of GDP in efficiency paths and around 0.4 percent of GDP in supply paths. See GEA database in http://www.globalenergyassessment.org/.

[15] Efficiency investments will, of course, be higher in efficiency policy paths but, as has been noted, total investment will be lower under efficiency policies. Interestingly, however, the adoption of an advanced transport mode tends to reduce needed efficiency energy investments.

[16] See corresponding results in GEA database in http://www.globalenergyassessment.org/.

[17] The estimates of additional public spending are in most cases based on the assumption that countries target the MDGs as agreed internationally, with few exceptions of adaptation of these goals to countries' contexts. Accordingly, they do not necessarily represent the investment needed in a reasonably conceived local development program. Nevertheless, these MDG estimates adequately illustrate the significant investment effort that might be needed to pursue sustainable development.

[18] According to World Bank data for the most recent year available, tax revenues as a percentage of GDP represented 17.0 in 2007 in Bolivia, 13.6 in 2012 in Costa Rica, and 13.0 in 2012 in Uganda. These are the three developing countries on which the scenario analysis of this section focuses. See http://databank.worldbank.org/data/views/variableSelection/selectvariables.aspx?source=world-development-indicators.

[19] See, for example, Alton et al. (2012); Bjertnaes (2011); Bjertnaes and Fehn (2008); Blackman et al. (2010); Devarajan et al. (2011); Fuentes (2012); Gale et al. (2013); Gonzalez (2012); Griffiths et al. (2012); IMF (2013); Jaafar Al-Amin and Siwar (2008); OECD (2013); Parry et al. (2012); Ploeg, van der, and Withagen (2011), Kosonen and Nicodeme (2010); Kruptnick and Parry (2012); Loisael (2009); Resnick et al. (2012); Sumner et al. (2009); Yusuf and Ramayandi (2008); Wiwanwiwat and Asafu-Adjaye (2013).

[20] The model was applied using, for each country, a dataset primarily consisting of a social accounting matrix (SAM), which essentially provides the accounting framework of MAMS. In addition, the dataset also includes data related to the MDGs, the labor market, and a set of elasticities

defining behavior in production, trade, consumption, and human development indicator functions. As for the later, country-specific logistic models were estimated, econometrically, to identify the influence of supply and demand factors on various outcomes, including those related to education, health, and coverage of safe water and sanitation. The findings of these empirical analyses have been used to calibrate MAMS.

[21] According to the IEA http://www.iea.org/statistics/topics/energybalances/, in 2012 Bolivia's volume of oil products imported was less than the volume of crude oil produced in the country (in thousand tones of oil equivalent, ktoe). Moreover, the lion share of energy production is taken by natural gas. In Costa Rica, the total supply of energy relies on oil imports, however, the other half is generated using renewable sources (i.e. hydropower, geothermal, and biofuels). Yet Uganda relies heavily on imports of oil products to generate electricity and primary biomass energy.

[22] See references in note 18.

[23] The level of disaggregation required to distinguish between energy and nonenergy outlays within the infrastructure investment aggregate was not available at the time of elaborating this chapter.

[24] Sánchez and Cicowiez (2014) simulate a number of scenarios in which public social spending is scaled up to meet human development targets by 2015 but analyze its impact beyond 2015. The analysis is applied to four developing countries, including Bolivia, Costa Rica, and Uganda. The results show that GDP could experience an additional percentage point growth of 0.2–1.0 between 2016 and 2030, with important employment repercussions, owing to the delayed impact of human development investments. The other key finding is that such economic gains are not larger in magnitude precisely because the economy's structure does not adjust commensurately to absorb the increased stock of better-educated workers. The supply of the most highly skillful workers increases to a point where the economy is no longer capable to absorb it. Such demand side constraints are likely to push down the skill premium, thus providing a disincentive to invest in education with adverse repercussions for education goals.

[25] A scenario analysis similar to that presented here shows that investing two additional percentage points of GDP in Uganda's agriculture infrastructure, mostly in irrigation systems, would bring about productivity gains that significantly contribute to agricultural output without expanding land use, while enhancing food security and even spurring export capacity (see United Nations, 2013, Box IV.2).

[26] In other experimental scenarios, not shown in this chapter for simplicity, the newly collected tax revenues were fully allocated to the health sector. In this case, child and maternal mortality rates fell remarkably whereas the primary completion rate improved slightly in most of the cases, although in a few cases, it essentially remained at the baseline levels.

[27] But even here there might be a decision to be made between achieving small additional progress in all growth and human development indicators and focusing on accelerating the pace in one particular human development indicator.

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Chapter 6. Key Determinants of Technological Capabilities for a "Green Economy" in Emerging Economies[1]

Xiaolan Fu and Jun Hou

Introduction[2]

Building a global green economy will require a technology transition in both developed and developing countries. Technology transfer in developing and the least-developing countries is an important component of the global efforts to move toward the green development path. Among the developing countries, the emerging economies have quickly established significant technological capabilities in fields related to green development. The growth of production capacity and diffusion of green technology in emerging economies have been dramatic. For example, China and India in particular have become global leaders in some of the emergent green technology sectors such as solar photovoltaic (PV) panels, wind turbines, and electric and hybrid electric vehicle sectors.

This chapter analyzes the determinants of technological capabilities in emerging economies with a special focus on the development of green technologies in China and India and discusses the policy implications for other developing countries with respect to their technological capabilities for a green economy transformation. By using the examples of wind power, solar PV, and environmental innovation system of China, the discussion intends to: (1) uncover the respective contributions of indigenous research and development (R&D) and technology transfer to technical progress in the green sectors; (2) highlight the important role of government policy and regulation; (3) understand what kinds of R&D programs and public interventions promote more effective technology acquisition and adaptation under the circumstances of having limited resources. In addition, the comparison of emergent innovation systems in Brazil, India, and China (BIC) offers valuable lessons for other developing countries on how to build innovation systems and climb the green technology ladder for a green economy transformation.

The rest of the chapter is organized as follows. A short overview presents the most recent science and technology accomplishments in China. This is followed by an analysis of the key determinants of the development of technological capabilities. The role of public policies and institutions as well as private actors in the innovation systems are discussed. The chapter concludes with an outline of some policy implications for developing countries.

Environmental technological capabilities in emerging economies: The case of China

Over the past three decades, China has experienced tremendous growth in its economy and a continued increase in per capita income. As GDP has grown, so has private and public expenditure in R&D. When compared to peers such as India and Brazil, China has had the largest increase in R&D expenditure at an annual rate of 19 percent since 1995 and draws the largest number of youth toward research and science careers.[3] Meanwhile, foreign firms had established over 1,200 R&D centers in China by 2008 (Zhu, 2010). Although there is still a gap between China's technological capabilities when compared to Organisation for Economic Co-operation and Development (OECD) countries, China's science and technology (S&T) sector has produced many innovative accomplishments over 2006–11 period. In terms of key output indicators, R&D intensity has improved from 0.6 percent in 1995 to 1.84 percent in 2011.[4] From 1995 to 2011, there was 250 percent increase in the total number of personnel involved in R&D activities, a 213 percent increase in granted patents, and a 544 percent increase in high-technology exports.[5] There have also been considerable breakthroughs in various areas of science and technology research, including substantial achievements in renewable energy and environmental protection (Table 6.1). In terms of the development of green technology, there are several notable milestones during 2009–11.[6]

Table 6.1. Indicative example of China's S&T accomplishments, 2006–10

General Sector(s)	Name of Project	Milestones	Innovation Accolades
Energy/Nuclear/ Manufacturing	Sanmen 1 & 2 (Zhejiang) and Haiyang 1 & 2 (Shandong)	Rapid development and expected to start going online by 2014, three years earlier than original estimates	Technical advances in steel components manufacturing, including pipes, safety dome, and other large components. First deployment of Third Generation Technology
Energy/Offshore Oil and Gas Exploration	COSLPIONEER, a Deep Water Semi-submersible Drilling Platform (Shandong)	First deep water semisubmersible Drilling platform delivered by China's offshore industry	Development of advanced seismograph and a semi-submersible drilling platform with compliance to strictest world standards including compliance with zero discharge policies: solid debris are transferred onshore for disposal and various wastewater treatment systems ensure that sewage and rain are adequately treated before disposal at sea.*
			Installation of municipal wastewater treatment processes and energy-saving

Water Resources/ Environmental Protection	Water Pollution and Control	Contribution to meeting emission reduction targets for 2010	sludge dewatering equipment to reduce emissions from chemical and pharmaceutical industries. Progressively strict legislation and explicit pollution reduction targets since 1996 has spurred development of an innovative environmental protection industry.

*Note: *(CIMC 2010).*

- *Pollution mitigation:* development of highly efficient water purification devices and, as of July 2009, began building an Integrated Gasification Combined Cycle (IGCC) power plant including set up 250 MW IGCC plant in Tianjin in 2009 and 400 MW power plant in 2015–20.[7]
- *Renewable Energy:* substantial progress on several adjustable speed wind energy power plants including two 1.5 MW in early stages of production as well as a 2.5 MW and 3 MW in later stages of installation; notable progress in solar energy and battery technologies including twenty-one cities using solar for illumination; collaboration with Japan to develop small generators for wind powered irrigation in arid areas.
- *Electric Cars:* the establishment of a policy framework to accelerate electric-vehicle technology development including the Auto Industry Restructuring and Revitalization Plan (US$1.50 billion); e-vehicle technology development investment from the State Council (US$ 3 billion); and a series subsidy program for e-vehicle customers; thirteen cities using electric vehicles for public transportation in 2009. In 2010, the government plans to expand the use of energy-efficient vehicles in public transportation to twenty cities.
- *Buildings and Infrastructure:* using the world's most powerful solar power supplier (4.5 MW) to supply heating and cooling at Shanghai Expo pavilions and at various sports facilities in 2009. In May 2011, the National People's Congress (NPC) set 5 GW as an official minimum PV target for 2015, with a longer-term target of 20–30 GW by 2020.

There are also substantial ongoing resources to support these efforts including budgeted allocations for 2009–10, such as RMB 20 billion for the development of solar power plants; RMB 200 million for the public electric cars project in thirteen cities; RMB 2 billion to boost related parts for electric cars; and RMB 6 billion to support innovation in battery technology (MOST, 2010). As illustrated in Table 6.2, China's total investment in environmental pollution control grew 37 percent in 2012, accounting for 1.59 percent of GDP, slightly above the average of previous years. Concerning the industrial pollution control, the total expenditure reached a zenith RMB 55.2 billion in 2007[8] and fell to RMB 39.7 billion in 2010, then grew back to RMB 50.1 billion in 2012. From 2005 to 2012, the direct investment in "Urban Environment" increased 284.7 percent whereas investment in "Three simultaneous policies" increased 320.3 percent over the same period. This encouraging trend suggests that China's innovation policies are making headway in incorporating sustainable technologies and methods in the building of infrastructure to reduce levels of pollution emissions.

Table 6.2. Total investment in environmental pollution control (in billions of RMB)

	2005	2006	2007	2008	2009	2010	2011	2012	Changes in 2012 (%)
Industrial Pollution Control	45.8	48.4	55.2	54.3	44.3	39.7	44.4	50.1	12.6
Urban Environment	129.0	131.5	146.8	180.1	251.2	422.4	346.9	506.2	45.9

"Three Simultaneous Policies"	64.0	76.7	136.7	214.7	157.0	203.3	211.2	269.0	27.4
Total	238.8	256.6	338.8	449.0	452.5	665.4	602.6	825.4	37
Percent of GDP	1.31	1.23	1.36	1.49	1.33	1.66	1.27	1.59	

Source: China Statistic Yearbook 2012 (National Bureau of Statistics 2012, http://www.stats.gov.cn/).

With regards to renewable technologies, the production capacity has grown rapidly in the last ten years. For example, in the wind power sector, China moved from ninth in the world of top wind markets in 1999 to the second largest market in 2009, having three of the global top ten producers in this sector (BTM, 2011). In 2010, China became the largest wind energy provider worldwide, with the installed wind power capacity reaching 41.8 GW at the end of 2010. In the solar PV industry, China's global share increased from less than 1 percent in 2003 to the world's largest producer in 2008 (Climate Group, 2009). As Table 6.3 shows, the capacities for Solar PV and wind power have increased dramatically in the past years. Moreover, China has set an ambitious national goal for 2020 (Table 6.4). Put in context, these targets translate to renewable energy generation by 2020 that is three times its 2006 level and an increase in renewable energy as a percentage of all power generation to 21 percent from a 2005 level of 16 percent. Finally, these forecasts envisage that solar powered water heaters will be installed in one-third of all households by 2020.

Table 6.3. Capacities of PV power and wind power in China, 2005–12 (Units in MW)

Year	2005	2006	2007	2008	2009	2010	2011	2012
PV power in China*	70	80	100	140	300	800	3,300	8,300
Wind power in the PRC**	1,260	2,599	5,912	12,200	16,000	31,100	62,700	75,000

* Source: Xu et al. (2011).

** Source: US Energy Information Administration: http://www.eia.gov.

Table 6.4. Renewable technology targets for 2020

Type of Power Generation	2006 Actual	2010 Estimates	2020 Target
Total Water (GW)	130	180	300
Small Scale Water (GW)	47	60	85
Wind (GW)	2.6	5	30
Biomass (GW)	2	5.5	30
Feed-in Solar (GW)	0.08	0.3	2
Solar Powered Water Heaters (m2)	100	150	300
Ethanol for Fuel (million tons)	1	2	10
Biodiesel (million tons)	0.05	0.2	2
Biomass Pellets (million tons)	0	1	50
Gas from Biomass (million tons)	8	19	44

Source: Martinot and Li (2007).

Technology transfer, indigenous R&D, and technical progress

Technology transfer, indigenous R&D, and technical progress in emerging economies

Innovation is costly, risky, and path-dependent. This may provide a rationale for poor countries to rely on foreign technology acquisition for technological development. In fact, most innovation activities are largely concentrated in a few developed countries. Expenditures for R&D are US$453.5 billion in the United States, US$151.7 billion in Japan, and US$102.3 billion in Germany [9]. Although the total R&D expenditure in China reached US$293.5 billion in 2012, the R&D expenditure as percentage of GDP (1.98) is still far below that of developed countries (2.13% of GDP for fifteen OECD countries).[10] International technology diffusion is therefore an important driver of global economic growth. If foreign technologies are easy to diffuse and adopt, a technologically backward country can catch up rapidly through learning and acquisition (Grossman and Helpman, 1994; Romer, 1994; Eaton and Kortum, 1995).

Technology can be diffused between firms and across regions and countries through various transmission mechanisms. While some knowledge transfer occurs intentionally, a large proportion of knowledge spillovers take place as unintended knowledge leakage. In recent years the mode of innovation is becoming more and more open and is making good use of external resources. International knowledge diffusion can therefore benefit countries and firms at every stage of the innovation process (Fu et al., 2011).

Foreign direct investment (FDI) and technology transfer

As a bundle of technological, managerial knowledge and financial capital, inward FDI has been regarded as a major vehicle for the transfer of advanced foreign technology to developing countries (Dunning, 1994; Lall, 2003). Multinational enterprises (MNEs) are regarded as the major driver of R&D in the world (Markusen, 2002). It is expected that in the medium to long run, domestic firms in the recipient country will benefit from MNEs spillovers and linkages. Spillovers can be horizontal technology spillovers (Caves, 1974; Fosfuri et al., 2001), vertical technology spillovers (Javorcik, 2004; Pietrobelli and Rabellotti, 2007),[11] and the induced competition effect is also expected to force local firms to become innovative. However, despite the potential benefits of FDI spillovers, these may also have significantly negative effects on technological upgrading in the domestic firms. FDI may not only crowd domestic firms out from the market (Aitken and Harrison, 1999; Hu and Jefferson, 2002), the induced competition effect may also discourage local firms' R&D efforts (OECD, 2002). Moreover, foreign subsidiaries may remain as enclaves in a developing country with a lack of effective linkages with the local economy. As a result, the net impact of inward FDI on the productivity and innovation capabilities of indigenous firms is mixed.

Among the BIC countries, China is the largest recipient of inward FDI. It is also the largest destination of inward FDI among all developing countries and received nearly US$111.7 billion in 2012.[12] China has also introduced a set of policies, such as local content and joint venture requirements to enhance the linkages and knowledge transfer from foreign to indigenous firms. Over certain time periods, FDI in China had to meet specific joint venture conditions; until 2010 in the automobile industry, for example, foreign investors could not have more than 50 percent of the total share of capital. China and Brazil both have negotiated export and local content requirements on FDI in certain industries such as the automobile industry so as to create linkages between foreign and local firms. They have also imposed training requirements on FDI in some cases. Empirically, Buckley et al. (2002; 2006) find a positive association between FDI and productivity of domestic firms at the industry level. However, using a large firm level panel data set from China, Fu and Gong (2011) find depressive effects of foreign R&D labs on local firms in China. This is consistent with the findings of Hu and Jefferson (2002) in the electronic and apparel industries in China. This is also consistent with recent firm-level evidence from India (Sasidharan and Kathuria, 2008).

Imports and technology transfer

Imports of machinery and equipment are another important channel for foreign technology acquisition. Cross-country studies on bilateral imports data suggest imports as an important channel for countries to acquire advanced technology and enhance competitiveness (Fagerberg, 1994; Coe and Helpman, 1995). Note, however, that technology transferred through imports of machinery and equipment is embedded in this machinery. Products that are produced by using these imported machines will probably be of higher quality, but this does not mean that developing countries thus necessarily master the technology of designing and producing those advanced machines. Substantial technological learning and reverse engineering are required to grasp the embedded technologies. Acharya and Keller (2007) empirically showed that the global patterns of technology transfer are highly asymmetric. The cause of the divergence attributes to the differences in absorptive capacity, such as domestic R&D investments or levels of education. In the case of the high-technology industries of China, Li (2009) found that investing in foreign technology alone does not enhance innovation in domestic firms, unless it is coupled with an industry's own in-house R&D effort.

Outward FDI and technology transfer

Although the leading role of outward FDI is still taken by the developed countries, developing countries, especially the emerging economies, have become an important player in the last two decades. Between 1980 and 2011, the share of outward FDI from developing countries rose from 6.2 percent to 26.9 percent and peaked in 2010 at 31.8 percent (UNCTAD, 2012). Firms carry out outward FDI for several reasons including seeking market, finding resource, improving efficiency, and securing of strategic assets. For MNEs from the emerging economies, one of the major motivations to invest in developed economies is for knowledge sourcing through the setting up of R&D labs, establishing joint ventures with foreign firms, research institutions and universities, and green fielding new production facilities with R&D function. There is also a motivation for merging and acquisitions of local firms and institutions who own the needed technology know-how or the research manpower. This type of asset-exploration FDI has become a major type of cross-border investment from emerging economies (Dunning et al., 2007). To the extent that this mode of innovation becomes increasingly open, active knowledge sourcing through outward FDI will serve as an effective mechanism to enhance the innovation capabilities of firms in emerging economies.

Indigenous innovations and catching-up

However, the diffusion and adoption of technology is costly and is not automatic. It requires certain pre-conditions and is sometimes difficult. Technology producers have an interest in transferring equipment through trade, but they may be reluctant or unwilling to share the underlying capabilities because these capabilities are the core competences that are central to their own competitiveness (Mallett et al., 2009). Moreover, technology diffusion is difficult to complete due to the tacit nature of many technologies. Therefore, indigenous innovation is a necessary element for the effective adaptation of transferred foreign technology during the catching-up phase of development.[13]

Another important role of indigenous innovation capacities is the other side of its dual function: a major source of absorptive capacity, the ability of an organization to identify, assimilate and exploit knowledge from its surrounding environment (Cohen and Levinthal, 1989). The level of absorptive capacity in a firm is a crucial condition that affects the actual benefits from any technology transfer. Technology transfer can take place at different degrees depending on the costs and variations in local firms' capacities to adopt new technology. An important component of absorptive capacity is the R&D activity carried out by local firms, which play the dual role of creating knowledge and promoting learning and absorptive capacity (Aghion and Howitt, 1998; Griffith et al., 2004). Li (2009) and Fu (2008) both support this hypothesis based on experiences from China. Foreign technology will generate a positive effect on local firms' technological upgrading only insofar as sufficient indigenous R&D activities and human capital are present.

International technology transfer and indigenous innovation in fact reinforce each other. Effective technological capabilities building in developing countries should make use of both the indigenous innovation efforts and foreign technology transfer, although the relative importance of each driver varies according to the different stages of industrialization and development in the concerned developing country (Fu et al., 2011; Fu and Gong, 2011). Such a strategy is also suitable to support technical progress in the green sectors. An outstanding question in this discussion is whether foreign technologies created in the developed countries are appropriate for the developing countries' context. Foreign technology may be inappropriate to the local socio-economic and technical conditions of countries since technological change is a "localized learning-by-doing" process (Atkinson and Stiglitz, 1969). All this points to the importance of indigenous innovation efforts to support technology upgrading, and catching-up in particular. Because of the innovator's incentive to maximize innovation returns, technical change will be biased to make optimal use of the conditions and factor for suppliers in the country where the technology is developed (Acemoglu, 2002). Using empirical evidence from a recent Chinese manufacturing firm-level panel dataset for 2001–5, Fu and Gong (2011) find that FDI has indeed served as a vehicle to disseminate advanced foreign technology from global reservoirs of knowledge. However, R&D activities of foreign firms appear to exert a significantly negative effect on local firms' technical change. Instead, it is collective indigenous innovation that contributes to the dynamic technological capabilities of local firms and pushes forward the technological frontier.

Technology transfer, indigenous R&D, and

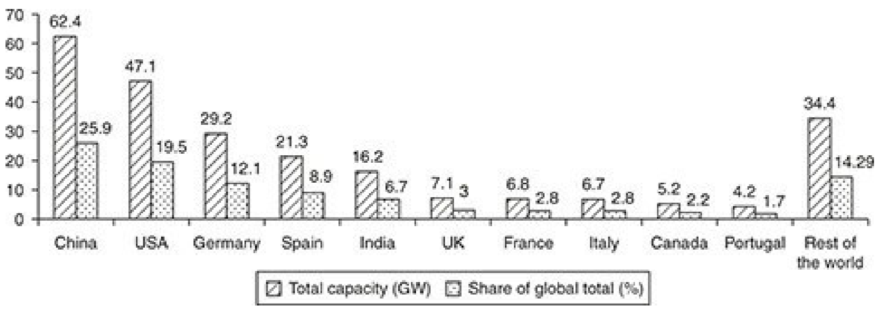
technical progress for a green economy

There is general consensus that development of the green economy in emerging countries requires strengthening of sustainability innovation capacities in order to accelerate the catching-up phase. Apart from reducing the domestic environmental pressures brought by fast economic growth, one incentive driving emerging economies toward a green development path is the fact that environmental technology advancement helps to improve their infrastructure and economic modernization (Walz, 2009). Another important incentive driving emerging economies into the development of green technology is the gain from first mover advantage; emerging countries are competing with developed countries for leading roles in supplying the international market for green technologies. While technology transfer remains a key driver in the technical progress for a green economy and has been a crucial part of the global solution for reducing greenhouse gas emission under the United Nations Framework Convention on Climate Change (UNFCCC) framework, the diffusion and adoption of technology is costly and requires certain preconditions; enhancing indigenous innovation capability is very central to accelerate the catching-up phase among emerging countries (Bell, 1990; Lema and Lema, 2010).

Technology transfer and indigenous innovation in the wind power sector in China

In the wind power sector, China has made substantial advancement, moved from a country with about 97 percent of wind turbines imported in the late 1990s to nearly 100 percent of turbines domestically produced in 2010 (CWEA, 2010). In 2011, China became the largest wind power provider worldwide, with the installed wind power capacity reaching 62.4 GW as shown in Figure 6.1. The market is set for continued high-growth, aiming to reach a combined 100 GW in 2020 (Schwartz, 2009). By the end of 2008, more than fifteen Chinese companies were commercially producing wind power turbines and components. Three Chinese companies have become global top-ten leading players in this sector, including Sinovel, Glowind, and Dongfang (BTM, 2011).

Figure 6.1. Top ten countries by total installed wind capacity (2011)



Source: BTM Consult, 2011.

The rise of the Chinese wind power sector demonstrated a classic example of a dynamic technology development model that combined indigenous innovation and foreign technology transfer. Conventional technology transfer channels, including FDI, licensing, and joint ventures, were critical to the rise of China as a leader in the wind power industry in the early years of the industry's formation. Once basic production capacity was gained, indigenous R&D based knowledge creation and acquisition activities have become more important in the catching-up phase, including in-house R&D, international R&D collaboration, and cross border acquisitions of technology and plants. The top three Chinese wind turbine producers all started from licensing arrangement from German companies and later moved to R&D collaboration with their foreign partners (Lema and Lema, 2010). Moreover, all these major companies have undertaken substantial in-house R&D with the support of government R&D grants (Tan, 2010).

Particularly noteworthy is to note that China required 70 percent local content to FDI in the green sector. This regulation provided two options for foreign manufactures: (1) establish a China-based manufacturing facility or (2) partner with a Chinese firm (Lewis, 2007). China's local content requirements and joint venture conditions for FDI flows were critical to accelerate the formation of this sector. Similarly in Brazil, local content requirements created linkages and spillovers between foreign and local firms (Fu, 2008). In contrast to Chinese regulation, India's trade policy strategy for competence building in wind turbine manufacturing was slightly different. Technological transfer was supported by a combination of a national certification program and customs duties that favored imports of components over complete wind turbine machines (Lewis, 2007).

The India domestic wind power industry started its fast growth from the mid-1990s and has significantly increased in the last few years; by early 2011, the installed capacity of wind power in India reached 16.3 GW (see Table 6.5). Similar to the Chinese technological development model, production capacities also started from joint ventures with large foreign producer in the industry such as Germany's Enercon and Denmark's Vestas and some wholly foreign-owned subsidiaries of other leading international producers (Mizuno, 2007). The major driver of growth in the Indian wind power industry was the development of indigenous capabilities through a supportive innovation system and interactive learning with international industrial and research leaders, the Danish firms and research institutions in particular (Kristinsson and Rao, 2008). The largest Indian company in the industry, Suzlon, has adopted a more active internationalization process; by investing directly in other countries this firm has built its technological capability through outsourcing substantial R&D in Germany, Belgium, and the Netherlands, and through the acquisition of manufacturing facilities in the United States, Europe, and China (Lewis, 2007).

Table 6.5. Major Chinese solar PV enterprises and their industry chain products

Enterprises	Silicon	Ingots	Wafers	Photovoltaic	Cells	Solar
Yingli Solar	PL	PL	PL	PL	MP	
Suntech Power				OP	MP	OP
Trina Solar		PL	PL	PL	MP	
LDK Solar	PL	PL	MP	PL		
Jingko Solar	PL	PL	OP	OP		
GLC Poly	MP	PL		PL		

Source: Li and Wang (2011); UNEP (2013).

The development experiences of the wind power industry in China and India shares some common characteristics, but they also differ in the relative weight they have given to various knowledge creation mechanisms, the relative importance of indigenous and foreign innovation efforts. Both China and India started off from joint ventures with foreign investors, but they also emphasized indigenous technological capabilities building. Yet the mode of knowledge acquisition of the leading Chinese and India companies in the wind power sector is somewhat different. The former mainly relied on a government supported China-based strategy, including inward FDI. For example, Goldwind has benefited from China's National Innovation System (NIS) policies of attracting international players to invest in China to such an extent that it is creating an international wind power innovation hub in the country. India has used more actively outward FDI through cross-border mergers and acquisitions and has built up transnational innovation networks to boost its competitive advantage. An example of this is Suzlon, a company that not only relied on indigenous technology development but also imported foreign technologies. In summary, efforts to use different combinations of indigenous and foreign innovation efforts have significantly contributed to technology catching-up in India and China, especially successful in green economy sectors such as solar panels and wind turbine production. These two countries have made interesting breakthroughs from mere use of knowledge to knowledge creation in a way that they have begun to rival OECD countries (Lema and Lema, 2010).

Technology transfer and indigenous innovation in the solar photovoltaics (PV) industry

Since 2006, China has witnessed remarkable investment in solar PV manufacturing. In 2003, China accounted for less than 1 percent of global solar PV production. In 2011, production of solar PV in China accounted for 48.5 percent of the total world production, and it has been the world's largest manufacturer for four consecutive years from 2008 to 2011 (UNEP, 2013). By 2009, there were already more than 500 solar PV firms and R&D labs in China with world frontier technology (Climate Group, 2009), and the total exports from these Chinese firms reached US$35.8 billion in 2011 (Scotney et al., 2012). Suntech, Yingli, and Trina Solar are ranked among the global top-ten companies in the industry (Lema and Lema, 2010).

The development model of the solar PV industry in China is different from that of the wind power industry. Although there is some licensing of foreign technology in the solar industry, a strong emphasis has been put on indigenous R&D. Given the large potential profits in the exports market and with strong supports from the government, the major solar firms are R&D intensive. The government "Golden Sun" demonstration program[14] offered the initial support for the development of domestic solar capacity. The Chinese authorities further offered incentives such as tax breaks and better intellectual property regulation to encourage an increase in R&D investment (UNEP 2013). As a result, the industry has not only invested greatly in R&D but it has also invested in the development of production lines along the value chain (See Table 6.5). The major firms in the industry, such as Suntech, have collaborated closely with research institutions in China and abroad and have developed their own core technology. China has now become a global leading location in solar PV research and production; it has attracted major MNEs to set up R&D labs or joint R&D labs in China (Lema and Lema, 2010). The model of technological capabilities building in the Chinese solar PV industry is a more advanced indigenous R&D-led model with close links between industry-university and research institutions and with increasing international R&D collaboration in China.

In the case of India the development of the solar PV sector is a mix of three major approaches that shaped the current level of the technology and production capacity of the Indian solar PV sector; these include patent licensing, joint venture and acquisition, and in-house R&D (Mallett et al., 2009). One factor that both China and India have in common is the fact that the export market has been the major driver of this sector. About 98 percent of China's PV cells export to the international markets in late 2000s, and about 75 percent of India's PV cell output sought the export market (Howell et al., 2010; Lema and Lema, 2010).

National innovation system and technology acquisition, adaptation, and development

Technology-push and demand-pull effects play critical roles in driving technological innovation.[15] The technologies for environmental sustainability differ from conventional ones in view of the failure of market demand-pull incentives. The formation of demand thence depends strongly on two factors: (i) policy coordination between different government bodies in charge of environmental, economic, and industrial policies and (ii) an incentive-driven innovation system. The framework of NIS is based on the perspective that a nation's propensity to acquire, adapt, and develop new technologies can be best explained by the different components of its innovation system and the interactive linkages among those components (Balzat and Hanusch, 2004). This occurs within a heterogeneous and multidisciplinary domestic backdrop and includes market driven public and private firms, all levels of government agencies, research and training institutions, and financial intermediaries.

The role of R&D programs and complementary innovation policies in China

As a clear departure from two earlier S&T plans, the "National Medium- and Long-Term Strategic Plan for Development of Science and Technology" adopted in 2006 emphasized the objective of promoting indigenous innovation for the creation of an "innovation-orientated" society by the year 2020. Objectives for 2020 include: (1) increase R&D intensity to 2.5 percent from 1.42 percent in 2006;[16] (2) innovate to contribute 60 percent of economic growth; (3) rely of foreign technology to be reduced to 30 percent; and (4) attain top five international ranking for all key innovation output indicators (Hutschenreiter and Zhang, 2007).[17] The Chinese government has also introduced various policy instruments to ensure that these objectives will be reached. Table 6.6 summarized a selection of them.

Table 6.6. Summary of national medium- and long-term strategic plan for S&T

	Policy Heading	Details and Examples
(1)	Increasing science and technology investments	Explicitly, to exceed that of the ordinary fiscal revenue during Tenth Five Year Plan
(2)	Targeted tax incentives	Including a 100% offset in taxable income for innovation investments by private firms. Tax reductions and holidays for incubators, science parks, and green economy-related enterprises.
(3)	Increasing R&D financial support through banks, insurance companies and other intermediaries	Including tax relief for high-tech venture capital. Creation of noncommercial "policy banks" in addition to state-owned and private banks to invest in promising R&D
(4)	Government technology procurement	Such as requiring over 60% of domestic content

(5)	Increasing public funding to support the adoption of imported technology	Such as improving technology transfer links between foreign procurement and local industries
(6)	Strengthening intellectual property rights	Such as shortening patent review periods and improving information services
(7)	Human resources development	Including encouraging talent to return from overseas
(8)	Investing in education and science	Including promoting careers in science and providing grants and tax incentives to intermediaries that promote awareness and dissemination of scientific knowledge
(9)	Investing in public research institutions and improving national standards	Including a new evaluation system to ensure efficient public resource use allocations (public research institutions) and aligning Chinese technology standards with international standards
(10)	Strengthening coordination	In particular between civil and military research and procurement

Source: Summarized from publications in various government website, including the National Long-Term Science and Technology Development Plan 2006–20 (MOST), the National Taxation Bureau, and People's Bank of China.

Many of these initiatives reinforce elements of previous strategic plans and government policies. However, with regards to the tax regime and government fiscal expenditure, there are some new polices worth noting: (1) policy to encourage accelerated depreciation of capital expenditure for R&D; (2) policy to import duty exemptions for R&D related materials; and (3) specific government technology procurement policy to support innovation. This last policy was inspired by the success of similar government procurement policies and objectives that were successfully implemented in OECD countries, notably Korea and the United States. (Hutschenreiter and Zhang, 2007).

University-industry linkages: The special role of universities in China

As an important player in national and regional innovation systems, universities have received increasing attention with respect to their role in strengthening the innovation, competitiveness, and wider social and economic development. In terms of R&D expenditure and patents for inventions, universities and research institutes are playing a leading role in China (Li, 2009). Reforms started in 1985 with the objective of rendering the science and innovation system more relevant to the market, in an important departure from the Soviet model where scientific research at public research institutions is completely separated from the production process in state-owned enterprises (Xue, 1997).

The mid-1980s witnessed several reforms in science policy in China. The most significant change was the cutting of government research funding in order to push research organizations into the market (Hong, 2008). The Chinese government has been advocating a use-driven science policy encouraging universities to serve the national economy by solving practical problems for industry (Hong, 2006). On the one hand, university-industry linkages in China are built through licensing, consulting, joint, or contract R&D and technology services, closely resembling how universities in the West interact with industry. On the other hand, a second form of use-driven innovation occurs as a result of university-affiliated or university-run enterprises (Zhang, 2003; Ma, 2004; Eun et al., 2006). Government-driven spin-off formation has proved an appropriate solution for technology transfer at Chinese universities (Kroll and Liefner, 2008).[18] Based on a recent firm-level national innovation survey, Fu and Li (2010) found that domestic universities have played a significant role in the diffusion of frontier technology and the creation of new country- or firm-level innovation outcomes in China. Still the creation of ground-breaking innovations is limited.

Environmental innovation system in emerging economies: The case of China

Analysis using the NIS framework is context specific; the effects of individual actors depend on the system's conditions such as the regulatory framework, which ultimately influences market demand and underlying technological push and pull dynamics (Walz, 2009). As such, government policies can guide the evolution of a country's NIS in a direction that helps to build competencies among domestic industries. In particular, as this paper will argue, environmental regulation is a key driver of domestic demand for sustainable technologies in water, energy, and transportation. When coupled with funding and favorable regulatory regimes, there are real possibilities for developing countries to develop indigenous technological expertise and take alternative paths toward "leapfrogging" into an internationally competitive green economy.

It has been generally acknowledged that environmental preservation and innovation in energy conservation are intertwined with regards to government policy and in relation to the impact that government policy will have on private domestic enterprises. Successfully moving closer to an energy-efficient and low-carbon society will require high-level policy decisions to direct investments to the grassroots level and to motivate and nourish the growth of indigenous small- and medium-sized enterprises (SMEs). Policy instruments that support this goal will have to harness incentives through the tax system, as well as public and private financial support with the overall objective of improving environmental protection and reducing energy consumption. In particular, government policies should give priority to the promotion of a "Resource Saving and Environmentally Friendly Society," using government procurement to strengthen green economy industries and supporting enterprises that reduce emissions through favorable tax policies.

While environmental protection regulations in China were introduced in the 1970s, effective government policies on pollution control actually began during the Ninth Five Year Plan (1996–2001) and continue through the Tenth and Eleventh Five Year Plans when the state formulated new laws and revised old ones (Xinhua, 2006b). During this time, the central government established explicit goals and a framework of environmental protection standards that has evolved into a system where governments, at all levels, are responsible for environmental protection within their jurisdiction (Xinhua, 2006a). As China's energy consumption had doubled within the last ten years and stood second highest in the world in 2006 (Martinot and Li, 2007), the Eleventh Five Year Plan heightened concern with the environmental costs of China's development model. The Eleventh Plan aimed to stimulate a balanced economic growth model with several targets related to the reduction in energy consumption (by 20% during 2006–10) and water consumption per unit of industrial added value. Achieving green development requires long-term policy continuity. On March 14, 2011, China officially adopted its Twelfth Five Year Plan, which includes a robust ambition to make the transition toward a more sustainable development model. The Twelfth Plan is the first plan formulated around the theme of green development. This five-year blueprint set up the development path from 2011 to 2015, and its green targets are shaping the country's environment innovation system with respect to energy and pollution reductions and the conservation of water and forestry. Yet China's NIS approach to the development of environmental technologies is strong in cleaning up the emission of pollutants but relatively weak in creating and deploying clean technology to reduce the root cause of emissions (Strangway, et al., 2009).

An important feature of the Chinese innovation system, including environmental innovation, is the collaboration and level of coordination that exists between the relevant regulatory regimes and the innovation policies that guide innovation for environmental sustainability. In addition to the Ministry of Environmental Protection, there are many other government bodies responsible for environmental innovation in China. These include, among others, the National Development of Reform and Committee (NDRC) and the Ministry of Science and Technology (MOST). These governmental bodies often issue joint policies and regulations (or separate but cohesive policies), which provide regulations and financial incentives to firms, as well as technology information and assistance. Although the coordination of the policies issued by different departments can be improved, they have mainly been coherent as they all served a common objective. Table 6.7 gives some selective government programs that involved different regulatory regimes.

Table 6.7. Selective government S&T programs for green innovation and authorities involved

Policies	Launched Year	Environmental-related contents	Authorities
"Golden Sun" program	2009	Promote renewable energy generation and create a domestic market for its solar cell and panel manufacturers	Ministry of Finance, MOST, and NDRC
"Ten Cities Thousand Cars" program	2009	Stimulate electric vehicle development through large-scale pilots in ten cities that would identify and address technology and safety issues associated with electric vehicles.	MOST, Ministry of Finance, NDRC, Ministry of Industry and Information Technology
Basic Research Program (also known as "973	1997	Includes environmental technologies in renewable energy, ecology of rural areas, and wastewater treatment	Central Government and MOST,

Program")			
"Huo Ju" (torch) program	1988	New material, new energy and environmental protection technologies account for 9.4%, 3.1%, and 9.4% of total projects, respectively	Central Government and MOST
"Xing Huo" program	1985	Research on environmental protection and resources exploitation account for 12.5% of the total of 454 projects	Central Government and MOST
State High-Tech Development Plan (863)	1986	9% for research on new energy and 6.4% focus on resource and environment research, accounting for 5% and 9.4% of total R&D expenditure	Central Government and MOST

Source: Various reports from Ministry of Finance (http://www.mof.gov.cn/), MOST (http://www.most.gov.cn/), NDRC (http://www.sdpc.gov.cn/), and Ministry of Industry and Information Technology (http://www.miit.gov.cn/).

In the national innovation system of China, the universities and government research institutions are the major creators of knowledge in the environmental science and technology system. Universities are widely regarded in their role in advancing basic scientific research and innovation of great novelty. Transiting from a centrally planned to a market economy, universities in China have historically played an important role in the national innovation system, similar to the case of the science and technology system in the former Soviet Union (Liu and White, 2001). However, the industry-academic joint research is not strong as yet, despite the substantial push from the government to foster greater research-industry linkages. On the one hand, the marketization of the S&T sector has led to the transformation of many applied research institutes into private companies, leaving a gap in the transformation from basic scientific research outputs into applied technologies—a transition badly needed for the development of industries (Strangway, Liu, and Feng, 2009). On the other hand, looking at the several successful large national champions in the green energy sector, many of them have research collaboration with domestic and international universities and research institutions. Global industry-academic linkage has also played a role in assisting Chinese firms move to the global technology frontier. For example, the latest knowledge on photovoltaic was learned from an Australian university. Leading companies such as Suntech in China also have international collaboration with foreign universities.

Turning to its green technology sector, Chinese private firms are the major force in the innovation system; they are undertaking R&D and transforming scientific inventions into production technologies, including their commercialization in the market. Most of the national champions in this sector are large private firms. Foreign firms have also been active players in the national innovation system through knowledge transfer, knowledge creation in China and through induced competition effects. Many MNEs from developed countries have good environmental consciousness driven by strict environmental standards at home. They tend to use relatively cleaner technology than domestic firms in developing countries even in heavy polluting industries. Accordingly, the possibility of clean technology being transferred from foreign to domestic firms emerges. This is especially the case in joint ventures in wind power and clean electric vehicles industries. Nonetheless, other MNEs are looking for institutional voids and are likely to locate in the so-called pollution heaven. Zhang and Fu (2008) found that due to the lower pollution standards and lack of enforcement, China has selectively attracted heavily polluting industries as foreign firms operating in such industries prefer to locate in regions with relatively weak environmental regulations. Therefore, the role of FDI in the national environmental innovation system is mixed. Realizing this problem, the Chinese government has recently modified its FDI policy by placing new restrictions on energy-consuming and environmental-polluting industries.

IPR protection and transfer of green technology

Compared to the developed world, developing countries are less able to adjust to the effects of climate change due to the lack of resources and technological means for mitigation. The UNFCCC[19] is a multilateral framework that facilitates the negotiation and transfer of information and technology to mitigate the effects of climate change through incentive mechanisms such as the Clean Development Mechanism (CDM) and Global Environmental Facility (GEF). This forum encourages conventional technology transfer across borders in order to deal with climate change (Lema and Lema, 2010).

With respect to formal technology transfer (e.g. licensing), the strength of the IP regime in technology recipient countries is a positive determinant of exports of high-technology goods from developed economies. More recently there is empirical evidence to argue that there is a positive association between high-technology FDI flows and the level of national legal protection of patent rights (Branstetter et al., 2006; Hall and Helmers, 2010). However, Maskus and Okediji (2010) argued that these findings seem to hold only for large- and middle-income emerging economies, where there is substantial capacity to adapt technologies; high-technology flows however, do not respond much to variations in patent rights among low-income countries. Moreover, empirical experience in the high-tech pharmaceutical industry, where there is solid evidence about a positive correlation between strengthened IP regulation and technology transfer, may not easily translated to green technologies. In contrast to the pharmaceutical industry, the market for green technologies has a large range of competing technologies and improvements in green technologies are usually incremental due to their nonrivalry characteristics and capability to be tweaked in new applications without significant loss of functionality (Hall and Helmers, 2010). Therefore, the efficiency gains from formal sustainability technology markets may limit developing countries access to external technological advances through informal channels such as reverse engineering and skilled labor mobility. Under these circumstances, the impact of strong IPR protection on environmental innovation is ambiguous and still needs further exploration.

Cross country studies of national environmental innovation systems: Brazil, India, and China (BIC)

An earlier study by Walz (2009; 2010) compares the relative strength of each one of the BRIC countries in relation to their sustainability-orientated innovation systems (SoIS). Although his data (2000–4) does not reflect recent developments, it provides useful information about the NIS of Brazil, India, and China over that period. Table 6.8 summarizes his arguments and findings. Among the three countries, India possessed the best NIS framework in terms of a well-established legal framework and formal mechanisms for coordination. The focus of China's NIS is oriented to support general manufacturing and trade whereas the innovation system in Brazil was established with a focus on water and transportation; in that sense, Brazil is moving faster toward the creation of a SoIS. During 2000–4, none of these countries specifically aimed at decoupling environment and resource consumption from economic development. As far as specific policy and program for sustainability research, Brazil is the only country that has earmarked R&D funds, for the energy, water, and transport sectors.[20] With respect to FDI attractiveness, the development of IP rights and the volume of exports of sustainability technology products, China had achieved remarkable progress due to its high level of technological absorptive capacity, while Brazil and India were relatively moving slowly. Finally, in India and Brazil, there is an increasing shortage of young scientists representing a large barrier for the development of public research in general and sustainable R&D in particular.

Table 6.8. bic countries sustainability-oriented innovation systems compared, 2000–4*

	China	**Brazil**	**India**
Technological Specialization	Solar (PV) and other energy efficiencies	Raw materials, agriculture, and transportation	Wind turbines, biopolymers, and desalination
NIS Framework conditions	Focus on general manufacturing and trade	Specific SoIS framework for water and transport sector	Best overall framework conditions for general innovation
FDI Attractiveness	Most attractive and far ahead in magnitude	Inflows behind China, yet far ahead	Lowest inflows

(Trade Policy)		of India	
Sustainable R&D	No specific policy on developing sustainable technologies in 2000–2004	Biomass, biofuels (ethanol)	Material efficiency and water technologies
Sustainable IP	Largest number of transnational patents in absolute numbers	Low amount of patents relative to exports	Low number of patents. High capabilities and IP in other sectors.
Exports of sustainability technology products	Highest exports: Solar (PV), transportation, and building technology	Behind China, yet well ahead of India	Exports play minor international importance
The role of sustainable technologies	Medium-important role of sustainable technologies. Weak in terms of future supply of energy and material resources. Large presence of FDI implies China possesses most absorptive capacity for technology.	Sustainable technologies play an important role. Energy supplied through hydro and other 27 renewable energies. Relatively strong technical capabilities in sustainable technologies. However, still lack of engineers to accelerate progress and for leapfrogging.	Sustainable technologies play a less important role despite best overall framework conditions. Legacy of weak environmental protection.

Source: Summarized from Walz (2009).

Looking at the BIC countries now, there has been a dramatic growth of green technology and improved conditions for the development of a green economy. India's wind turbine exports for example have increased tremendously. As mentioned above, since 2006, China has made sustainable technologies a primary component of national policy and has made strides in many fields including catching up in wind turbine technologies. Careful evaluation of the SoIS in BIC countries will be key to improve understanding of the role of NIS for the development of environmentally sustainable technology. In the last ten years, local companies in China and India have successfully manufactured complete turbine systems in spite of the fact that they had no wind turbine production capacity in the past (Lewis, 2007).

Conclusion

The technological capacities in China and India have grown very fast in wind power, solar PV panels, and electric cars in a very short time. Such successful leapfrogging in environment-related green industries in emerging economies has provided encouraging examples on how developing countries can effectively catch up in the emergent green industries. Meanwhile, the development of green industries in emerging economies provides developing countries more alternative sources of technology. Green technologies in the South may make better use of the factors that the developing counties are abundant of and hence are more appropriate to their economic, social, and technical conditions. South-South collaboration for innovation and environmental technology transfer should be seriously taken into consideration and encouraged.

Along the development models of green technologies, there are some similarities between China and India. Development of green industries in China and India has made good use of international technology transfers based on indigenous innovation systems, although the importance of these mechanisms varies with the different levels of technology capabilities and development stage. Specifically, most of the green industries in both countries started from international technology transfers through licensing and joint venture with MNEs, while substantial effort have been put into the development of indigenous technological capabilities for the assimilation and adaptation of the transfer of technology. Once the basic production and technological capabilities are built up, they start more active knowledge acquisition and creation through indigenous innovation, international R&D collaboration, and cross-border merges and acquisitions based on their comparative advantages. The experiences of the emerging economies suggest that to accomplish such a catch-up process requires a combination of international technology transfer and indigenous innovation. Technology transfer is feasible, and its evidence has proven to be an entry point for developing countries, but indigenous innovation systems are also important.

Once the basic production technology has been acquired, developing countries should continue to catch up in the technological frontier based upon their own comparative advantages. Many of the developing countries are abundant in semi-skilled labor and relevant resources, such as sunshine and wind in Africa. Once countries have acquired the basic production techniques through cross-border transfers, they will have a comparative advantage in producing low-cost outputs (as was the case in the solar PV panel manufacturing industry). Moreover, the export-market orientation of the solar PV industry in China and India also suggest that the international market can be a major driver of growth. Both China and India have cheap semi-skilled labor available for production; for African countries to effectively build up their capabilities in the green industries, education and training of semi-skilled labor will be crucial.

Due to the market failure (demand side) in driving the green technology development, government policy and incentives become essential. The experience of the emerging economies, China in particular, suggests that there is a crucial role of the State in initiating the transition toward the development of green technology development and in maintaining the momentum in the catch-up process. Given the public good nature of technology and the public bad nature of environment degradation, government-funded support through focused R&D programs has been crucial in promoting technological breakthroughs and hence the development of indigenous technological capabilities. Government programs focused on the diffusion of technology, such as the “Golden Sun” and “Ten Cities Thousand Cars” programs in China, has greatly facilitated technological diffusion and the development of other applications. Furthermore, the experience from China also demonstrates that the incorporation of environmentally sustainable technology is not the task of a single actor; it requires a set of complementary and coherent policies from various government bodies covering regulatory, financial, technological, and industrial policies, as well as being effective for the private sector. The synergy of multiple actors is important to promote and ensure a substantial change.

In sum, technological development and innovation are complex, path-dependent, and embedded within the socioeconomic fabric of each country (Saviotti, 2005). Technology transfer can be interpreted as a means of providing building blocks for local experimentation. In the context of developing countries, indigenous innovation is less the development of ideas that are “new to the world” but rather the application and adaption of old knowledge to new environments (Fisher, 2010). Despite the ostensible benefits of technology transfer, “foreign technology may not fit the specific socioeconomic and technical context prevailing in the technology recipient” especially where there is large divergence of income between developed and developing countries (Fu et al., 2011). Our evidence from emerging economies imply that most benefits are yielded from a two-pronged strategy in which technological transfers are complemented by localized innovation to help with adaptation and diffusion. Therefore, the legacy concept of technology as being static and embodied in equipment, which literally was transported across borders through FDI is inappropriate in a forward-thinking NIS framework. Rather, technological development is a process of acquiring, learning, and building local capabilities in which developing countries can feasibly contribute to the development process through adaptation by local firms.

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[3] As of 2011, China is only second to the European Union (fifteen countries) with 1.3 million full-time researchers. Data source: OECD statistics on science, technology and patent:

http://stats.oecd.org/.

[4] R&D intensity is defined as the ratio of total expenditures on R&D to GDP (in the country or region in question) in a given year. Data source: OECD statistics on science, technology and patent: http://stats.oecd.org/.

[5] Data source: China Statistic Yearbook 2012. National Bureau of Statistics of the People's Republic of China: http://data.stats.gov.cn.

[6] Adapted from MOST (2010).

[7] The US$1 billion project is planned to have three stages of development. It started building a 250 megawatt (MV) IGCC plant in Tianjin in 2009 and the plant was scheduled to begin operation by 2012. The second stage involves a smaller pilot plant, which uses both fuel cell and turbine to generate electricity while converting CO_2 for industrial use at the same time. The third stage, 400 megawatt power plant with carbon capture and storage (CCS) technology is scheduled for 2015–20.

[8] In December 2007, 1 US$ is equivalent to about 7.355 RMB. 1 US$ = 6.616 RMB (December 2010); 1 US$ = 6.312 RMB (December 2012).

[9] R&D expenditures are the gross domestic expenditure on R&D (with PPP adjustment) from OECD statistics 2012. Data source: http://stats.oecd.org/

[10] Data source: OECD Science, Technology and Patents statistics 2013: http://stats.oecd.org/

[11] In value chain, horizontal linkages are longer-term cooperative arrangements among firms at the same level that involve interdependence, trust, and resource pooling in order to jointly accomplish common goal. Vertical linkages are the cooperative activities between firms at different levels of the value chain such as suppliers, customers, and clients.

[12] Data source: China Statistic Yearbook 2012. National Bureau of Statistics of the People's Republic of China: http://data.stats.gov.cn.

[13] The idea of catching up (also sometimes known as "convergence") is the hypothesis that fast economic growth in poor developing countries will eventually lead to converge to the level of per capita income of richer countries.

[14] The "Golden Sun" demonstration project was established in July 2009 and provided upfront subsidies for qualified demonstrative PV projects in the years 2009–11. The aim of the program was to promote renewable energy generation and create a domestic market for its solar cell and panel manufacturers.

[15] Technology push implies that a new invention is pushed through R&D, production, and sales functions onto the market without proper consideration of whether or not it satisfies a user need; Demand pull innovation implies a new invention has been developed by the R&D function in response to an identified market need (Martin, 1994).

[16] R&D intensity is calculated as the share of GDP in China, the value in 2006 is obtained from Science and Technology Statistic Yearbook 2007.

[17] Output indicators here are those proposed by the OECD (2008) as follows: high-technology employment, high-technology exports, sales shares of new-to-market/firm products, and number of patents, trademarks, and designs.

[18] Research-based spin-offs are generally understood to be small, new technology-based firms whose intellectual capital originated in universities or other public research organizations.

[19] The United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty signed by most of the world's nations about ten years ago. The Kyoto Protocol is an extension of this treaty and includes legally binding measures.

[20] The conclusion was drawn based on the study of Walz (2009). It meant to highlight and compare the earmarked R&D policy and programs in China, India, and Brazil during 2000–4. There are many other policies in these three countries to promote investment in R&D, which are not included in the comparison made in the text.

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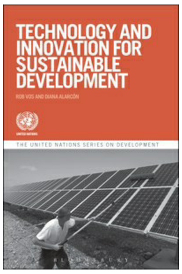

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Chapter 7. How to Feed the World and Save the Planet[1]

Diana Alarcón and Christina Bodouroglou

Summary

Global food prices have more than doubled over the past decade, reaching unprecedented highs. Increased prices have made food less affordable to many and exposed deep structural flaws in the global food system. Meanwhile, the increase in food production necessary to meet the needs of a rapidly expanding population will—under current technologies and practices—lead to further environmental destruction in the form of greenhouse gas emissions (GHG), water pollution, and land degradation.

Meeting the double challenge of expanding global food production while ensuring environmental sustainability will therefore require a major technological transformation in agriculture. In this endeavor, valuable lessons can be learned from the so-called green revolution of the 1960s and 1970s, which helped boost agricultural productivity worldwide. However, the green revolution did not conduce to a sustainable management of natural resources or to food security for many of the world's poor. A "truly green" revolution in agriculture is hence needed—one conducive to the kind of technological innovation that aims to radically improve the productivity of small farm holdings through environmentally sustainable natural resource management embedded in broader developmental support measures.

A wealth of technologies and practices in agriculture is currently available to spearhead the

radical transformation needed to increase food production in a sustainable manner. However, the current policy environment has not supported the adoption of such sustainable agricultural technologies and practices at a large scale. Instead, a much more radical, systemic and integrated policy approach is needed to promote sustainable food production at both national and international levels.

The transformation of agriculture so as to increase its productivity, profitability, resilience, and sustainability requires long-term support by governments. Increased state funding is needed toward agricultural research and development (R&D), rural education and extension services, improved rural infrastructure, and enhanced market access, as well as better distribution of land and other productive assets.

The international community also has much to contribute to a global agenda for food security and environmental sustainability. Donors need to honor existing commitments toward food security, as well as mobilize additional resources for R&D and for climate change mitigation and adaptation in the agricultural sector. International action is also needed to reform agricultural policies in Organisation for Economic Co-operation and Development (OECD) countries, including subsidies to biofuels, nontariff measures on food trade, and regulation of commodity futures markets.

The twin perils of global food insecurity and environmental degradation

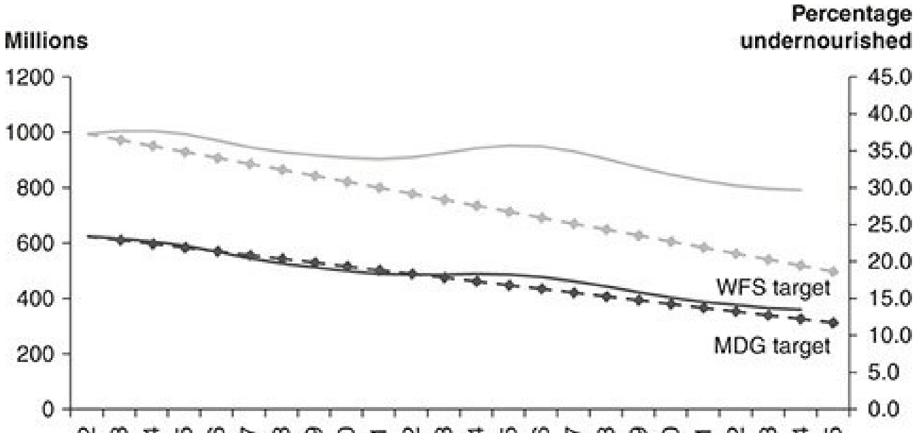
Persistent global food insecurity

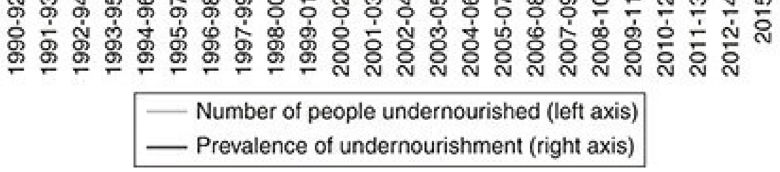
The 2007–8 global food crisis, as well as the renewed increases in food prices contributing to the 2011 food crisis in the Horn of Africa, have exposed the presence of serious threats to the sustainability of the global food system and its capacity to provide adequate and affordable access to food. As of 2012–14, a total of 805 million people, or around one in eight people in the world, were estimated to be suffering from chronic hunger—regularly not getting enough food to conduct an active life (FAO, IFAD, and WFP, 2014).

The overwhelming majority (98%) of the world's undernourished people live in developing countries, with close to two-thirds of them concentrated in seven nations (Bangladesh, China, the Democratic Republic of the Congo, Ethiopia, India, Indonesia, and Pakistan). Most hungry people (526 million) reside in Asia, although the highest share (24%, or 214 million people) is found in Sub-Saharan Africa (FAO, IFAD, and WFP, 2014).

While the estimated overall number of undernourished people has dropped since 1990, the rate of progress is insufficient to meet the international target for hunger reduction set at the 1996 World Food Summit (WFS) of halving the *number* of undernourished people in the world by 2015. Developing countries as a group have only made modest inroads toward meeting the WFS target: the number of undernourished people declined by 20 percent since 1990–92. More encouragingly, the less ambitious Millennium Development Goal (MDG) hunger target of halving the *proportion* of undernourished people appears within reach: the share of hungry people decreased from 23 percent in 1990–92 to 14 percent in 2012–14 (FAO, IFAD, and WFP, 2014) (Figure 7.1).

Figure 7.1. Undernourishment in the developing regions: Actual progress and target achievement trajectories toward the MDG and WFS targets



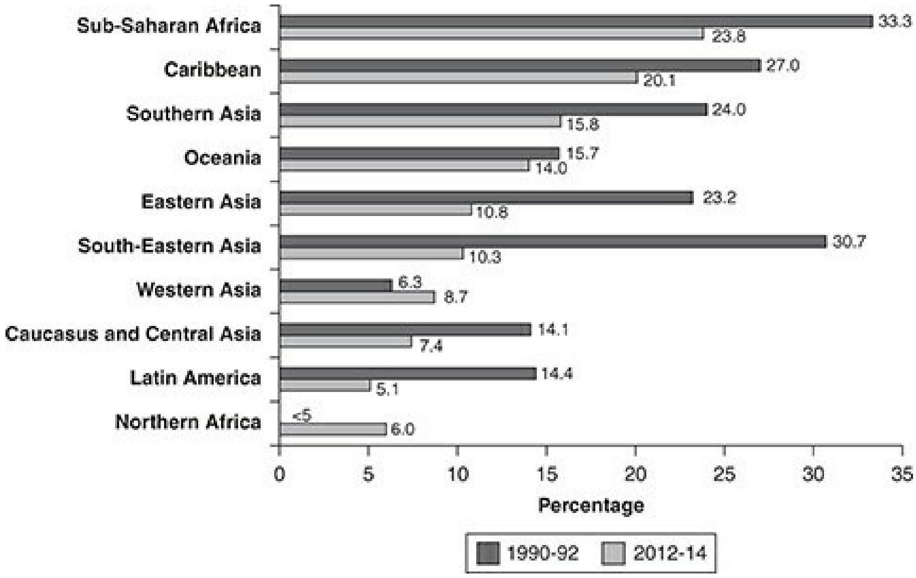


Note: Data for 2012–14 refer to provisional estimates.

Source: FAO, IFAD, and WFP (2014).

Despite overall progress, marked differences across regions and countries persist (Figure 7.2). Sub-Saharan Africa remains the region with the highest prevalence of undernourishment, with some improvement in recent years. While the share of undernourished is lower in Western Asia than in most other regions, it is nevertheless the only region that has registered an increase since 1990–92. The most significant reduction in prevalence of undernourishment has occurred in Southeastern Asia, with a decline from 31 to 10 percent.

Figure 7.2. Undernourishment trends by region

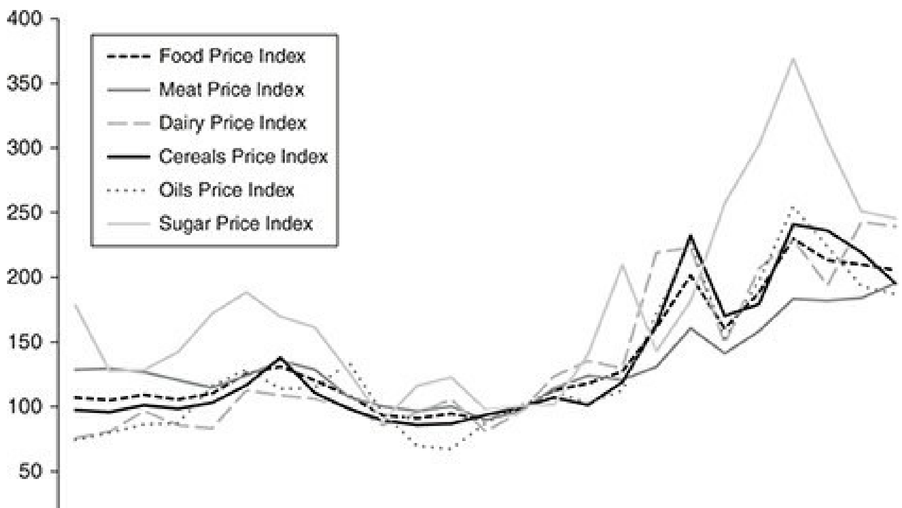


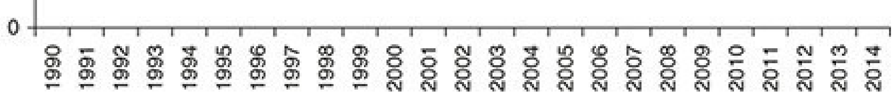
Source: FAO, IFAD, and WFP (2014).

Impact of high food prices

Rising food prices, partly attributable to adverse climatic conditions, have been the main driver of the 2007–8 and 2010–11 food crises. Global food prices have more than doubled over the past decade, reaching record highs in 2007–8 and 2010–11 (Figure 7.3). International prices for corn, wheat and rice more than doubled between 2006 and 2008. While prices declined in late 2008, food prices then rebounded, attaining new record highs in February 2011. Despite conflicting evidence, it would appear that recent price increases have also been accompanied by higher volatility, which increases uncertainty, thereby hindering investment in human and physical capital, technology, and innovation (FAO, 2009).

Figure 7.3. Food price indices (2002–4=100), annual averages, 1990–2014





Source: FAO http://www.fao.org/worldfoodsituation/foodpricesindex/en/.

The severe impact of the 2007–8 food crisis on living conditions was attested by the riots that broke out in over thirty countries. Increasing food prices have had a particularly negative impact on the poor who spend 50–70 percent of their income on food (von Braun, 2009). It has been estimated that higher food prices pushed a further 150 million people into poverty between 2007–10 (World Bank, 2008c; 2011).

In assessing the causes of the recent food crises, these have exposed deep structural flaws in the world food system. Although increased financial activity in commodity future markets may have amplified short-term price fluctuations, the global food price spikes have been the result of a long-term structural imbalance in the demand and supply for food. Demand for food has risen owing to continued global population growth, rising incomes, altered dietary patterns, and trade policies. At the same time, however, agricultural output has failed to keep pace with growing consumption due to competition for land, adverse climatic conditions, biofuel policies, high energy prices, and dwindling agricultural production and investment.

Unsustainable natural resource management as a threat to both food security and the environment

The aforementioned shortfall of agricultural supply is likely to persist, aggravated by the need to double food production by mid-century in developing countries in order to feed a rapidly expanding population (Bruinsma, 2009). Limits to the expansion of cultivated land area means that some 80 percent of the projected growth in food output in developing countries would need to derive from intensification of crop production (Bruinsma, 2009). With current agricultural technology, practices, and land-use patterns, this cannot be achieved without further contributing to environmental destruction in the form of GHG emissions, land degradation, biodiversity loss, water scarcity, and pollution. But the consequent environmental damage will, in turn, undermine long-term food productivity growth. Unsustainable agriculture and land management can thus also lead to negative socioeconomic consequences including food insecurity, poverty, migration, gender inequality, and ill health (IAASTD, 2009).

Attempting a closer look at the environmental impact of unsustainable natural resource management, the past half-century has witnessed shrinkage in the availability of natural resources, which has occurred more rapidly than in any comparable time in history.

The issue of land degradation is among the world's greatest environmental challenges. Defined as a long-term decline in ecosystem function and productivity, land degradation is driven mainly by poor land and water management, including overcultivation, overgrazing, deforestation, and inadequate irrigation (Berry, Olson, and Campbell, 2003). The phenomenon of land degradation is increasing, in severity and extent, in many parts of the world, with about 40 percent of the world's land surface degraded (25% has been degraded over the past quarter-century alone) (Bai et al., 2008).

Land degradation, driven by unsustainable natural resource management, in turn has negative effects on the climate, biodiversity, water ecosystems, landscape, and other ecosystem services. As summarized in Table 7.1, agriculture and land degradation contribute significantly to the problem of climate change, by generating GHG emissions leading to warming, as well as impacting land surface albedo and creating adverse weather patterns. Notwithstanding significant uncertainty in estimates, the agriculture, forestry, and other land use sector accounts for 24 percent of emissions of GHGs, the second largest emitter following the energy sector (IPCC, 2014a). The most important source of GHG emissions in agriculture is methane (CH_4) emissions from enteric fermentation in livestock and nitrous oxide (N_2O) emissions from synthetic fertilizer application. Deforestation and forest degradation in developing countries are the primary sources of carbon dioxide (CO_2) emissions from these countries, accounting for 35 percent of CO_2 emissions in developing countries and 65 percent in least developed countries (United Nations, 2009). GHG emissions from agriculture, forestry, and fisheries have nearly doubled over the past fifty years and are forecasted to increase by an additional 30 percent by 2050.[2]

In addition, increasing and competing demands for water have led to serious depletion of water resources (Smakhtin, Revenga, and Döll, 2004). Agricultural irrigation accounts for some 70 percent of all water withdrawals. Moreover, it appears that water quality has been degraded partly owing to intensive agriculture, which makes excessive use of agrochemicals (pesticides and fertilizers) and has become the main source of water pollution in many developed and developing countries, rendering it unsustainable and a source of risks to human health (Molden and de Fraiture, 2004). Intensive livestock production is probably the largest sector-specific source of water pollution (Steinfeld et al., 2006).

The past century has also seen the greatest loss of biodiversity through habitat destruction, primarily through the conversion of forests for agriculture. The problem of deforestation is particularly severe in the humid tropics (Moutinho and Schwartzman, 2005). Africa and South America suffered the largest net loss of forests from 1990 to 2005, with Africa accounting for over half of recent global losses, even though the continent hosts just over 15 percent of the world's forests (University of East Anglia, Overseas Development Group, 2006). Over the 2005 to 2010 period, 3.6 and 3.4 million hectares of forest per year were lost in South America and Africa, respectively.[3]

The spread of industrial agriculture has also promoted the simplification of agro-ecosystems, with reductions in the number of and variety of species. Moreover, overexploitation of marine resources is so severe that an estimated 20 percent of freshwater fish species have become extinct (Wood, Sebastian and Scherr, 2000), while certain commercial fish and other marine species are threatened globally (IAASTD, 2009).

Table 7.1. Global environmental impacts of land degradation

Environmental component/process	Bases of impact of land degradation
Climate change	• Land-use change, deforestation in particular, is a critical factor in the global carbon cycle. • Soil management changes can result in the sequestration of atmospheric carbon. • Agriculture is a major source of methane (CH_4) and nitrous oxide (N2O) emissions. • Land surface change (for example, as regards to albedo and roughness) plays an important role in regional and global climate change. • Human activities accelerate the occurrence of sandstorms. • Biomass burning contributes to climate change.
Biodiversity	• Deforestation leads to loss of habitat and species. • Land-use change and management, including fragmentation and burning, lead to loss of habitat and biodiversity. • Nonpoint pollution from crop production damages aquatic habitats and biodiversity.
Water resources	• Agricultural activities are a major source of water pollution. • Land-use and cover change alters the global hydrologic cycle. • Atmospheric deposition of soil dust damages coral reefs.

Source: University of East Anglia, Overseas Development Group (2006).

In addition to negative environmental impacts, unsustainable natural resource management also has adverse socioeconomic impacts. In particular, land degradation can lead to substantial productivity losses, thereby posing risks to food security.

Importantly, agriculture—albeit a contributor—is also vulnerable to the effects of climate change, with changes in temperature and precipitation affecting the timing and length of growing seasons and yields (Agrawala and Fankhauser, 2008). Evidence already points to the negative impact of climate change on net global yields of maize and wheat (IPCC, 2014b). Extreme weather events also have a negative impact on agricultural production. Recent food price spikes and supply shortages caused by exceptional conditions of drought in the Russian Federation, Ukraine, and countries in East Africa, as well as floods in Pakistan, Australia, and the United States, are prima facie evidence of the catastrophic impacts of adverse climatic conditions, possibly related to climate change.

Looking ahead, with temperature rises, crop productivity is forecast to decrease in both tropical and temperate regions. For instance, it is estimated that in Africa and South Asia, average crop yields could fall by 8 percent and fisheries by 40 percent by 2050 (Knox et al., 2012; IPCC, 2014b). While yields may increase in some high latitude areas such as China and the UK, overall decreases are predicted to offset any increases even with only moderate warming (Knox et al., 2012). By 2080, 600 million additional people could be at risk of hunger as a direct consequence of climate change (UNDP, 2007).

Aside from food insecurity, the degradation of arable land is a predominant factor in the migration of people. Use of inorganic fertilizers and pesticides and the spread of pests and livestock diseases can further adversely affect human health (IAASTD, 2009). Natural resource degradation can also exacerbate gender inequalities by increasing the time requirement for fulfillment of female traditional responsibilities such as food production fuel wood collection, and soil and water conservation.

Current efforts to promote sustainable agriculture among small-scale farmers

The analysis thus far makes clear that combating hunger and malnutrition in a sustainable manner and guarding against high and volatile food prices will require a radically different approach addressing the structural constraints on food production. This would entail both the establishment of a comprehensive national framework for sustainable use of resources and a harnessing of the technology and innovation needed to increase the productivity, profitability, stability, resilience, and climate change mitigation potential of rural production systems.

The reality that up to 90 percent of the food consumed in developing countries is locally produced, mostly by small-scale farmers. According the latest estimates family farms produce over 80 percent of the world’s food (FAO, 2014). Smallholder farmers are at the heart of both the challenge of and solution to food security and environmental sustainability. Combating poverty and hunger in a sustainable manner will therefore require not only a radical transformation in the use of technology in agriculture and the management of natural resources but also a profound change in the focus of development strategies on agriculture to improve the productive capacity and livelihoods of people in rural areas.[4]

In assessing current efforts to boost sustainable food production, while there have been some notable developments in the right direction, these have nevertheless tended to be localized in nature and far from sufficient.

The green revolution in the 1960s and 1970s

Commendable efforts responding to widespread poverty and food insecurity date back to the 1960s and 1970s, when developing countries and donors pursued policies that induced a dramatic rise in agricultural productivity and production. Nevertheless, these policies did not have universal reach and came at a cost to the environment.

The so-called green revolution policies brought new technology and innovation to farmers in Asia and Latin America as part of an effort to increase food production at a time when close to one-third of the world’s population (1 billion people) were vulnerable to hunger and malnutrition (Spielman and Pandya-Lorch, 2009).

Technological innovations were based on breeding new varieties, mainly wheat, rice, and maize that were more resistant to pests and disease and more responsive to chemical nutrients and that allowed double- and even triple-cropping (IFPRI, 2002). In Asia, annual cereal production doubled between 1970 and 1995, and countries in Asia and Latin America saw higher calorie intake per person and a substantial increase in real per capita income, with subsequent poverty reduction (Hazell, 2009).

The technological innovation and diffusion triggered by the green revolution were facilitated by a large and interconnected system of international research centers, coordinated by the Consultative Group on International Agricultural Research (CGIAR) and sustained with adequate funding from developed and developing countries and private donors. These centers sustained research operations, gene banks, and nursery programs in an environment of open and free exchange of information and plant genetic materials (Dubin and Brennan, 2009). The budgets available to CGIAR centers grew from $15 million in 1970 to $305 million in 1990 (Pardey and Beintema, 2001).

Governments expanded rural roads, irrigation and electrical power facilities, and improved storage facilities. Basic education, agricultural research, and extension services to support farmers also improved, and international lending for agricultural development was prioritized.

Unfortunately, the "technical package" that accompanied the green revolution was not replicable in regions with different agro-ecological conditions in terms of climate, soil, weeds, and pests, most notably Sub-Saharan Africa, and where the consumption of staples was more diversified. Also, the technology arising from the green revolution was based on intensive use of fertilizers, chemical pesticides, and water, which had negative environmental impacts.

Local innovation in agriculture

While the technology and innovation of the 1960s–70s green revolution was underpinned by a concerted international research effort, current approaches to technological innovation for sustainable agriculture tend to be more localized in nature, arising from the capacity of farmers and rural communities to innovate in response to weather and other shocks.

Indeed, there is a wealth of successful experiences of localized enhanced pest and weed management, water efficiency and biodiversity, including stories of highly successful innovation in the most challenging circumstances characterized by a poor natural resource base and widespread poverty (see, for example, Pretty et. al., 2006). Yet, prevailing conditions typically prevent the widespread use of these experiences.

Nevertheless, there are several well-known exceptions with large-scale impacts, including the integrated pest management (IPM) approach, the Farm Field Schools (FFS), the System of Rice Intensification (SRI), the networks of millers, and politicians that popularized the use of New Rice for Africa (NERICA), the diffusion of micro-irrigation in Bangladesh, and watershed management in India (Hall et al., 2010; Brooks and Loevinsohn, 2011). Common features among these widespread efforts in sustainable agriculture intensification include extensive experimentation to adapt to the variety of local contexts with explicit support from governments, multilateral and civil society organizations, and with direct involvement of local farmers, including women, in donor-led initiatives.

In addition, contrary to the green revolution, which relied on the wide-scale adoption of a single "technical package," in today's context there is no single "technical solution" toward greater agricultural productivity and environmental sustainability. Instead, a whole range of technical options need to be made available to a large number of small-scale producers in very different agro-ecological regions.

A wealth of technologies and sustainable practices in agriculture is currently available to spearhead the radical transformation needed to increase food production without a major expansion of cultivated areas and a further depletion of natural resources.

The menu of existing technological options includes traditional technologies and practices which have been successfully adopted with important productivity and environmental gains. Examples include low-tillage farming, crop rotation and interplanting, green manure utilization, agroforestry, integrated pest management, water harvesting and water-efficient cropping.

Further, the technology that emerged from the green revolution continues to play an important role in the development of new crop breeding and higher-yielding varieties with substantial productivity gains. However, continuing innovations are needed for reducing the use of external inputs and increasing efficiency of water so as to minimize negative environmental impacts.

Modern technologies such as biotechnology, genetic engineering, food irradiation, hydroponics, and anaerobic digestion also provide complementary options to improve the resistance of food crops to pests and extreme weather, increase their nutritional value, and reduce food contamination and greenhouse gas emissions. More research is needed, however, to adapt crops and processes to local conditions and to the needs of the poor.

Overall, although a wide range of sustainable agricultural technologies and practices already exist, the policy challenge is to identify and support the scaling-up of local instances of agricultural innovation and make available appropriate technical options to farmers in poor and food insecure countries and regions.

Policy responses to the food crises

The previous analysis highlights the need for an enabling policy environment to address the issues of food insecurity and environmental degradation. This requires both short-term policy responses to scale up and improve humanitarian relief to alleviate hunger and starvation, as well as longer-term action to expand resources and foster innovation in agriculture to accelerate food production in a sustainable manner.

The recent food crises induced policy reactions at national and international levels. National governments responded to the 2007–8 global food price crisis with a range of mainly short-term policy measures including import tariff reductions, price controls, export restrictions, stock reductions, and food programs. A study evaluating such responses in ten emerging economies revealed the importance of providing targeted safety nets for the poor as emergency responses to food shortfalls.

The international community also reacted to the food crises with emergency food assistance. For instance, in the case of the 2011 food crisis and famine unfolding in the Horn of Africa, the United Nations World Food Programme (WFP) led a humanitarian response targeting about 8 million drought-affected people.

Importantly, the food crises have also prompted greater global political attention. For example, at the G8 Summits in Hokkaido Toyako in 2008 and L'Aquila in 2009, donors pledged to provide $10 billion in Official Development Assistance (ODA) to fight hunger and $20 billion over three years to address food insecurity in a sustainable manner (Group of 8, 2009). The 2012 G8 Summit in Camp David saw the launch of the "New Alliance on Food Security and Nutrition," which focuses on private sector investment in production and innovation. At the 2012 G20 Summit in Los Cabos a further "AgResults" initiative was launched to promote innovation in agricultural products and systems (OECD, 2012a). In addition, the UN Secretary General has afforded top priority to eliminating hunger through the launch of the "Zero Hunger Challenge," and he launched the "Global Alliance on Climate-Smart Agriculture" at Climate Summit in September 2014.[5] These new donor-led initiatives complement existing ones, such as the "Alliance for a Green Revolution in Africa (AGRA)," founded by the Rockefeller and the Bill & Melinda Gates Foundations.

Despite such welcoming developments, current national and international efforts are insufficient to address the magnitude of the challenge of food insecurity and depletion of natural resources. This is to a large extent owing to the limited public investment and foreign aid directed toward agriculture in recent decades. For instance, only a handful of signatory countries have achieved the 10 percent national budget allocation to agriculture as prescribed by the 2003 Maputo Declaration on Agriculture and Food Security in Africa (Fan et al., 2009). Furthermore, foreign aid to agriculture and rural development has fallen from almost a quarter of sector-allocable aid in the mid-1980s to less than 10 percent in 2009–10 (OECD, 2012b). Dwindling resources for agriculture has also translated in decreased international support for agricultural research, alongside the scaling back of by national agricultural research centers of their programs for the production and distribution of seeds (Dubin and Brennan, 2009). Moreover, what limited resources are allocated to agricultural research and development (R&D) tend to be concentrated in a few major developing countries (Beintema and Elliott, 2009).

More generally, past policies have failed to *jointly* address the twin challenges of food insecurity and environmental degradation. Hence, policies aimed at reducing hunger may have focused on means of increasing agricultural productivity and production, without explicitly addressing sustainability concerns. With respect to policies aimed at adapting to the impacts of climate change, such measures have tended to focus on short-term on-farm agronomic changes, with limited efforts—and a lack of research on options—for more systemic and transformational adaptation.

National strategies for food security and sustainable agriculture

The sustainable agricultural innovation system (SAIS) framework

The preceding section demonstrated that current policies to foster agricultural innovation are insufficient and piecemeal in nature, and therefore unlikely to have an impact at a large scale, at the scale required to reach the goal of achieving food security with an environmentally sustainable agriculture. Instead, a much more radical, systemic, and integrated policy approach is needed to promote sustainable food production at both national and international levels.

In this endeavor, a sustainable agricultural innovation system (SAIS)—recognizing the dynamic nature of learning and innovation and the multiplicity of actors engaged in the innovation process and the institutional contexts within which they interact—provides a useful framework for policy making.

The SAIS perspective facilitates the recognition of the multiplicity of actors that produce and use global knowledge (including universities, research institutions, firms, farmers, extension workers, civil society organizations and private foundations), their interests, the institutional contexts within which they interact, and the dynamics of learning and institutional change (Spielman, 2005). The SAIS perspective also serves to underline that the concept of innovation extends beyond technological solutions in production to also encompass innovation in processes, products, and marketing, as well as innovative partnerships, policies, and forms of governance of natural resources (for instance, by emphasizing the participation and empowerment of small-scale and poor producers).

An innovation systems perspective enables the recognition of the evolutionary nature of innovation, and hence of the need for a new technological revolution in agriculture to build on the rich experiences of innovation in the last thirty years. The policy challenge is how to move beyond the recognition of a multiplicity of innovative experiences, toward the design of policies to expand, transfer, adapt and/or disseminate the plethora of existing technological approaches so as to reduce poverty, hunger, and environmental destruction.

In designing suitable policies and incentives to stimulate innovation among small-scale farmers to increase sustainable food production, the direct involvement of farmers in learning and innovation is seminal for adapting knowledge, technology, and management practices to the local context. Moreover, active participation by various actors including governments, nongovernmental organizations, and multilateral organizations can be critical not only to scaling up innovations but also to disseminating knowledge, building capacity among farmers, fostering trust, and reducing the risks associated with new technology and agricultural practices. Importantly, technical knowledge needs to be made relevant and accessible to small-scale farmers and be accompanied by an enabling environment within which they can overcome the constraints that they face in respect of adopting new technology and agricultural practices (Berdegué, 2005).

Some useful lessons to be learned from the past experience of the green revolution include: (a) the development of new technology requires long-term financial support for R&D and effective and free flowing dissemination of information; (b) the adoption of new technology requires an enabling institutional framework and large investment in infrastructure, and capacity development among farmers, as well as easy access to inputs, credits, and markets; and (c) innovations in agriculture require long-term commitments from national governments and international stakeholders.

On the whole, building new institutions that pave the way toward sustainable agriculture and food security by strengthening the multiple nodes of the SAIS and changing behaviors is a long-term process requiring commitment of resources, a clear vision of the overall direction of change, and capacities to adapt to a changing environment. National strategies to achieve food security and sustainable agriculture will help governments ensure consistency in typically decentralized agricultural innovation systems and help guide the direction of donor resources and private sector investments. Without this minimum framework, rural structural change may not occur in time to prevent irreversible human and environmental damage to the current food production and consumption systems.

National strategies for sustainable food production

National governments have a critical role in designing and implementing policies and incentives to stimulate innovation to increase food production in a sustainable manner. In particular, governments have an important part to play in pursuing food security as an integral part of their national development strategies; channeling resources toward agriculture (including investment in agricultural research and development); expanding access to technology and information (including through rural education, extension services, and technical training); improving market access (including for credit, inputs, and insurance); building and maintaining rural infrastructure (including roads, storage facilities, and irrigation systems); providing social safety nets; securing property rights (including land redistribution); and encouraging coordination among multiple stakeholders (including through public-private partnerships).

Integrated national development strategies

As mentioned, sustainable agriculture to achieve food security needs to be an explicit component of countries' national development strategies, including the identification of financial resources to expand agricultural research, rural infrastructure, and supporting services to small-scale agricultural producers.

A holistic, cross-sectoral approach should consider trade-offs and build on synergies between sectors and objectives, to prioritize and promote technically available and economically feasible options that ensure food security, poverty reduction, and environmental sustainability. For instance, an integrated national development approach should recognize conflicts and promote synergies between forests and agriculture. In view of their competitive land uses, many solutions, involving difficult choices, can be reached through open and inclusive discussion and negotiation. However, the potential synergies among the sectors (resulting, inter alia, in reduced land degradation and increased productivity) present important "win-win" options through better resource management facilitated by an enabling institutional environment.

Investment in agricultural R&D

Governments committed to end hunger while protecting the environment need to allocate sufficient resources toward the agricultural sector. In particular, there is a need to halt and reverse the pattern of shrinking resources for agricultural R&D, including for the adaptation of technology to local conditions.

While current agricultural knowledge and technology provide a range of alternatives for achieving sustainable agriculture, the adoption of new practices and technology requires additional investment in R&D to ensure adaptation to the diversity of agro-ecological conditions in which small-scale farm holders operate. In addition, rapidly changing climate patterns and food markets require continuous research and the development of new technology and crop management. The intensification of research efforts to breed new crops, and the development and adaptation of new technology to increase sustainable food production require significant long-term public and private funding for agricultural R&D.

In addition to sustainable financial resources, the model of operation of public research institutions also needs to become more flexible and inclusive so at to improve their responsiveness to the needs of small-scale farmers, including through joint experimentation and learning. Public research institutions also need to expand their traditional disciplinary approach to encompass an interdisciplinary focus in response to wide-ranging farmer demands. Transformation of diverse agro-ecological rural economies requires the expertise of biologists, agronomists, water engineers, nutritionists, economists, and social and political scientists (Lipton, 2010). Participation of women, especially in Sub-Saharan Africa, where women constitute a large proportion of the agricultural labor force, will also be critical to enhancing their low levels of representation and decision making in agricultural research and extension services and to addressing their specific needs.

Building the capacity of national public research centers is a long-term process requiring substantial and sustainable investments and radical changes in their organizational culture. In the case of small and poor countries, pooling resources to strengthen regional research agendas is perhaps the most effective option for improving their collective capacity. Promising experiences of regional and South-South agricultural cooperation include, for instance, agreements between research institutions of Brazil and China and African institutions.

Furthermore, rapid technological innovation for achieving food security and tackling climate change will require closer collaboration with the private sector toward expanding research in frontier areas.

For instance, in the case of biotechnology, a legitimate concern relates to the concentration of research and products in few large firms (namely, DuPont Pioneer and Monsanto) that exert influence over prices. The high cost of seeds and inputs may prohibit use of this technology by small farm holders. Yet, biotechnology can still be an effective instrument for facilitating the transformation of agriculture in poor agro-ecological regions with low productive capacity under current technology (namely, in parts of Africa, Central America, and Asia with degraded natural resources). However, the structure of incentives and governance of innovation in this area require radical changes, which ensure, inter alia, that the objectives of food production and environmental sustainability become central to the research agenda in biotechnology.

While there are no simple answers in this regard, publicly funded research should maintain an explicit focus on strategic priorities for food security, including improving yields and resistance of staples, improving the nutritional value of crops, facilitating sustainable use of natural resources and/or reducing the use of external chemical inputs. Innovative mechanisms designed to engage the private sector need to be explored: results-based performance contracts—for the development, for example, of improved seed or crop varieties with higher water-stress tolerance and greater responsiveness to fertilizers—granted on a competitive basis may be one means of stimulating private research. Patent buyouts, prizes, and proportional prizes may be other means of doing so (Bhagwati, 2005; Elliot, 2010). Use of more traditional subsidies, co-financing arrangements, and joint ventures should also be explored, within a framework of appropriate protocols for maintaining the public-good nature of research products (Pardey and Beintema, 2001).

More generally, building partnerships with the corporate private sector is important, but in the specific case of food security, governments and public research institutions in developing countries need to be fully involved in setting the research agenda, including comprehensive risk assessments and suitable regulations on the use of new technologies (Lipton, 2010).

Provision of rural education and extension services

In addition to higher investment in agricultural research and development, increased awareness and the accelerated adoption of sustainable technologies and crop management practices will require wider dissemination of information and information and communications technology (ICT) through quality education in rural areas and adequate extension services.

The dissemination of information and technology in the rural sector has traditionally be carried out by agricultural extension workers. In the current context, a larger number of actors (civil society organizations, the private sector, farmers, and multilateral organizations) contribute toward this end.

It has been estimated that about half of a billion agricultural extension workers exist globally, most of them being public workers. Although the number appears large, the general perception is that it is inadequate, especially when measured against the needs of small-scale farm holders who, for the most part, have been deprived of the services of such workers (Lele et al. 2010). Agricultural extension workers, free from any particular interest in promoting the use of commercial products, are still an important vehicle for the transmission of knowledge, information, and training for small farm holders, provided that they have adequate training themselves, a clear mandate, and appropriate incentives to perform their job. It is therefore vital that governments continue to provide quality rural extension services at a large scale to address the specific needs of famers.

Exclusion of women from technical support needs to be explicitly addressed. In Africa, women receive 7 percent of agricultural extension services and less than 10 percent of credit offered to small-scale farm holders. Moreover, inasmuch as educational curricula tend to exclude topics with particular relevance to women (such as nutrition, sanitation, hygiene, gender-specific tools, and management), gender analysis and targeted initiatives must be incorporated in agricultural education, research, and extension services (Davis and others, 2007).

A longer-term commitment to providing adequate funding for public research and training needs to be accompanied by a new approach to technical education—one that is more practical in nature and oriented toward problem solving and decision making and with greater capacity to involve farmers and civil society organizations in finding interdisciplinary and creative solutions to new problems.

While technical education and training is vital for the adoption of new farming methods and technologies, this needs to be accompanied by investment in basic education in rural areas, including adult literacy. The ability of farmers to innovate, learn from one another and adapt to change largely depends on their capacity to access and process information including through information and communications technology. Rapid expansion of quality rural education, including adult literacy and training, should receive the highest priority in any strategy aimed at strengthening farmers' responsive capacity to rapidly changing agro-ecological and market conditions.

More innovative mechanisms for the transmission of knowledge and training also need strengthening. The experience of the Farm Field Schools—operating in eighty-seven countries—shows that innovation and flexible land management can be advanced through farmer-to-farmer learning, with participation from formal and informal research institutions. In-service and on-the-job training and distance education have also proved effective and are increasingly complementing extension services.

Education is also central to bringing about the requisite societal transformation needed to ensure food security and protect the environment. Formal and informal education, extension services, advertising, and information campaigns, and political and civil society mobilization are important means of creating more sustainable food production and consumption patterns.

On the production side, farmers need to be informed and trained and stimulated to adopt more sustainable practices. However, the challenge of feeding a rising and increasingly affluent population also requires behavioral changes in terms of consumption, including dietary patterns. In particular, the livestock sector, which has grown rapidly to meet the increasing demand for meat, is a prime cause of water scarcity, pollution, land degradation, and GHG emissions. This has prompted calls for support for vegetarian diets. However, the nutritional importance of animal protein, particularly in developing countries, and the differences, in the context of production efficiency and environmental impact, between different types of livestock, may warrant, instead, warnings against consumption of red meat and dairy products (Godfray and others, 2010). Publicity, advocacy, education, and even legislation can also be used to bring about ideological, cultural, and behavioral changes so as to reduce high levels of retail and domestic food waste in the developed world.

Expanding support services and land reform and overcoming political obstacles to agrarian change

Aside from the aforementioned emphasis on agricultural research, education, and training, achieving the goals of food security and environmental sustainability will further require complementary government policies. These include building rural road infrastructure and crop storage facilities; improving access to input and product markets; expanding rural credit and innovative mechanisms for weather-based crop insurance; securing land tenure and improved rental agreements; and ensuring adequate social safety nets.

Major policy transformations are needed to strengthen the systems of agricultural innovation and increase resources for rural development and sustainable natural resource management. To the extent that innovation is strongly associated with risk-taking, risk reduction mechanisms need to be introduced to avert devastating losses of income of small farm holders. Grants, tax incentives, innovative insurance policies, and new forms of venture capital may be able to provide this kind of protection (Leeuwis and Hall, 2010).

The policy challenge resides in how to mobilize the resources needed to expand the range of supportive services that are critical to improving the capacity of small farm holders to innovate and to compete in dynamic markets. Increasing investments for rural development and shifting the focus of attention toward support of small-scale farm holders will require, in many contexts, overcoming the obstacles put in the path of change by prevailing power relations (Spielman, 2005). Rural poverty and food insecurity are frequently the result of “institutional failures” (including coordination failures, land insecurity, gender discrimination and marginalization of indigenous populations), which prevent the development of more dynamic food production systems.

One of the most contentious issues in most counties is land distribution. To a large extent, low income and food insecurity among small-scale farm holders can be traced back to the lack of adequate access to land. Traditional land reform designed to improve access to land and provide support to different forms of association among farmers would help to effect economies of scale in production and, most importantly, in the marketing of food crops. However, changing land distribution practices, securing property rights and creating incentives that benefit small farm holders often require the formation of political coalitions that might challenge the status quo.

A related issue concerning access to land involves the increased purchases of farmland by foreign investors, which has resulted in the favoring of exports over domestic food production. An estimated 56 million hectares of land in developing countries were bought by foreigners in 2009, a tenfold rise from the previous decade, with two-thirds of these sometimes controversial “land grabs” occurring in Africa (Deininger et al., 2010). Improved national dialogue and empowerment of communities and traditional small-scale farmers is essential in countries engaged in land leasing to foreign investors. A full evaluation of the impact of land grabbing needs to be part of any long-term contract to avoid the displacement of small-scale producers (often using land with no formal titles) and the invasion of community land used to support rural livelihoods. Additional support to countries engaged in long-term land leasing to foreigners is also important to develop the mechanisms for the enforcement of contracts, especially in areas related to employment creation, infrastructure development, and the transfer of technology. A full evaluation of the developmental impact of land grabbing needs to be incorporated in countries’ decisions and national strategies for food security in a process of open and effective consultation with potentially affected groups.

On the whole, national strategies for food security and sustainable agriculture need to explicitly recognize the socioeconomic and political obstacles to inducing a radical transformation in agriculture that is focused on improving the productive capacity of small-scale food producers. For instance, policies to promote innovation in agriculture need to have an explicit gender focus to address the institutional constraints that prevent better access by women to secure land tenure, credit, new technologies, technical assistance, and other supportive services.

In countries like Brazil, China, and India, whose governments had chosen to prioritize poverty reduction and food security, dynamic innovation systems emerged in support of agricultural development. In other instances, the scaling up of innovative practices—for instance, for rice intensification and watershed management—was possible through the endorsement by international organizations, national nongovernmental organizations, and local governments of new practices in support of dissemination of knowledge, greater participation by and capacity development of farmers, building of missing infrastructure, and improving access to credit, information, and other supportive services.

Innovative partnerships

The previous analysis highlighted the critical role of governments in inducing a technological transformation in agriculture. Yet, governments need to also build partnerships with other stakeholders, including the private sector, so as to strengthen the capacity of small-scale farmers to access technology, inputs, and larger markets.

For instance, it was mentioned earlier that effective agricultural research demands closer collaboration among public research institutions, the private sector and small-scale farmers through innovative partnerships. Such partnerships could take the form of results-based performance contracts, patent buyouts, prizes, joint ventures, cofinancing and advance-purchase agreements, comprehensive risk assessments, or suitable regulatory schemes (Pardey and Beintema, 2001; Bhagwati, 2005; Elliot, 2010; Lipton, 2010).

While the corporate private sector has played an increasingly important role in accelerating innovation in agriculture through a variety of mechanisms, the risk of excluding small-scale farmers is also large. Through appropriate regulation to prevent monopolistic practices in food markets, and better access to information, credits and, risk insurance, small-scale farm holders would be in a better position to engage in mutually beneficial partnerships with the corporate private sector.

Perhaps one of the most important drivers of change in recent years lies in the transformation in food retailing. The emergence of large supermarket chains, which control between 40 and 50 percent of the food market in Latin America, about 10 percent in China, 30 percent in South Africa, and 50 percent in Indonesia, has concentrated the purchase of large quantities of food subject to strict quality standards, a phenomenon that has led to the displacement of traditional wholesalers and small retail shops. For small farm holders, participating in these markets depends on their capacity to meet strict quality standards and to achieve an organized commercialization of their products through cooperatives and other forms of association. The risk of exclusion, however, is large, especially for farms in remote and difficult to access areas (Berdegué, 2005). Technical assistance to farmers in meeting with quality standards would help to expand their opportunities for participation in larger markets.

In addition to the private sector, civil society organizations and private philanthropies are becoming important players in the area of agricultural innovation. Most of the recent stories of innovation characterized by pro-poor and positive environmental impacts have also entailed the active participation of international and national civil society organizations, which, among others, can serve as intermediaries between research and agricultural practices; facilitate collective action and creation of farmers' organizations for the purchase of inputs and marketing of food; and strengthen the capacity of women to participate in marketing production and innovation.

Government policies have an important role to play in enhancing the contribution of the multiple stakeholders that are part of the Sustainable Agricultural Innovation System and creating a regulatory framework to "promote trust and cooperation, delimitation of contributions and rewards, timely information on compliance of obligations, enforcement of agreements, recognition and protection of the rights of each party" (Berdegué, 2005, p. 21). While any government's policy will have to respond to the specific context of its own country, building stronger partnerships within an SAIS will require the participants to collaborate in developing a clear-cut strategy directed toward achieving the objectives of agricultural reform and ensuring that there are resources adequate for expanding rural infrastructure and supporting provision of services to small-scale farmers.

International action for food security and environmental sustainability

Governments, in their capacity as coordinators of the multiple stakeholders in a SAIS, can further benefit from regional and global partnerships. The international community has much to contribute to a global agenda for food security and environmental sustainability.

Toward this end, a renewed focus of development assistance on agriculture and sustainable land management is critical. Delivering on the financial pledges made in the aftermath of the food crisis of 2007–8 would constitute a good down payment on realizing the commitment to the goal of eradicating hunger. Availability of financing for climate change mitigation and adaptation activities in the agriculture sector in developing countries is further important to spur and enable the transition toward sustainable and climate-resilient food production.

In the very short term, preventing export bans on food crops and panic buying in response to weather-related catastrophes could help to reduce large food price spikes. In addition, mechanisms to protect vulnerable populations utilizing safety nets and food assistance are necessary in order to reduce the impact of increasing food prices. Building global grain reserves may be an option in responding to food emergencies but the management and deployment of assistance require closer scrutiny so as to ensure that it represents an effective emergency response and to avert longer-term negative impacts on local food production systems.

In the longer-term, foreign donors can accelerate countries' transition toward sustainable food production through increased investment in agricultural R&D. Adequate funding for the effective functioning of CGIAR during the green revolution was critical to facilitating rapid innovation through proactive adaptation and dissemination, often with supportive and facilitative (subsidized) public provisioning of infrastructure and other needed inputs. Reconstituting the global, regional, and national capacities for agricultural R&D with international financial support can result in the generation of a rapid increase in agricultural productivity. There is a need to support international institutions such as the CGIAR to better globally coordinate and complement large public investments in agricultural infrastructure, as well as facilitate technological diffusion by making freely available information on agricultural processes and plant genetic materials.

International action is further needed to reform agricultural subsidies in OECD countries, which undermine the ability of farmers in developing countries to compete. This includes rethinking subsidies to biofuels, and support to new generation biofuels to reduce the diversion of agricultural land use from food production. Nontariff measures on food trade must be reformed so that these are truly science-based and adequate assistance is provided for small-scale producers to meet them. The WTO Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) and other bilateral and regional trade agreements that incorporate TRIPS-based provisions—which introduce monopolistic and exclusive rights regimes into plants and seed varieties—may also need to be modified to permit knowledge and seed sharing in developing countries. Developments such as the signing of the International Treaty on Plant Genetic Resources for Food and Agriculture—which promotes international cooperation and open exchange of genetic resources of crops—are welcoming in this regard.

New financing mechanisms should also be developed to expand payments to small farm holders in developing countries for environmental services (PES) that help to protect natural resources, to preserve biodiversity, and to increase carbon sequestration in agriculture and forestry.

Finally, effective regulation of commodity futures markets can help minimize unwarranted price volatility, which dilutes incentives to invest and undermines the viability of poor farmers and rural workers around the world.

[1] The views expressed in this chapter are those of the authors and do not represent the official position of the organizations where they work.

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[2] http://www.fao.org/news/story/en/item/216137/icode/ (accessed July 1, 2014).

[3] http://mdgs.un.org/unsd/mdg/Resources/Static/Products/Progress2013/English2013.pdf.

[4] This year's flagship publication of the FAO *The State of Food and Agriculture Report 2014* is dedicated to Innovation in Family Farming, in recognition of the need to focus attention to the production conditions of small-scale farming.

[5] http://www.fao.org/climate-smart-agriculture/85725/en/.

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