How Much Technological Change, Research and Development is Enough?

Nebojsa Nakicenovic, TU Wien and IIASA

Industrial revolution and technological change

The last two centuries of unprecedented development have undeniably improved the human condition. For example, population has increased more than sixfold, economic product some seventy times and energy some thirtyfold. The pace has been exponential, so that just during the last fifty years the world economic output increased tenfold to an average world per capita income of almost ten thousand US dollars.[1] This is a level high enough to allow for the fulfillment of basic needs. And yet, the number of poor, measured by those struggling for survival at an income level of 2.5 US dollars per day has increased to almost three billion by the end of the century to decline slightly worldwide while still growing in Sub-Saharan Africa and South Asia.[2] Furthermore, it is estimated that 1.4 billion people live in extreme poverty.[3] Thus, economic development to date has not alleviated poverty in absolute terms[4] while at the same time it did vastly increase resource use and has thereby interfered with planetary processes such as climate.

Technology has been one of the main drivers of the economic and social development during the industrial revolution. Also in the future, technology is likely to be an essential component of resolving the multiple challenges from the elimination of poverty to avoiding “dangerous climate change”.[5] Paul Gray has characterized this phenomenon as the paradox of technology, namely that it is both a part of the problem and of possible solution.[6]

In the broadest sense, technological advance has liberated the humanity from the constraints of natural environment.[7] It has replaced human and animal work by inanimate energy sources, primarily fossil energy, first coal followed by crude oil and natural gas. For millennia, societies were organized to harness the work of animals and slaves. Technological innovation and diffusion allowed for liberation from physical toil of about half of the humanity now living in affluence, most of them in urbanized areas. It has let to almost universal abolishment of slavery and in general a great advance of humanity.

Three hundred years of scientific research have facilitated this process by continuously improving the knowledge and human capacity to generate ever increasing portfolio of goods and services while ever decreasing their unit costs. Undeniably, energy has played a central role in this process. Figure 1 illustrates this improvement for the case of lighting in the UK. Figure 1a shows the exponential

---

[1] Global population increased from one to six and half billion people during the last two centuries since the beginning of the industrial revolution while economic output increased more than seventy fold to about 66 trillion US dollars, energy thirty fold to about 450 EJ and carbon emissions twenty fold to about 36 $GtCO_2$. The resulting global temperature increase was about 0.8 degrees Celsius, Nakicenovic, 2009, World Bank and IPCC.

[2] Chen, S., and Ravallion, M., 2008: The developing world is poorer than we thought, but no less successful in the fight against poverty, World Bank Policy Research Working Paper No. 4703, World Bank, Washington DC, USA and Inter-American Development Bank (IADB), 2005: MDG Goals in Latin America & Caribbean. http://www.iadb.org/sds/mdg/file/Cover,%20Foreword%20and%20Introduction.pdf

[3] World Bank, 2008: World Bank counts more poor people: New figure represents change in methods, not in fortunes. http://go.worldbank.org/CUQLLRX1Q0

[4] Even though the reduction was significant, from about half to quarter of the world population during the last two decades, World Bank Development Report 2010, draft.

[5] UNFCCC, 1992, Article 2.

[6] Paul Gray, 1989, paradox of technology.

[7] Arnulf Grubler, 1998. Technology and global change.

increase of the service, expressed in lumen-years for a range of technologies. Since millennia the artificial light was made by fire, later shifting from wood to lamps fueled by animal fat and later kerosene from crude oil. Public light has always been a heavily regulated market and an essential source of tax revenues, much like the motor fuels today. In some ways, it is the advent of the oil age that has saved the last whales. This is an excellent illustration of the "technology paradox".

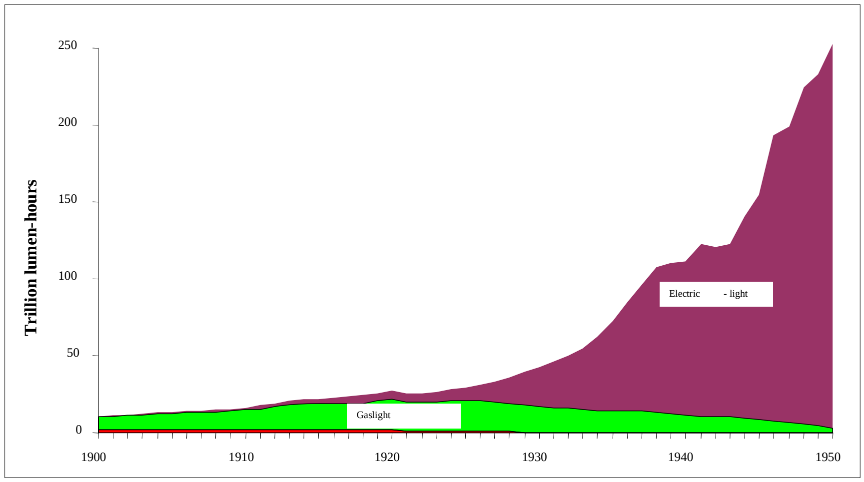

Figure 1a. Lighting in the UK shown in trillion lumen-hours. Source: Fouguet and Pearson, 2003.

Thereafter, vigorous technological change took place. The next source of light was the city gas generally won by coal gasification followed by the advent of electricity that revolutionized lighting along with almost all facets and the very fabric of our societies. The generation of light increased exponentially while the whole underlying technological system has been transformed through a series of technological substitutions, e.g. ever-better incandescent lights, fluorescent and most recently LED lights. Figure 1b shows the radical decline of costs of lumen-hour across a wide range of lighting systems. The vigorous decline of the costs along with the increasing incomes explains the exponential growth of the services purchased across all urban areas in the world, starting the earliest in the areas at the forefront of the industrial revolution and eventually spreading throughout the world.

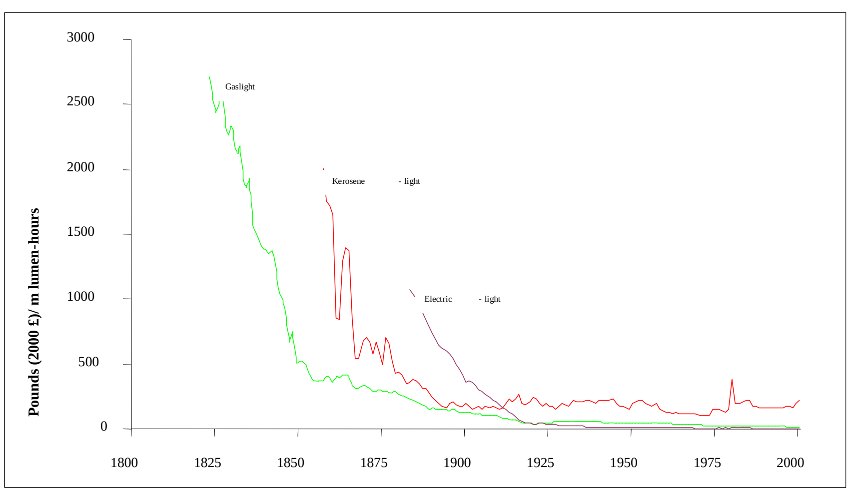

Figure 1b. Cost of lighting in the UK shown in pounds per lumen-hour. Source: Fouguet and Pearson, 2003.

The main hypothesis posed in this paper is that similar radical improvement in technology systems accompanied with vigorous declines of their costs are needed to provide decline in resource requirements of those living in affluence and to bring affluence to the half of the global population excluded today. Specifically, decarbonization of the global energy system is required to providing the services to those without today and for reducing the global greenhouse gas emissions.

Central role of energy services and their planetary implications

The example of lighting illustrates the central role of energy and energy services in human development. Figure 2 shows the historical replacement of traditional energy sources, used since man harnessed fire, by fossil energy sources. Two phases of development are clearly discernable, first the diffusion of coal technologies that is sometimes characterized as the age of coal and the second associated with the age of oil and gas. In reality, both phases are representative for whole techno-economic paradigms that fundamentally changed the rapidly industrializing parts of the world. Not only did coal replace fuel wood and human and animal work, but it catalyzed a giant leap in mobility and manufacturing. Railways became truly continental means of transporting goods and people. Industries and human settlements developed along this new infrastructure further concentrating and increasing the production and consumptions of goods and services. The advent of electricity in conjunction with steam technologies increased manufacturing so that machines were literally making new machines. Internal combustion for the first time connected the world and advanced communication technologies culminating in the self-organizing internet have globalized our planet.

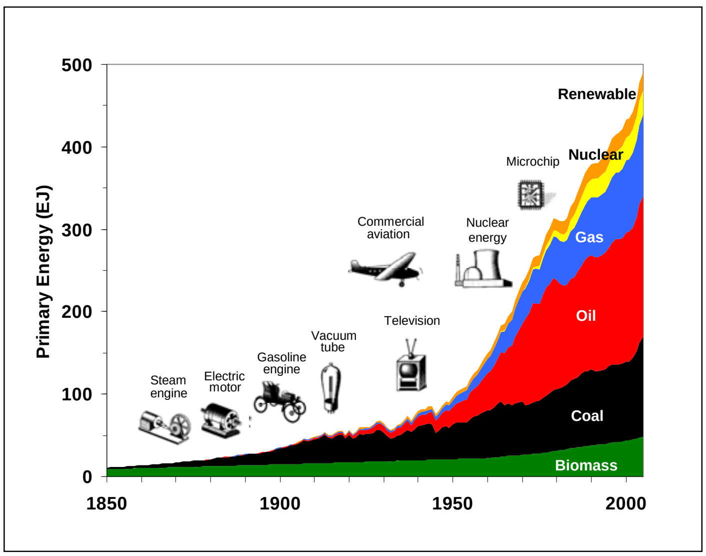

Figure 2. Global primary energy development in exajoules-years. Source: Nakicenovic, 2007

The possible advent of the post-fossil age is indicated by rapid diffusion, but still humble shares of "modern" renewables and nuclear energy. After half of century of nuclear power, the world has more than 400 operating power plants with almost half a terawatt of installed electric capacity (TWe).[8] Wind and photovoltaics have been expending at astonishing rates. Between 2005 and 2008, the global wind installed capacity increased threefold to some 120 gigawatts (GWe) while the

[8] International Atomic Energy Agency, 2009.

photovoltaics grew fourfold to some 16GWe.[9] These developments could be the embryonic elements of the transition toward the post-fossil societies.

In the meantime, the global energy system remains to be predominantly fossil. Figure 2 shows that in the span of the last 150 years the contribution of fossil energy sources increased from some 20 to over 80 percent. A direct consequence of this development during the last 150 years is the twentyfold increase in carbon dioxide emissions compared to the thirtyfold increase in primary energy. In other words, despite an increase in the shares of fossils in the global primary energy, there was a clear historical trend toward decarbonization. This is so because less-carbon intensive fossil energy sources oil and gas replaced coal during the last 70 years. Despite this decarbonization, the increase in total emissions has contributed to an “unequivocal” change in global climate system as illustrated in Figure 3.[10] The global mean temperature change has increased by some 0.8 degrees Celsius during the last 150 years with much of this increase directly attributable to anthropogenic sources of climate change, most of these directly associated with fossil energy extraction, conversion, distribution and end use. In 2007, the Intergovernmental Panel on Climate Change (IPCC) noted that eleven of the last twelve years have been the warmest ever measured on the instrumental record.[11]

This is another example of the technology paradox. Vigorous increase of energy services has brought prosperity to many but has at the same time interfered in the climate system bringing adverse and dangerous changes to most of the humanity especially those who have been excluded from the this development as they are generally the most vulnerable.

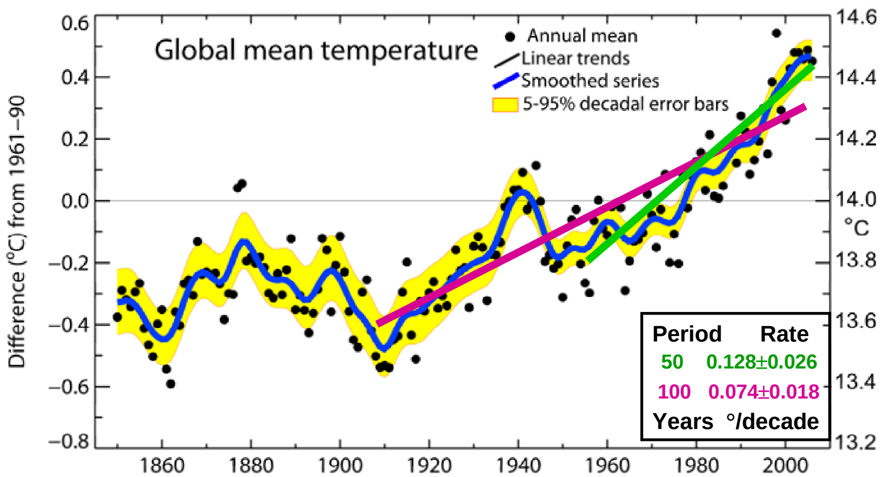

Figure 3. Global mean temperature increase measured in degrees Celsius. Source: IPCC AR4, 2007.

The need for transformational change

Modern energy services in the majority of developing countries are often unaffordable and are characterized by inequitable access, notably between the poor and affluent; as well as, between rural and urban areas. Consequently, most have to rely on traditional energy sources meaning hours of collection of fire wood along with water while other half of the global population takes the amenities of modern live for granted. Adverse environmental impacts can be recognized on all scales, from indoor air pollution to biodiversity loss and climate change.

[9] REN21, 2009.
[10] IPCC, AR4, 2007.
[11] Ibid.

Particularly concerning is the recent confluence of financial, ecosystems, climate and other crises in the world. As Buzz Holling notes, these crises have been recognized for a long time, but what is new is their simultaneity and the need to resolve them at the same time.[12] Many are affected by this confluence of crises, while half of the globe did not benefit from the materials and carbon intensive nature of economic growth that caused the adverse planetary emergencies. The current development patterns are thus clearly unsustainable. A fundamental paradigm change is needed for a shift toward more sustainable development paths called for in the UN Secretary General's initiative toward the Global New Green Deal.[13]

The recent financial crisis, the ensuing ever deeper economic depression and price volatility are no doubt going to bring additional hardship especially to a third of the global population that is still without access to basic human needs such as energy and food services. A predominant social issue that is increasingly becoming a major preoccupation for world leaders is addressing social inequality and poverty, especially in the developing world.[14] The longer the economic crisis deepens, the more threatened will be those living in poverty.

Affordable access to modern and environmentally sound energy services has a significant role to play in meeting all development goals as it is a fundamental prerequisite for improving human condition and life styles. However, modern energy services in the majority of developing countries are characterized by inequitable access, notably between the poor and affluent; as well as, between rural and urban areas. At the national level, this is demonstrated by the low levels of modern energy in the primary energy supply; low electrification levels; and low consumption levels of clean fuels for cooking, lighting and sustaining economic livelihoods.

About two billion people in the world, a third of the world population, are without access to modern energy and about 1.6 billion are without access to electricity – the very symbol of affluence and modernity – while still about 2.4 billion cook with traditional forms of biomass.[15] Limited access to cleaner energy services supplied by modern energy carriers is an important contributor to rising levels of poverty in some sub-Saharan African countries.[16]

Even in the developed parts of the world, price volatilities and lack of long-term investments have resulted in aging of energy systems and infrastructures threatening their security and reliability while resulting in ever growing emissions of greenhouse gas emissions (GHGs).

Thus, there is a clear need to embark on a new development path toward sustainable and affordable access to adequate energy services and towards environmental sustainability in general. Fortunately, many policies and measures directed toward increasing access to modern energy services have

---

[12]Buzz Holling, Paper delivered at IIASA Strategy visioning workshop, 2008.

[13]Barbier, E.B., 2009: A Global Green New Deal, University of Wyoming, http://www.unep.org/greeneconomy/docs/GGND_Executive_Summary.pdf

[14] Karekezi, S. and Sihag, 2004: A. "Energy Access" Working Group Global Network on Energy for Sustainable Development. Synthesis/Compilation Report. Risø National Laboratory, Roskilde, Denmark.

[15] Nakicenovic, N., Grübler, A., and McDonald, A. (eds), 1998: Global energy perspectives, Cambridge University Press, Cambridge, UK, 281 pp., and United Nations Energy (UN-Energy), 2005: Energy Challenges for Achieving Millennium Development Goals, http://esa.un.org/un-energy.

[16] United Nations Development Programme (UNDP), 2007: *Mainstreaming access to energy services: Experiences from three African regional economic communities*. UNDP Rural Energy for Poverty Reduction Programme, 2007-05-01 and United Nations Development Programme (UNDP), 2007: *A review of energy in national MDG,* Reports by Takada, M., and Fracchia, S. UNDP Publications, New York, NY, USA. `
http://www.energyandenvironment.undp.org/undp/indexAction.cfm?module=Library&action=GetFile&DocumentAttachmentID=2088

multiple benefits for other development goals, from the reduction of in-door air pollution and its assaults on human health to reductions of GHG emissions.

Energy investments in the confluence of the financial and economic crises

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

There is ample evidence for adverse effects such as the decreasing investments. For example, Figure 4 shows that the investments in modern renewables might decline by as much as 40 percent in 2009 after increasing fourfold between 2005 and 2008.[17] They were on the order of some US$80 to 120 billion (2008).[18] Particularly significant are the expected declines in the wind and photovoltaic investments (after vigorous growth during the past years, see above).

The investments in the coal sector indicate similar decline of about 40 percent in 2009 compared to 2008.[19] The reduction of upstream investments in oil and gas is for the time being less dramatic with an expected decline of about 20 percent corresponding to some $100 billion.[20] In addition, according to the IEA some 20 oil and gas projects, valued at some $170 billion, have been deferred between October 2008 and April 2009.[21]

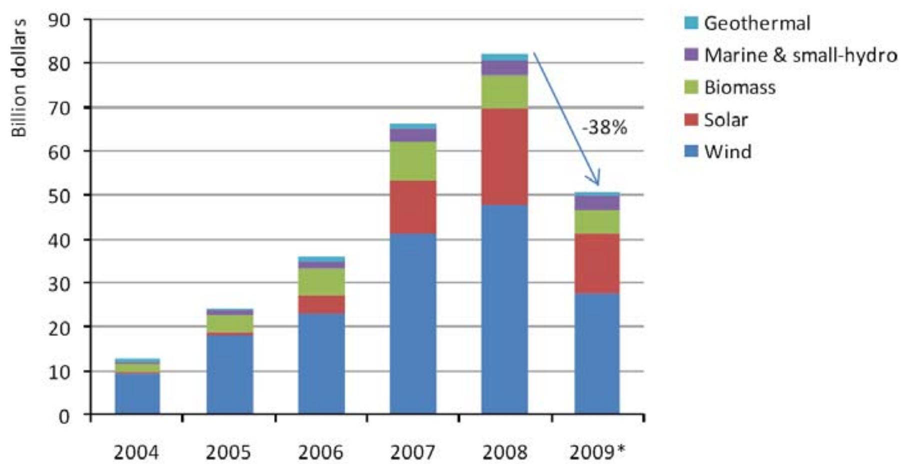

Figure 4. Global investments in new renewable energy sources. Source: IEA, 2009.

The cutbacks in investments are likely to deepen the longer the financial and investment crises last. They are significant given that the total energy supply investments in the world are at most about $500 billion per year. At the same time, energy subsidies are valued at between $200 and 300 billion per year, or roughly at half of the total investments.

These setbacks in global energy investments can cast a long shadow on future development prospects and further constrain economic growth through the aging of the energy systems and lack of adequate

[17] International Energy Agency, Impact of the financial and economic crises on global energy investment, 2009.
[18] International Energy Agency, Impact of the financial and economic crises on global energy investment, 2009 and REN21, 2009.
[19] International Energy Agency, Impact of the financial and economic crises on global energy investment, 2009.
[20] Ibid.
[21] Ibid.

infrastructures and supply. The aging of the systems would postpone the shift toward less carbon-intensive sources of energy while at the same time making access to energy services by those excluded even more permanent. This means that the carbon dioxide emissions might fall with the declining demand and production of energy but would increase as soon as the economy starts recovering. Aging energy systems would increase significantly the inherent energy vulnerabilities, risks of systems failures and security of supply and demand.

Opportunity for transformational change and climate protection

At the same time, this crisis of the "old" is an opportunity for the "new" to emerge. This is an opportunity that needs to be sized and should not go to waste. Joseph Schumpeter has referred to this kind of paradigm-changing transformations as "gales of creative destruction".[22] As old techno-economic and institutional development paths saturates, the chances for fundamentally new development paths to emerge and eventually diffuse are more likely.

Decarbonization of the global economy toward a carbon-free energy future is and example of such a paradigm-changing transformation. It appears to be a must, given the ever more threatening manifestations of global climate change. As mentioned, the unequivocal message of the IPCC Fourth Assessment Report is that climate change is accelerating and is almost certainly largely man-made. The adverse effects of the climate change can already be felt. The changes in average temperature are not a primary concern, but rather increasing climatic variation in climate patterns. Regions traditionally suitable for settlements and agriculture might not longer be so due to changing precipitation patterns, hydrology and ecosystems. Determined action from the international community is required to promote innovation and technological developments for climate protection. This is a major planetary urgency.

Figure 4 illustrates some of the "reasons for concern" regarding "dangers" of climate change for different sectors. [23] It shows five (so-called "red-amber") columns for different risks of climate change. All five indicate significant reasons for concern for global mean temperature increase in excess of two degrees Celsius above the present. The horizontal bar labeled as two degrees Celsius indicate the global temperature increase above the preindustrial levels (as the increase of 0.8 degrees has been already realized). They have significantly increased since the IPCC Third Assessment Report published in 2001. [24]

[22] Schumpeter, J.A., 1942: Capitalism, Socialism and Democracy, Harper & Brothers, New York, NY, USA. The notion that gales of creative destruction lead to the emergence of the new is particularly challenging in the context of rescue and stimulus strategies to counter the economic slowdown because the majority focuses on supporting the old with the inherent risk of postponing the structural change toward the new thus deepening the crisis.

[23] Smith et al. PNAS, 2009

[24] IPCC, AR3, 2001.

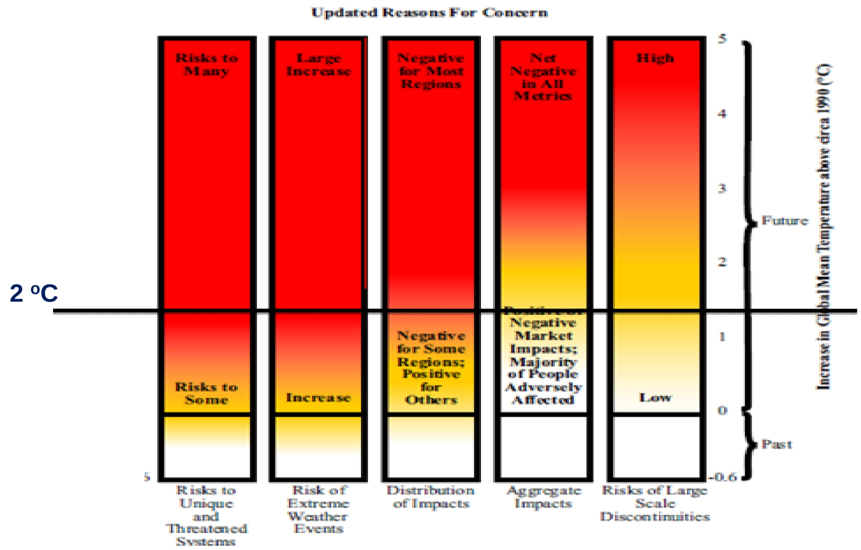

Figure 4. Reasons for concern regarding consequences of climate change indicated by the global mean temperature change in degrees Celsius. Source: Smith et al. PNAS, 2009.

As mentioned above, the United Nations Framework Convention on Climate Change (UNFCCC) in its Article 2 calls for stabilizing greenhouse gas concentrations in the atmosphere at a level that ‘‘would prevent dangerous anthropogenic interference with the climate system.’’ While the question of what constitutes dangerous climate change is somewhat ambiguous, IPCC and other studies suggest that increases greater than two degrees Celsius above preindustrial levels sharply increase risks, so that “significant benefits result from constraining temperatures to not more than 1.6ºC—2.6ºC”[25].

More recent scientific publications further support the notion that warming should be constrained to remain below two degrees Celsius above preindustrial levels.[26] These include the European Commission,[27] Scientific Expert Group on Climate Change,[28] International Scientific Steering Committee,[29] the World Bank’s Development Report[30] and so on. The organizers of the 2009 International Scientific Congress on Climate Change in Copenhagen concluded that “there is increasing agreement that warming above two degrees Celsius would be very difficult for contemporary societies and ecosystems to cope with.”[31] Most recently, the G8 meeting in meeting in L’Aquila “… recognize(d) the broad scientific view that the increase in global average temperature above pre-industrial levels ought not to exceed 2°C.”[32] Consequently, this aspirational temperature target has been reflected in many private sector and public climate stabilization goals including all of the European Community countries, many other countries, many private companies and cities.

Much controversy still exists about how the uncertainty associated with any such aspirational target. For example, in the IPCC Fourth Assessment Report, the temperature interval of 1.6 to 2.6 degrees Celsius was given instead of a single number and indicates significant uncertainty associated with

[25] Fisher and Nakicenovic, et al., IPCC, 2007; Parry et al., IPCC, 2007.
[26] Mann, Science Focus, 2009; Smith et al, PNAS, 2009.
[27] European Commission, 2007.
[28] SEG, 2007.
[29] International Scientific Committee, 2005.
[30] World Bank, Development Report, 2010, draft.
[31] Climate Change: Global Risks, Challenges and Decisions. http://climatecongress.ku.dk/
[32] G8 Declaration, 8 July 2009.

any temperature target. Often, two degrees target denotes a 50 percent chance of being below this temperature increase but also 50 percent of being above. Recently, there have been numerous calls for associating the target of two degrees with much higher likelihoods of achieving it than just half a chance.

Any temperature stabilization target has implications for future emissions pathways. In the first approximation, it can be translated into a cumulative "emissions" budget. Higher initial emissions require deeper cuts thereafter. The more significant such an overshoot becomes, the lower the emissions must be later, dipping into negative regions in most of such scenarios. Figure 5 shows such future emissions paths for a range of stabilization scenarios consistent with the two-degree target. They are shown against the backdrop of the range of all possible emissions scenarios in the literature shown as dashed lines.[33] The "stylized" picture that emerges indicates the fossil era that started some two to three hundred years ago would peak in a decade or two and senesced within half a century followed perhaps negative emissions for a while before retuning to zero like in the preindustrial era.

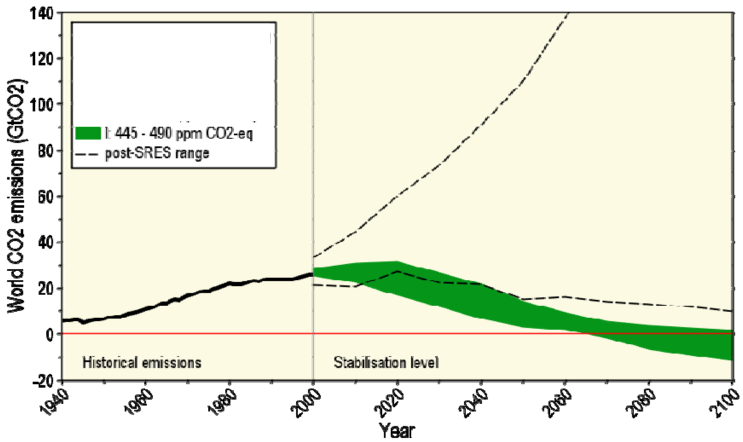

Figure 5. Historical global carbon dioxide emissions and in scenarios, dashed lines indicate the range of the literature while the green band shows the emissions for scenarios that stabilize global mean temperature increase at two degrees Celsius.

All of the stabilization scenarios indicate a global emissions peak between now and 2020 with emissions declining thereafter. Many become negative in the second half of the century implying diffusion of carbon-removing technologies. These could be enhanced carbon sinks, "artificial threes" that remove carbon from the atmosphere or sustainable biomass in conjunction with carbon capture and storage (resulting in effectively negative emissions). The technological challenges associated with this transformational change in such a relatively short span of time are truly revolutionary. The replacement of current vintages with low to zero-carbon technologies needs to be immediate. This will require large investments in technologies and infrastructures to be able to enable pervasive diffusion. A prospect that is hampered by declining energy investments even though large opportunities may occur if rescue and stimulus packages are directed toward "green" energy investments.

Future technology portfolios and their diffusion

Climate protection and energy systems decarbonization is effectively blocked today by the addictive dependence on fossil energy sources. This explains the need for Schumpeterian "gales of creative

[33] Fisher and Nakicenovic et al., IPCC, 2007.

destruction". Today, 80 percent of global energy is from fossil sources and this needs to be reversed so that 80 percent of energy would be carbon-free or carbon neutral after the mid-century.[34] The old energy systems need to be replaced by innovative, highly efficient, environmentally and climate friendly alternatives. In parallel, the reliance on inadequate access to traditional energy services by the poor which constitutes some 20 percent of primary energy also needs to be replaced by more efficient and modern renewable and other clean energy sources.

In the energy area, this implies a shift from traditional energy sources, in the case of those who are excluded from access, to clean fossils and modern renewable energy, and in the more developed parts of the world a shift from fossil energy sources to carbon-free and carbon-neutral energy services. In all cases this means a vigorous improvement of energy efficiencies, from supply to end use, expanding shares of renewables, more natural gas and less coal, vigorous deployment of carbon capture and storage, and in some cases where it is socially acceptable and economically viable also nuclear energy.

Improved access to energy services and improvement of energy efficiencies especially in end us should be initiated immediately as it does not need much innovation but rather income redistribution and deliberate access and rational energy use policies. It is estimated that connection of a household without access to electricity costs on the order of thousand dollars resulting in total capital needs of about $500 billion, assuming on average about four persons per household and two billion without access. Distributed over say twenty years, this translates into annual investment requirements of some $25 billion. This represents a huge investment that is lacking but that does not appear excessive in comparison to gigantic scale of the government guarantees and dept cancellation in the financial sector since the crisis has emerged. To be effective, this kind of investment would have to be enhanced with a certain level of affordable energy for the poorest, say 700-1000 kWh per year or about two to three kWh per day.[35]

Thus, a comprehensive portfolio of options is needed in moving towards more sustainable energy systems and more equitable access to energy services. Efficiency improvements are above all an essential prerequisite for embarking on a development path toward full decarbonization of the global economy. Up to half of all measures and policies toward lower energy intensiveness and emissions are attributed to efficiency improvements across a wide range of studies because they have the lowest costs and in principle can be implemented swiftly.[36]

Another key technology is carbon capture and storage (CCS). Most of the scenarios developed by the scientific community to understand how to achieve the stabilization of temperature at about two degrees Celsius, identify CCS technology as being central and necessary. It appears that it would be difficult to reach the climate and other development goals without a vigorous deployment of CCS. Most of the components of CCS systems have been tested on the pilot level, in the range of storing about million tons of carbon dioxide per year. What is still outstanding is a full scale-up and

---

[34] Nakicenovic, N., and Riahi, K. (eds), 2007: Integrated assessment of uncertainties in greenhouse gas emissions and their mitigation, Technological Forecasting and Social Change, Special Issue, 74(7), September 2007.

[35] Wissenschaftliche Beirat der Bundesregierung Globale Umweltveränderungen (WGBU), 2009: Welt im Wandel: Zukunftsfähige Bioenergie und nachhaltige Landnutzung, Berlin. http://www.wbgu.de/wbgu_download.html

[36] International Energy Agency (IEA), 2008: *Energy technology perspectives, scenarios and strategies to 2050*, Organization for Economic Co-operation and Development (OECD) and International Energy Agency (IEA) Publications, Paris, France, 600 pp, Nakicenovic, N., and Riahi, K. (eds), 2007: Integrated assessment of uncertainties in greenhouse gas emissions and their mitigation, Technological Forecasting and Social Change, Special Issue, 74(7), September 2007, and Intergovernmental Panel on Climate Change (IPCC), 2007: Climate Change 2007 – the Fourth Assessment Report of the IPCC, Cambridge University Press, Cambridge. .

integration in the energy systems. This is necessary for gaining experience, social acceptability, reduction of risk and other adverse technology impacts and reduction of costs.

Renewable energy sources as well as nuclear energy faces similar challenges of acceptability, scale-up, integration into the energy systems and often higher costs compared to traditional alternatives. This is despite substantial deployment of in many parts of the world. Deployment of new and advanced technologies will require dedicated and sustained investments. Most of the studies indicate that portfolios of multiple options need to be pursued, even if at the end a few may not prove practical, economic, or socially acceptable.

Figure 6 shows ex post “learning curves” implicit in the scenarios of future energy systems development. Today, there are some 4 TWe installed capacity in the world in form of large power plants. The installed capacity of all car engines is an order of magnitude larger with some 40 TW of mechanical power. Most of the key technologies for electricity generations would reach in the second half of the century installed capacities compared with the global car fleet. In a way, this also indicates how large are the opportunities offered by the development of so-called “smart grids” to interface electric and hybrid cars with the electric networks.

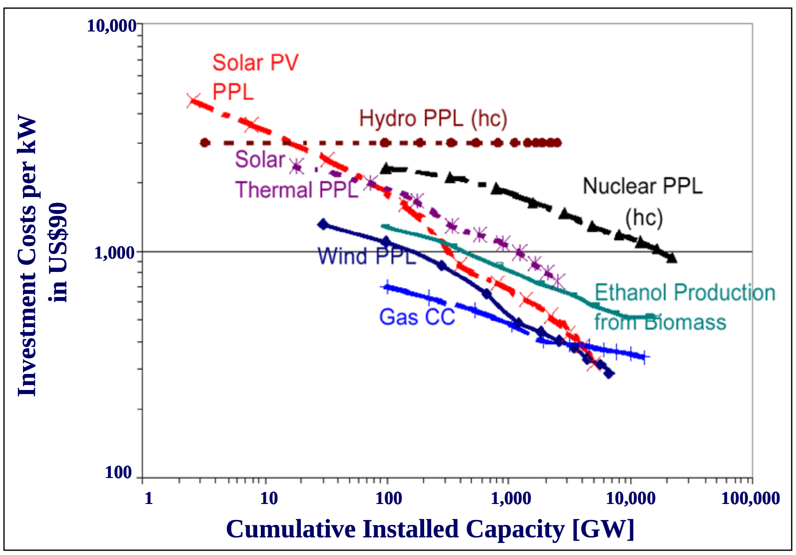

Figure 6. Costs reductions and installed capacity increase across IIASA emissions scenarios, from 1990 to 2100. Source: Riahi, 2005.

As mentioned above, the current wind installed capacity is 120GWe and this would increase 10TWe corresponding to some ten million wind mills each with a capacity of 10MWe or twenty million with unit capacities to be expected to be reached over the next years. The growth of photovoltaics would be even more extreme from some 16 GWe today to 10 TWe, almost a thousandfold increase.

These enormous increases in installed capacities of global power plants would need to be accompanied by vigorous declines in unit costs to become affordable and attract sufficient investments. In the scenarios, it is envisaged that the unit cost would decline by an order of magnitude. In addition to vigorous investments, such costs reductions would require dedicated and sustained research and development efforts across different systems and for their integration.

The current investments in the global energy system are estimated at some $350 to 500 billion per year.[37] This includes investments in energy production, conversion and distribution but excludes most of the end use such as vehicles, heating systems or industrial facilities. Adding end-use investments would bring the estimate to some $750 billion per year. The scenarios that achieve sustainable development in the world and stabilize global temperature change at about two degrees Celsius by the end of the century would require at least twice this effort during the coming decades of about one trillion per year by 2030 or about $20 trillion cumulative investment by 2030. In comparison the investments for providing access to the two billion are relatively small with about $25 billion per year or about $500 cumulative investment by 2030.

Figure 7 shows the future energy investments across a range of scenarios developed at IIASA.[38] The difference in investment needs for different stabilization levels is very small in comparison to the total investment requirements. This might appear to be a very surprising finding. Often, scenarios with vigorous mitigation options lead to substantially higher investment needs and costs compared to the baseline. The reason is that the marginal abatement costs tend to increase with lower emissions levels.

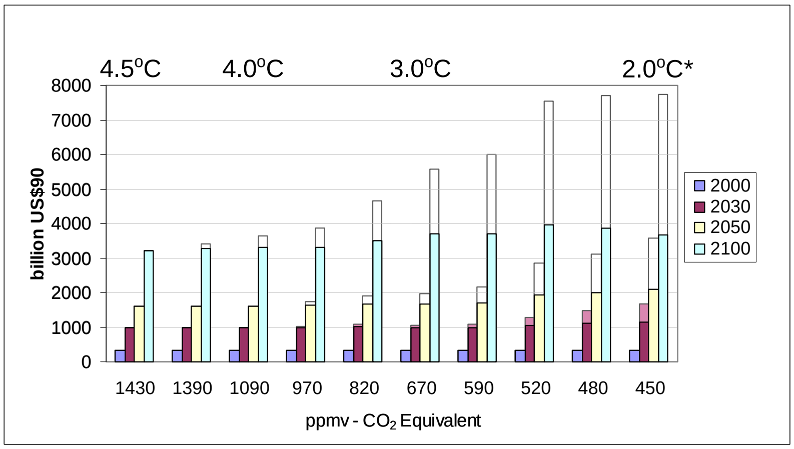

Figure 7. Energy investment requirements across IIASA stabilization scenarios ranging from 1400 to 450 ppmv CO2-equivalent. Color bars show investments in energy supply and transparent ones in energy end use. Source: IIASA, 2009.

However, here the lower emission levels are associated with drastic improvements in energy efficiencies that become and integral part of the mitigation portfolio. Efficiency is not only the cheapest mitigation option but it also helps reduce investment costs upstream. Higher efficiencies offset higher capital intensiveness of carbon-saving technologies including those that result in negative emissions such as sustainable biomass with carbon capture and storage. By 2030, the investment requirements in the two-degree stabilization case are about ten percent higher on the upstream supply side.

However, there appear not to be any free lunches in these mitigation strategies. Efficiency improvements and energy savings encompass the end use. This implies life-style changes such as in mobility but also higher investments in end-use technologies. This can significantly increase the

[37] Nakicenovic and Kimura, 2005: Global Scenarios for the Energy Infrastructure Development, IR-05-028, International Institute for Applied Systems Analysis, Laxenburg, Austria, and International Institute for Applied Systems Analysis (IIASA), 2007: GGI Scenario Database, http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=htmlpage&page=series.
[38] See IIASA scenario database at: http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=htmlpage&page=series.

overall investment requirements to some 60 percent over the scenarios that stabilize in the range of three degrees and more.

The stimulus packages across the world make the energy investments appear to be humble with about one trillion dollars in by 2030. The total funds unveiled for stimulus packages exceed three trillion[39] and might be as large as ten trillion.[40] The "green new deals" are substantively smaller with an average of 14 percent and range from just a few percent up to almost 70 percent in South Korea.

Research and development as a driver of innovation

Strong research and development efforts are needed in order to create the necessary scientific foundations for the paradigm-changing transformations, from energy access to climate protection. Also needed are enhanced science and research efforts to gain better understanding of the complexity of processes and interactions within and across human dimensions of change, the climate and the earth systems. All told, the important aim is to enhance innovations diffusion to help achieve structural changes in the society, the economy, institutional structures, and lifestyle and consumption patterns. We need to establish a foundation for the deployment and adoption of new systems and services that lead toward complete decarbonization in the world.

In other words, research and development of innovations that lead to diffusion of new and advanced technologies and practices are a possible long-term solution to the double challenge of providing the development opportunities to those who are excluded and allowing for further development of the more affluent. This needs to occur without risking irreversible changes in ecological, biophysical and biochemical systems. Another way of seeing this challenge is as yet a further example of the technology paradox.

The nature of technological change and the associated deep uncertanties require innovations to be adopted as early as possible in order to allow for experimentation, and to ultimately lead to lower costs and wider diffusion in the following decades. The longer we wait to introduce these advanced technologies, the higher the required emissions reduction will be. At the same time, we may miss the opportunity window for achieving substantial cost reductions. This requires research, development and deployment as well as investments to achieve accelerated diffusion and adoption of advanced energy technologies. It also requires immediate efficiency improvements to improve access and reduce emissions at all scales. Resulting lower energy requirements support in an important way and are a prerequisite for diffusion of low-carbon and even more efficient technologies.

Current energy research and development trends are unfortunately not commensurate with unprecedented need for technology development and diffusion. Public expenditures in OECD countries have declined to some $8 billion from about $18 billion two and a half decades ago, while private ones have declined as well. Many studies indicate that research and development needs to increase by at least a factor of two to three in order to enable the transition toward new and advanced technologies in the energy systems.[41]

---

[39] HSBC, 2009.
[40] Sten Nilsson, IIASA, 2009.
[41] Bierbaum, R., Holdren, J.P., MacCracken, M., Moss, R.H., Raven, P.H., Nakicenovic, N. et al.: 2007, Confronting climate change: Avoiding the unmanageable and managing the unavoidable, Scientific Expert Group Report on Climate Change and Sustainable Development, United Nations Foundation and Sigma Xi, The Scientific Research Society, North Carolina, USA.

Figure 8 shows the public energy research and development efforts in the OECD countries that contribute about 90 percent of the global public expenditures. It is clear from the figure that most of the public research and development funds were allocated to nuclear energy. Efficiency, fossils and renewables in aggregate receive substantially less funding than nuclear alone.

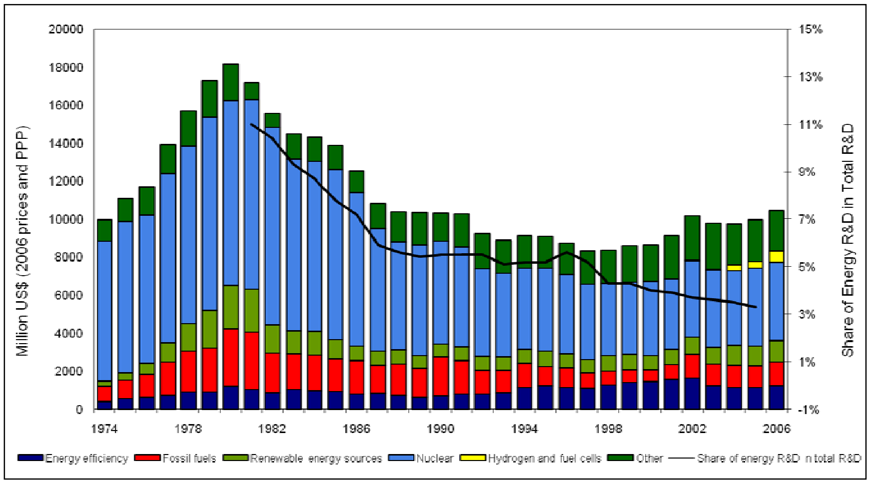

Figure 8. Public energy research and development in the OECD countries in billion dollars. Source: Source: IEA Databases, Doornbosch, et al., 2008.

Clearly, energy research and development needs to be enhanced as efficiency, renewables and advanced fossils including carbon capture and storage are the key technologies for achieving transformational change of energy systems and deep reductions in greenhouse gas emissions. Furthermore, the share of energy research and development efforts in total has decreased in unison with the total outlays since the aftermath of the last energy crisis in 1973 to 1979. The decrease was from some 11 down to 3 percent.

Thus, at least a threefold to fourfold increase in energy research and development efforts would appear to be commensurate with the huge challenges ahead and would be consistent with the historical high some quarter of the century ago. The IEA assessment of technology perspectives indicates that climate change has emerged as a key driver for public research and development investments in energy along with energy security and economy.[42] Most countries foresee an increase in RD&D investments in the coming years, although generally modest in scale. It appears that much of the research and development efforts are focused on shorter-term payoffs. Notable exceptions are the recent energy research and development plans in the United States.

As mentioned, the required investments in energy systems are about four orders of magnitude larger with about half a trillion dollars per year compared to the less than about $50 billion of global research and development efforts ($8 billion public and roughly five time more from the private sector) or at least twice the curmnent level of investments with most of the requirements being in developing parts of the world. To achieve a transition toward more sustainable development paths requires substantially larger investment both in energy systems and infrastructures and in energy research and development.

[42] IEA, Technology Perspectives,

A number of studies call for research and development efforts need to be tripled[43] and energy investments at least doubled in order to assure the timely replacement of energy technologies and infrastructures.[44] There is a large ambiguity how large energy research and development efforts should be given the multiple challenges. However, to effectively spur economic growth in the new knowledge economy, public policies must go beyond its traditional roles of spurring consumption Keynesian style or simply cutting taxes on capital.[45] Science, technology, and innovation are the major drivers of the needed transformational change. On top of that, research and development are inherently a public good so that one should expect the private sector to underinvest in these efforts, which needs to be spurred by higher public outlays.

However, in contrast to embodied technology investments, the disembodied nature of research and development is notoriously difficult to measure. We have only sporadic data on the public sector efforts and very little reliable information on the private ones. Furthermore, the data are input-oriented, namely they account for monetary inputs but do not measure adequately the outputs.

Given all of these limitations and ambiguities, we will use very simple analogies to derive some estimates of the needed research and development efforts to be commensurate with the energy challenges.

- Public energy research and development was about 11 percent of total efforts in 1979 and is about three percent today. Total public OECD research and development expenditures are over $250 billion today translating into more than $27 billion taking the historical high share of 11 percent to be commensurate with current needs. This translates into a threefold increase.
- In 2004, the OECD public research and development efforts were allocated in the following way across the sectors: $54 billion in basic research; $59 billion in competitiveness; $53 billion in sustainability; and $84 billion in defense and homeland security. Assuming that energy is an essential prerequisite for resolving the other challenges from competitiveness to sustainability, one could infer that a fivefold increase compared to the current efforts of some $8 billion would be appropriate.
- The cumulative OECD public research and development efforts in nuclear energy translate into some $180 billion since 1974. During the same period, some 300 GWe installed capacity came on line. This translates into about $0.6 billion per GWe installed. In contrast, 160 GWe of modern renewable energy have been installed since 1974 with the total research and development outlays of some $30 billion over the same period. Applying the nuclear numbers to the renewables would increase the total cumulative energy research and development needs to some $100 billion for the period or by $6 billion today assuming a liner increase from 1974. Doing the equivalent calculation for efficiency improvements would triple the current public research and development outlays.
- The OECD GDP was about $4.5 trillion at current prices in 1974 and is now about $34.4 trillion. Applying the energy research development intensity in GDP of 0.4 percent from 1974 to 2004 GDP translates into some $140 billion or a 17-fold increase compared to the current outlays.

---

[43] Bierbaum, R., Holdren, J.P., MacCracken, M., Moss, R.H., Raven, P.H., Nakicenovic, N. et al.: 2007, Confronting climate change: Avoiding the unmanageable and managing the unavoidable, Scientific Expert Group Report on Climate Change and Sustainable Development, United Nations Foundation and Sigma Xi, The Scientific Research Society, North Carolina, USA.
[44] See investment requirements across IIASA scenarios shown in Figure 7 above.
[45] The Case for Technology in the Knowledge Economy R&D, Economic Growth, and the Role of Government1 Kenan Patrick Jarboe and Robert D. Atkinso, In Policy Brief, June 1998.

Summary and conclusions

In summary, we were not able to answer the question how much research and development in energy would be required to catalyze the needed investments over the coming decades by helping lower energy costs and investments through technological improvements. The rough indicators is that pubic and private energy research and development should be in the range of $150 billion per year assuming that the tripling of current efforts would be commensurate with the investment needs which should be increased to about a trillion per year. Both goals would be difficult to achieve. The confluence of the financial and economic crises has made the investment capital scarce with early indicators that energy investments are declining rather than increasing. The energy research and development budget appear to be increasing but there is a danger especially in the private sector that they are predominantly focused on potential short-term benefits.

At the same time, the pledged stimulus packages are in the range of three to ten trillion and in some countries like South Korea and China a substantial part is directed toward “green” investments. There is a great opportunity of dedicating an increasing part of these sums toward enhancing energy research, development and investments toward the needed transformational change.

These investments should be made because technology, innovation, and knowledge are critical factors in human development and economic growth:[46]

- There is a significant private return on research and development investment at the firm and industry level—but an even greater return for society as a whole;
- There is a positive social value of raising the level of investment in technology and knowledge creation over that determined solely by the market and this is especially true for energy research, development and investments;
- Technology and knowledge interact with a number of other factors, such as investment in equipment and education; and,
- Knowledge creation and technological innovation require special attention to institutional arrangements but are critical for furthering the development in the world and helping the half of the humanity that was left behind during the industrial revolution leapfrog toward sustainable affluence.

Post script

The salient finding of a number of recent integrated assessment studies is that additional costs for achieving more sustainable futures and climate stabilization are relatively small in comparison to these ovearll investment needs. In some cases, they are even “negative”, namely lower, compared to traditional scenarios of future developments, sometimes called business-as-usual (BAU). However, the more sustainable futures require higher “up-front” investments during the next decades. The great benefit of these additional investments into a future, characterized by more efficient and carbon-free energy systems and a more sustainable development paths, is that in the long-run (to 2050 and beyond) the investments would be substantially lower compared to the BAU alternatives. The reason is that the cumulative nature of technological change translates the early decarbonization investments into lower costs of the energy systems in the long run along with the cobenefit of stabilizing greenhouse gas concentrations. This all points to the need for radical change in energy policies in order to assure sufficent investment in our common future and thereby promote accelerated

[46] The Case for Technology in the Knowledge Economy R&D, Economic Growth, and the Role of Government1 Kenan Patrick Jarboe and Robert D. Atkinso, In Policy Brief, June 1998.

technological change in the energy system and end use. In other words, the global financial and economic crisis offers a unique opportunity to invest in new technologies and practices that would both generate employment as well pave the way for a more sustainable future with lower rates of climate change. The crisis of the “old” is a historical chance to saw the seeds of the “new”.