The ecological and economic consequences of Global Climate Change

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RUNNING TITLE: GCC Impact Projections
**ABSTRACT**

Our planet has always experienced climate changes during its geological history, but because of the massive emission of greenhouse gases, climate is now expected to change at unprecedented rates. Quite likely, neither ecological nor anthropological systems will have the time to straightforwardly adapt to the new conditions. What should we expect for the following years? Which will be the cost of the do-nothing alternative? Which will be the benefits and the costs of effectively implementing the Kyoto Protocol? In this paper we intend to briefly review the potential impacts of global climate change. Before actually addressing the issue of prospective impacts, the first section of this work is devoted to briefly addressing the two following questions: a) do we already have evidence of climate change with respect to only half a century ago? If so, are these changes to some extent induced by anthropogenic activities, specifically by Greenhouse Gases (GHG) emissions by humans?; b) which are the predictions concerning future climate change? And which are the prospective consequences of these changes on physical and ecological systems?

In the second part of this paper, we briefly review the economic consequences of climate changes deriving them under different assumptions and scenarios. Specifically, after a brief description of the economic methods commonly used to value the impacts of GHGs we present a cost-benefit analysis of the Kyoto Protocol. We then conclude by briefly reviewing other economic studies related to the reduction of GHGs emissions and the opportunities and the costs of carbon sequestration.

**KEYWORDS:** physical impacts; biological impacts, economic impacts, projections, uncertainty, externalities, monetary evaluation, cost-benefit analysis.
INTRODUCTION

In the past ten years following the Rio Conference, Global Climate Change (GCC) has emerged from substantial obscurity to one of the prominent and most controversial environmental issues in the political agenda of governments around the world. Much has been argued about the potential effects of fossil fuel use and an endless number of words has been spent to support or criticize the often partial and contradictory projections carried out by several research centers in the 1990’s on the effects of greenhouse gasses (GHG) emissions. The lack of consensus originated from, and thrived on, the scientific uncertainty that characterized the issue in the last ten years, but it was indeed rooted also in the different social and political priorities and value judgments regarding the risks and the costs of GCC. As a consequence, it is still hotly debated whether climate will really change so badly, whether it is worthwhile to take action in the face of uncertainty and who is going to pay the costs - or enjoy the benefits - of either reducing GHG emissions (mitigation) or minimizing the damages due to GCC’s if they will ever occur (adaptation). The opponents to a substantial reduction of GHG emissions have typically defended a business-as-usual strategy on the basis of the two following arguments:

- Earth’s climate has always changed, both on a geological time scale and in the short term. Climate variability on an annual and seasonal basis is so high that it is simply impossible to detect whether any perceived anomaly in climate patterns is actually due to human activity or to any other unknown natural process.

- Any potential effect, whether positive or negative, will become evident only in the long term. Consequently, costly actions aimed at reducing GHGs should not be taken, as they would rapidly depress the market and pose an unbearable burden on consumers in the face of vague and undefined benefits that will be received only in the distant future. Rather than trying to guide policy action on the basis of unknown or ambiguous phenomena characterized by a great number of positive and negative feedbacks, Science should focus only on gathering unequivocal evidence and perfect projections of the potential consequence of fossil fuel use. Government and society shall pursue a sit-and-wait strategy and thus invest on adaptation to cope with those effects of GCC that will actually occur.

The aim of the present work is to briefly address the previous issues, by answering the following questions: 1) is climate change real? 2) is the future so grim? and 3) how much will it cost to us?

As for the phenomenological aspect of GCC and its consequences of the biosphere, the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) is certainly the most comprehensive analysis and discussion on scientific evidence and projections of future climate change. Produced by several hundred academic scientists and researchers from many nations, its aim is to provide an assessment of the understanding of all aspects of climate change, especially on how anthropogenic activities can influence climate patterns and can be impacted by them. Since its publication in 2001 after an extensive peer-reviewing process, many other papers, comments and analyses have appeared on scientific journals to further integrate, and in some cases improve, the projections provided by IPCC.

As for the expected economic impacts of GCC and the main mitigation policies addressed by the Third Conference of the Parties held in Kyoto in 1997, we anticipate that a full, comprehensive economic analysis of the implication of global climate change does not exists yet. However, making reference to a recent research work by De Leo et al. (ref. 2) we show how to account also for socio-environmental costs of climate change along with industrial investment and management costs.
The present work is organized as follows. In the first section we briefly review the evidence of present climate change and address the question whether the detectable changes in climate pattern might be ascribed to human activities. In the second section, we briefly summarize the most credited hypotheses on possible impacts of GCC in the short, medium and long term. Specifically, potential impacts are described for the physical, biological and human environment. Finally, in the last and longer section, we discuss the issue of socio-economic evaluation of GCC. After a brief review of the economic approach to account for environmental externalities, we assess the effectiveness of different alternatives of energy production in the rigorous framework of a cost-benefit analysis.

IS CLIMATE CHANGE REAL?

As GHG emissions have considerably increased since pre-industrial time, it is reasonable to wonder whether any significant change in Earth climate is already detectable with respect to the last 200 years and, if so, whether these changes can be ascribed mainly to human activities or to natural processes. Hereafter we report evidence of climate change according to the Third Assessment Report of IPCC and other publications on the subject.

GHGs’ concentration

The atmospheric concentration of anthropogenic GHGs such as carbon dioxide, methane, nitrous oxide and tropospheric ozone has significantly increased as a consequence of fossil fuel combustion, agriculture and land-use change. The famous data recorded at the Mauna Loa Observatory in Hawaii (USA) - the longest continuous record of atmospheric CO2 concentrations available in the world - show that CO2 concentration has increased from 316 parts per million by volume (ppm) in 1959 to 371 in 2001. Carbon dioxide concentration in the atmosphere has been close to 280 ppm for at least a millennium before pre-industrial time. In the past 400 thousand years CO2 has exhibited long term oscillations between 180 and 290 ppm, with rates of change that are order of magnitudes smaller than that experienced in the last 150 years.

Temperature

An increasing body of observations provides a collective picture of a warming world and other critical changes in the climate system that can be related to the increase of GHGs. The U.S. National Oceanic and Atmospheric Administration, the World Meteorological Organization, and the Goddard Institute for Space Studies, all of which work with different data sets, agree that the average surface temperature of the globe in 2000 was the second-highest for which comprehensive thermometer records exist – almost 0.6 K warmer than the average of the period 1961-1990. Nine of the 10 warmest years after 1860 have occurred since 1990. Since 1976, global temperatures have risen three times faster than the warming that occurred over the 20th century as a whole. While the number of hot days exhibits an increasing trend, cold/frost days decreased for nearly all land areas during the 20th century. 2002 is not finished yet while writing this paper, but new records have been hit already, with the first three months of the year being in fact the hottest since 1860.

Precipitation patterns, flooding and droughts

TAR reports that heavy precipitation events increased at mid-to-high northern latitudes. Summer drying and associated incidence of drought in a few areas also increased. In parts of Asia and Africa, the frequency and intensity of droughts have increased in recent decades. Moreover, changes in sea level, snow cover, ice extent, and precipitation are consistent with a warming climate near the Earth’s surface. A statistically significant positive trend in risk of large floods has been observed by analyzing recent hydrological series of 29 basins larger than 200,000 km² with
discharge observations spanning at least 30 years: in the observational record of 2066 station-years, 16 of the 21 flood events with a 100-yr return time occurred after 1953, in the second half of the record.

Observed effects on ecological systems

These recent regional and global changes in climate have already started to produce effects on terrestrial\(^8,9\) and marine ecosystems\(^10\) (coral bleaching, invasion of tropical exotic species, increased range of malaria mosquitoes) in many parts of the world. All the changes are very likely to be correlated with increase in temperature and changes in climate patterns. See ref. 11 for a comprehensive review on ecological responses to recent climate change.

Possible effects on human activities

Both droughts and floods have major impacts on the socio-economic well being of countries. In 2001, Africa, Algeria, Mozambique, and Zambia were hit by spring floods, while Somalia and Ethiopia continued to experience severe drought. A World Meteorological Organisation\(^12\) press release reports that in summer 2002 floods in more than 80 countries have caused hardship for more than 17 million people world-wide. Almost 3,000 people have lost their lives while property damage is amounting to over thirty billion US dollars. The total area affected by the floods is over 8 million square kilometers, almost the size of the United States of America. WMO also reports that the global annual costs for property damage due to meteorological events lies between 50 to 100 billion US dollars. Asia has been the continent most frequently hit by hydro-meteorological disasters, accounting for 43 per cent of the total number of events and 80 per cent of the people killed during last decade. At the opposite extreme, a delayed monsoon in India has resulted in unseasonably hot and dry conditions throughout northern and western parts of the country; its impact is a 10 million-ton drop in India’s rice crop. Serious droughts have been occurring in southern and central Africa in the last years, resulting in starvation and global outcry for food aid.

Natural vs. anthropogenic causes

According to WMO, there is no way to state whether each single flooding episode recently experienced in Europe and China is directly associated to climate change and to which extent anthropogenic greenhouse emissions should be blamed for it. Yet, the observed patterns are consistent with the scenarios predicted by IPCC and by more recent analyses\(^7,13\). What is known for sure is that a) the increase of GHGs since industrial revolution has to be largely ascribed to human activity and b) that GHGs trap more energy in the low atmosphere, which, consequently, can affect climate patterns. The acknowledgment of human responsibility for the sharp increase of GHGs does not rule out the role of intrinsic weather variability and other natural causes of climate change. In fact, the best agreement between explanatory models and field observations over the past 140 years has been found when both anthropogenic and natural factors are combined\(^3\).

IS THE FUTURE SO GRIM?

Once acknowledged that climate is changing already, the next logical step is to wonder what we should expect in the next 30-to-100 years. Before answering this question by illustrating the projections, we should anticipate that the actual impact of GCC on the biosphere and human welfare a) will depend upon the actual emissions and the mitigative capacity at the global level; b) will not be uniformly distributed on the globe, but will vary among regions, as a function both of the local nature and consequences of climate change impacts, and also of the adaptive ability to locally cope with climate change.
Projections provided by IPCC are based on the six illustrative emissions scenarios presented in the Special Report on Emission Scenarios (SRES) released by Working Group III of IPCC\(^{14}\). The six scenarios make different assumptions on world population growth, economic development, technological innovation, etc. According to SRES all scenarios should be considered equally sound, that is no prior likelihood is associated to the six SRES scenarios. Moreover, none of them explicitly assumes implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol. Projections and potential impacts are briefly described hereafter.

**GHGs concentration**

For the six illustrative SRES emissions scenarios, the projected concentration of CO\(_2\) in the year 2100 ranges from 540 to 970 ppm, compared to about 280 ppm in the pre-industrial era and 371 ppm in the year 2001.

**Temperature Increase**

According to the Third Assessment report of IPCC, projections with a range of climate models using the SRES emissions scenarios result in an increase in globally averaged surface temperature of 1.4 to 5.8 K over the period 1990 to 2100. This is about two to ten times larger than the observed warming over the 20th century and the projected rate of warming is very likely to be without precedent during at least the last 10,000 years, based on paleoclimatic data. The range of projections is consistent among the several different models used by different and independent research centers in the world\(^{15}\) and is at least 0.4 K higher than the previous assessment by IPCC back in 1996. A more recent analysis\(^{16}\) shifts the 95% confidence upper estimate up to 7.7 K. Agreement about projections is even stronger for the next two to three decades, the typical time scale of interest for developing policies, plans and programs for mitigation and adaptation\(^{17}\). According to more recent estimates derived through very different approaches\(^{18,19}\), the probable warming for 2020-2030 relative to 1990-2000 is 0.5-1.1 K (5-95% likelihood range). Moreover, even after stabilization of the atmospheric concentration of CO\(_2\) and other greenhouse gases, surface air temperature is projected to continue to rise by a few tenths of a degree per century for a century or more\(^{21}\).

**Meteorological and hydrological effects**

Models project that increasing atmospheric concentrations of greenhouse gases result in changes in frequency, intensity, and duration of extreme events, such as more hot days, heat waves, heavy precipitation events, fewer cold days and water shortages and droughts. Glaciers are projected to continue their widespread retreat during the 21\(^{st}\) century. Global mean sea level is projected to rise by 0.09 to 0.88 m between the years 1990 and 2100 for the full range of SRES scenarios. Globally averaged annual precipitation is projected to increase during the 21\(^{st}\) century although with significant regional variations.

The Gulf Stream is expected to weaken in the next 100 years, even though it will not likely shut down in the present century. This and other projected abrupt/non-linear changes in physical systems (such as major melting of ice sheets), plausible beyond the 21st century, would be effectively irreversible on a time scale of interest to humans.

**Effects on agriculture**

If temperature increases beyond a threshold, which varies by crop and variety, it can affect key developmental stages of some crops (e.g., spikelet sterility in rice, loss of pollen viability in maize, lack of tubers’ development in potatoes) and thus the crop yields\(^3\). According to TAR, models of cereal crops indicate that in some temperate areas potential yields increase with a small increment in temperature but decrease with larger temperature changes, even though there is still an
incomplete understanding of these processes. In most tropical and subtropical regions, potential yields are expected to decrease for most projected increases in temperature. The diffusion of pests and diseases as a consequence of warmer climate will pose a serious threat to commercial yields, which can largely overcompensate the positive effects on plant growth of a small increase in temperature and of CO2 fertilisation. Similarly, the increased frequency of extreme meteorological and hydrological events (floods and droughts) can also negatively impact on agricultural production.

**Ecological Effects**

According to TAR, ecological productivity and biodiversity will be altered by climate change and sea level rise, with an increased risk of extinction of some vulnerable species. The actual ecological effects will depend upon the adaptive response at the physiological and population level, and the interspecific relationships and dispersal ability at the community level. Climate warming can increase pathogen development and survival rates, disease transmission, and host susceptibility. Ultimately, changes in climate could increase the risk of abrupt and non-linear changes in many ecosystems, which would affect their function, biodiversity, and productivity. Obviously, the greater the magnitude and rate of change in climate, the greater the risk of adverse impacts.

**Impacts on human activities**

Temperature increase, desertification, increased frequency of extreme events, sea level rise, diffusion of tropical diseases, effects on agriculture due to water shortage and pest diffusion will all have impacts on human activities and will increase threats to human health, particularly in lower income populations, predominantly within tropical/subtropical countries. Some impacts of anthropogenic climate change may be slow to become apparent, and some could be irreversible if climate change is not limited in both rate and magnitude before associated thresholds, whose values may be poorly known, are crossed. The IPCC Third Assessment Report predicts that projected climate change will have beneficial and adverse effects on both environmental and socio-economic systems, but the larger the changes and rates of change in climate, the more the adverse effects predominate.

In many developing countries, the aggregated market sector effects, measured as changes in gross domestic product (GDP), are estimated to be negative for all magnitudes of global mean temperature increases studied because of lack of adaptive capacity, while they are projected to be mixed for developed countries for up to a few Kelvin warming, but negative for warming beyond a few degrees. More deaths from heat waves, storms and contaminated water and increased incidence of tropical diseases are also expected under each SRES scenario for people living in both industrialized and developing countries. Insurance premiums against natural catastrophes are expected to increase as a consequence of GCC, thus diverting financial resources from other market sectors. Populations that inhabit small islands and/or low-lying coastal areas are at particular risk of severe social and economic effects from sea-level rise and storm surges. In the end, the impacts of climate change will fall disproportionately upon developing countries.

**Uncertainty, mitigation and adaptation**

Much has been argued about the confidence of IPCC projections, as none of SRES emission scenarios (nor the corresponding projections) were associated to likelihood levels. More recent studies have made use of marginal probabilities distributions thus producing 95% confidence intervals for climate sensitivity in 2100 ranging between 1.4 and 7.7 K and between 0.5 and 1.1 K for 2020-2030.

It is substantially harder to quantify the range of possible changes in the hydrological cycle at the local and regional level, both because the observations are less complete and because physical constraints are weaker. It is anyway acknowledged that the projected rate and magnitude of
warming and sea-level rise can be lessened by reducing greenhouse gas emissions. Yet, it should be clear that GHGs remain in the atmosphere for tens and in some cases for hundreds of years. The GHGs concentration reflects long term emissions, and the benefits of even an immediate, substantial reduction will not be seen for decades or more\textsuperscript{21}. As a consequence, the earlier are reductions in emissions introduced, the smaller and slower the projected warming and perspective damages. Anyway, while the Kyoto Protocol goal of a 5.5\% reduction of GHG emissions with respect to 1990 is the first step in the right direction, a reduction of at least 50\% of GHG emissions is considered necessary in order to stabilize the anthropogenic radiative forcing. In the short run, as well as in the long one, if GHG emissions are not substantially reduced, we have to rely also on an adaptive strategy which, according to TAR, has the potential to reduce adverse effects of climate change and to produce immediate ancillary benefits, but will not prevent all damages.

**HOW MUCH ARE WE GOING TO PAY (OR SAVE)?**

As shown in the two previous sections, an increasing amount of scientific evidence, with respect to just ten years ago, clearly indicates that climate change is indeed occurring, that man should be held responsible for a substantial fraction of these changes, that some effects are already measurable and the potential medium- and long-term consequences might have a dramatic impact on human life and welfare. Despite this rising awareness and the promising commitment by Russia and China to ratify the Kyoto Protocol, even the recent Johannesburg World Summit on Sustainable Development has failed to undertake significant actions towards GHGs reductions, partially but not exclusively because of the US veto to list Climate Change in the agenda. Why? The failure of international agreements on GCC is rooted in many different causes, but the most classical argument used to justify delay in taking action is the lack of reliable and comprehensive estimates of the economic costs and benefits of stabilizing atmospheric concentrations of GHGs. As national budgets are obviously limited, governments have continuously to tradeoff among competing goals, such as the increase of industrial production vs. the enhancement of the health service or educational system, the conservation of natural heritage vs. the maintenance of a reliable but costly retirement scheme for citizens. Budget constraints and value judgments along with contingent problems (social and market pressures included) set priorities on where to invest first. Consequently, even without mentioning the problem of vested economic interests and human greediness, we should not be surprised if distant issues such as GCC, intergenerational equity and biodiversity loss inexorably fall to the bottom of the political agenda after more pressing economic and social problems, as the long-term benefits of mitigation are difficult to understand, and are thus strongly discounted for with respect to the corresponding direct, short term costs of its implementation. Nevertheless, in the last ten years great progress has been done in the economic evaluation of environmental damages, and this may actually help decision makers to correctly perceive the benefits of an anticipatory mitigation policy for GCC vs. those of a sit-and-wait strategy. These methods of evaluation are shortly reviewed hereafter.

**Direct and external costs of GCC**

According to the economic theory, when assessing the economic consequences of climate change, a distinction needs to be made between goods and services that are currently exchanged on the market - and thus have a market value - and those commodities and services that are not marketable for ethical or practical reasons, such as biodiversity and human health. Monetary damages to infrastructures due to GCC, for instance, can be easily assessed in terms of replacement costs, once that physical entity of the damage is known or can be reasonably estimated. Similarly, damages to agricultural yield can be evaluated as economic loss of agricultural production, as the market discloses the monetary value of agricultural goods. In this case, the economic approach for monetary evaluation is the same used by insurance companies to account for damages due to the
hurricanes that have wiped USA in the last 10 years or the storms and floods that hit Europe and China in summer 2002. But GCC will actually affect also ecological systems and services for which there is no market, and generate secondary and indirect impacts on human welfare and health. Costs imposed to the society and to the environment that are not included in the market are known in the literature as environmental externalities. These are “external” costs, as those who bear the damages do not receive any compensation through the market. External costs are not usually accounted for in traditional economic assessments.

The value of Human Health

Different methodologies have been developed to price the damages due to air pollution and climate change on human health in terms of a) morbility, on the basis of average statistical costs of drugs and medicines, hospitalization, reduced productivity, loss of working days or b) mortality, on the basis of an estimation of the number of years of life lost as a consequence of pollution or climate change\textsuperscript{24}, and of the average annual income per age, sex, ethnic group, etc. While the ethical bases of such accounting process are very debatable, the estimation methodologies are considered fairly acceptable from a technical viewpoint and are currently used by insurance companies in all industrialized countries.

The value of biodiversity and ecosystem services

When we come to the realm of biodiversity loss or damages to biophysical and ecological systems, the picture is even much fuzzier. In this case, monetary estimates are usually based on Contingent Valuation Methods\textsuperscript{25}, CVM. These methods require that individuals express their preferences for some environmental resources by answering questions about hypothetical choices. In particular, respondents to a CVM questionnaire will be asked how much they would be willing to pay to ensure a welfare gain from a change in the provision of a non-market environmental good, or how much they would be willing to accept in compensation to endure a welfare loss from a reduced provision of the commodity. Unfortunately, these methods have a few drawbacks, because they are strongly dependent upon the actual group of people being interviewed and upon the way that the interview is performed\textsuperscript{26}. Moreover, for many ecological services there is simply no possibility of technological substitution, as the precise contribution of many species is not known, and it may not be known until the species is close to extinction. Many services should not be separated from each other and valued individually\textsuperscript{27} because the importance of any piece of biodiversity can be determined only considering the value of biodiversity in the aggregate. Also, CVM are based on the use of marginal value theory. This may be invalidated by the erratic and catastrophic behavior of many ecological systems\textsuperscript{28}, which has potentially detrimental effects on human health and the productivity of renewable resources\textsuperscript{29}.

Despite these limitations, the monetary evaluation of non marketable commodities and services still retains a great appeal. The methods of monetary evaluation have a great communication power towards the general public, as the multi-dimensionality that characterizes complex problems can be collapsed into a unique monetary scale which is easily understood by the most. As a consequence, more and more attempts to assess the economic value of biodiversity and ecosystem services have been performed in the last ten years\textsuperscript{30-38}.

ExternE: European assessment of external costs of energy production

In the area of climate change and air pollution, \textit{ExternE}\textsuperscript{39}, a research project of the European Commission, represents probably the most comprehensive effort to use a consistent 'bottom-up' methodology to evaluate the external costs associated with 12 different fuel cycles of electric energy production (coal, nuclear, oil, gas, lignite, peat, orimulsion, hydro, photovoltaics, wind, biomass, and waste incineration). The term 'fuel cycle' refers to the full chain of processes linked to
the generation of electricity from a given fuel, starting from fuel extraction (when applicable) and ending with power generation and electricity transmission.

To estimate impact assessment, ExternE has developed an integrated software package called Ecosense based on i) a database of emission factors for each technology, ii) a small scale air pollution model (ISC) and a regional air quality model (the Harwell Trajectory Model) to compute diffusion of pollutants at the local and European level; and iii) a number of dose-response functions to estimate the actual impacts on human health as well as the damages to infrastructures and agricultural production. Of the six macro areas - human health, building materials, crops, forests, freshwater fisheries, biodiversity - analyzed in ExternE by using essentially CVM and replacement costs, only the first three have been actually accounted for in an extensive way, while the contribution of the others to the final monetary value is basically neglected.

Local vs. global external costs
External costs are usually classified in two further broad categories: global external costs and local external costs. The first ones are caused by GHGs and are associated with Earth climate change. By contrast, local external costs are associated with the damages produced by other macro- and micro-pollutants (such as NOx, SO2, CO, and Total Particulate Matter) on a local and regional (European) scale. While estimates of damages to human health, infrastructures and agricultural production due to macro-pollutants are quite certain, as these pollutants are governed by fairly known phenomena on a tractable and observable scale, global impacts associated with Earth climate change are much more difficult to estimate at the local and regional level\textsuperscript{13}. By using specific models\textsuperscript{40,41,42}, ExternE has estimated that global costs can range between 4 and 140 euros per ton of CO2. The local external costs for 20 main traditional and alternative sources of energy are reported in Table 1, along with specific carbon dioxide emissions. The overall external costs are thus given by the sum of the local costs plus the global environmental costs.

The tradeoff between industrial and external costs
As discussed above, the most common argument held against mitigation policies is that industrial cost of power generation via renewable energy sources (RES) is much higher than the cost of fossil fuel technologies. This is certainly true, as shown, for instance, in Table 1 for the case of Italy. RES industrial costs – especially for photovoltaic energy - is expected to decrease in the future, following a consistent trend over the last 20 years, thanks to technological innovation and scale economies\textsuperscript{43}. This will partially reduce the cost gap between RES and traditional technologies based on fossil fuels, but is not expected to change the overall picture for the next ten years.

On the other hand, from a public viewpoint, energy policies should take into account not only direct industrial costs, but rather the total costs imposed to the society which are a sum of industrial costs and external costs (local and global). In other words, the convenience of undertaking action for GHGs reduction with respect to a sit-and wait strategy depends upon the tradeoff between the industrial external costs, which obviously increase with the adoption of RES, and the external costs, that, on the contrary, are expected to decrease with a larger use of RES. However, if we want to conduct an economic evaluation of this tradeoff, we have to take into account a set of constraints, namely: a) the satisfaction of short-term energy demand; b) the maximum power generation capacity of a country during a given time period; c) other political constraints, such as the willingness to put a cap on GHG emissions, e.g. in agreement with the Kyoto Protocol.

The analysis of future power generation in Italy
An example of how external costs of GCC can be incorporated in an economic evaluation is the study\textsuperscript{1} conducted for the problem of power generation in Italy. The cost-benefit analysis of alternative scenarios of electric energy production has been quantitatively performed for Italy based on detailed information concerning the potential market penetration of RES, the costs of alternative
energy sources and the national energy demand (353 TWh/yr) expected 10 years from now, a time horizon that coincides with the prescription of the Kyoto Protocol. The technical and physical constraints for each energy source (classified in four broad categories: oil, solid fuel, gas and renewable sources) are reported in the first two columns of Table 1.

We have compared three alternative scenarios:

1) in the first one, the goal is to minimize only the sum of energy production costs (business as usual, BAU); external costs are not included in the minimization function but can be accounted for thereafter, once the optimal strategy has been identified under the current constraints;

2) in the second one (BAU+Kyoto), we minimize again energy production costs but with a further constraint of a 6.5% reduction of GHG emissions with respect to 1990 in agreement with the Kyoto Protocol commitments; once again, external costs are not explicitly included in the optimization problem, but will be accounted for only afterward.

3) in the third alternative, the goal is to minimize the overall social costs (MSC), namely, the sum of industrial costs plus local and global environmental costs. This case is the only one in which external costs are explicitly included in the optimization function.

As safeguarding the regularity of power supply remains one of the main concerns of the European Union, each alternative scenario should be evaluated also in terms of diversification of energy sources.

Unless specified otherwise, all the following analyses for the Italian case have been performed by assuming a global external cost equal to 30 Euros/CO2 ton, the central value provided by the ExternE project. A detailed description of the computation algorithm is reported in Ref. 2

Results of the Italian study

The minimization of industrial costs only (BAU scenario) implies 137.24 millions tons of CO2 emissions, a value largely exceeding the limit of 115.7 millions tons required to satisfy the Italian commitment to the Kyoto Protocol. Total social costs are of the order of 7 billion Euros, which is the highest value among the three scenarios considered in the study. Consequently, the overall specific cost of energy (sum of industrial costs and environmental costs) is 5.41 Euro cents per kWh and is the highest of the three scenarios.

The optimization according to the second alternative (BAU+Kyoto) requires 17% reduction of CO2 emissions with respect to the BAU scenario. This corresponds to a 3% increase of the industrial costs (300 million Euros/year), which is anyway overcompensated by a reduction of 1.5 billions Euros of external costs (-902 million Euros for local environmental costs and –655 for global environmental costs). The overall specific costs (sum of industrial costs and external costs) is about 5.12 Euro cents/kWh.

The minimization of the overall social costs (MSC scenario) provides a convenient alternative under many respects, as it allows a saving of 2.35 billions Euros/year in external costs with a 5.5% increment of direct industrial costs, equivalent to 0.6 billions Euros/year. The overall specific costs of energy production is only 4.85 Euros cents/kWh, the lowest of the three scenarios. This scenario is characterized by a strong dominance of gas-based technologies, which are characterized by a more efficient combustion efficiency lower emission of GHGs and other pollutants and the possibility of co-generation, and a larger penetration of alternative sources. The large dependence on natural gas implies a reduction in energy supply diversification. On the contrary, the BAU scenario guarantees a larger diversification of energy supplies, the BAU+Kyoto scenario being intermediate between the two.

Sensitivity Analysis

As the estimation of the global external costs is affected by a high level of uncertainty, the study has performed a sensitivity analysis with respect to the global external costs, letting it range between 0
and 250 Euro/CO₂ ton. The significant outcomes of this further analysis are two. First, if the cost of
global climate changes turns out to be larger than the 30 Euro/CO₂ ton suggested by *ExternE* as a
median value, the monetary gain provided by choosing the BAU+Kyoto alternative - and, to a
larger extent, the MSC scenario - rather than the BAU alternative will be obviously even greater
and a stronger preference to RES will be given. The second interesting result of the sensitivity
analysis is obtained when, by contrast, the global external cost is assumed to be zero, because of
the uncertainty associated to GCC, thus implicitly stating that no such a thing as a Global Climate
Change will ever occur. In this case, in fact, despite global costs are neglected, the reduction of the
local external costs in the MSC scenario (+1,450 millions Euro/year) is able to more than
compensate the increase of industrial costs (+559 millions Euros/year) with a net benefit to the
society of about 900 millions Euros/year. This shows that a policy for cleaner energy production
would actually be convenient (because of the ancillary benefits at the local level) in the face of
uncertainty on the actual consequences of GCC⁴⁵.

*Caveats, limitations and generality*

We are aware that the economic analysis here presented is not exempted from criticism. First of all,
the MSC scenario, the most convenient of the three, requires a high dependence on natural gas and
thus reduces the safety of energy supply, while the MIC scenario allows for a higher diversification
of energy sources. Moreover, the benefits of reducing GHG emissions in terms of reduced global
external costs will be perceived only if carbon dioxide concentration will be controlled at the global
level, regardless the specific policy followed by the Italian government. As Climate Change is a
global problem *per se*, the reduction of CO₂ emission in one country only is not likely to change the
medium/long-term picture. Finally, the analysis described above refers only to the power generation
sector, which in Italy (as in most of the industrialized countries) comprises only about one-third of
the emissions. A comprehensive economic analysis should of course consider also the production of
thermal energy for industry as well as the transportation and building sector.

Despite these limitations, our analysis shows that a sustainable energy policy would be convenient
even when not accounting explicitly for the perspective damages due to climate change.

**CONCLUSIONS**

With almost no exceptions, the scientists have now reached a consensus concerning the occurrence
of Climate Change and the human liability for the increase of GHGs in the atmosphere. The
economic analysis performed for power production in Italy shows that the use of less polluting
energy sources and more efficient technologies can reduce measurable impacts with a limited
increase of industrial costs. Other studies have shown that reducing dependence from fossil fuels is
indeed possible and convenient, even without accounting for external costs. Using a comprehensive
macroeconomic model that includes the sectors of building, transportation, industrial production
and power generation (but no external costs evaluation), the Oak Ridge National Laboratory of the
of the US Department of Energy has recently shown⁴⁶ that a) smart public policies - making use of
voluntary agreements, efficiency standards, domestic emission training and increased research &
development- can significantly reduce not only carbon dioxide emissions, but also air pollution,
petroleum dependence, and inefficiency in energy production and use; b) the overall economic
benefits of these policies appear to be comparable to their overall costs; and c) uncertainties in the
technical and economic assessment are not likely to alter the overall conclusions.

Similarly, an economic analysis performed by the Tellus Institute⁴⁷ has shown that by implementing
a set of domestic policies proposed within Canada’s National Climate Change Process it would be
possible to achieve more than half of Canada’s emission reduction target set by the Kyoto Protocol
with ancillary benefits including:
- cumulative net economic savings of $4 billion across the economy reaching $1.6 billion per year or $47 per capita in 2012;
- the net addition of an estimated 52,000 jobs in the economy generally, due to the redirection of consumer spending away from fuel and electricity and toward other goods, services, activities and investments;
- a $135 average annual gain in household income related to the creation of new jobs; and a $2 billion increase in the national GDP beyond that projected in the business as usual scenario.

Although indirect environmental and public health co-benefits were not included in Tellus study, further analysis suggested that an annual emission reduction of only 68 million tons of CO₂, a little more than half the reductions forecast in the Tellus study, would yield approximately $1.2 billion in avoided health damages alone.48

While the cited studies estimate the expected costs and benefits of Renewable Energy Sources and Energy Saving policies, the first operational programs launched at the beginning of the nineties have started to provide factual results. The most striking experimental project is probably that operated by ÖÖ.Energiesparverband, the Energy Agency of Upper Austria.49 In this region, thanks to a comprehensive building program involving 18,000 houses (95% of all new single-family houses), energy consumption has been cut by more than 30% since 1993. At the same time, in industry energy consumption has decreased by 2% annually since 1994. This was done through an innovative program which combines a financial soft loan with an information element (energy advice session). The original goal of increasing the share of renewable energy sources to 30% in 2000 (starting from 25% in 1991) was already reached in 1996 and was therefore increased to 33%. Since the beginning of the implementation of the regional energy plan in 1993, a CO₂ reduction of 11.7% has been achieved, which corresponds to a saving of 19 millions of kg of carbon dioxide and 100 millions kWh/year. Over the last 20 years, from 10,000 to 15,000 jobs have been created or maintained in forestry and in the production and installation of biomass systems.50

Other measures to reduce the impact of GHG emissions are being explored. For instance, forests, agricultural lands, and other terrestrial ecosystems offer significant carbon mitigation potential. According to TAR, the order of the estimated global potential of biological mitigation options is 100 Gt C (cumulative) by year 2050, equivalent to about 10 to 20% of projected fossil-fuel emissions during that period. Although there are substantial uncertainties associated with this estimate, related to land and water availability as well as the rates of adoption of land management practices,52,53 silviculture and suitable reforestation programs could enhance at least temporarily the potential for carbon sequestration, thus allowing further time for other options to be developed and implemented. In fact, as shown in this journal issue, non-biological carbon sequestration seems very promising, even though the costs associated with these techniques and the relative monitoring programs might potentially offset the benefits.

Cost estimates1 reported to date for biological mitigation vary significantly from US$0.1 to about US$20 per ton C in several tropical countries (where the largest biological potential for atmospheric carbon mitigation is set). In non-tropical countries the specific costs per ton C is expected to be from 5 to 200 times higher. Moreover, these costs are only underestimates of the real ones, as costs for infrastructure, implementation, maintenance, as well as opportunity costs of land and appropriate discounting, are often lacking or overlooked. With a better accounting of these costs, it will be possible to conduct benefit-cost analyses of the various methods of biological and non-biological carbon sequestration.

Unfortunately, the time goes by and the inertia of climate and of ecological and socio-economic systems makes adaptation inevitable and already necessary in some cases. The potential for irreversible changes in the systems that support human life on our Earth is a compelling reason that should convince all of us that mitigation actions should be undertaken with no further hesitation.
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