nonetheless indicative of the extreme conditions inside the bubble at collapse and therefore demonstrates the violence of the event.

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Carbon emissions

The economic benefits of the Kyoto Protocol

The third Conference of the Parties in Kyoto set the target of reducing greenhouse-gas emissions by an average of 5.3% with respect to 1990 values by 2008–2012. One of the main objections to the protocol's ratification is that compliance would pose an unbearable economic burden on the countries involved[1]. But we show here that this is not the case if costs apart from the direct costs of energy production are also considered. Costs are also incurred in rectifying damage to human health, material goods, agriculture and the environment related to greenhouse-gas emissions.

We have analysed alternative scenarios for electricity generation[2] (which contributes roughly one-third of total greenhouse-gas (GHG) emissions) in Italy in about 10 years' time (2010) by considering different technologies, including co-generation (combined production of electric and thermal energy). These technologies are based on oil, solid fossil fuels such as coal, gas (methane, for example) and renewable sources such as hydropower, wind, photovoltaic or biomass.

We accounted both for direct, annual industrial costs and for social and environmental costs. These latter are 'externalities' to the energy producers[3] and are not included in companies' balance sheets, but need to be considered in national balances. These external costs can be classified as local (derived from direct damage to the country in question — for example, as a result of increased air and water pollution and land deterioration) and global (derived from damage to the entire biosphere by GHG emissions).

We improved recent estimates[4] of production costs using experience curves[5] (diminishing costs due to technological innovation) and assessed external costs through a comparative analysis of the three main studies conducted in Europe (Project ExternE, probably the best and most comprehensive analysis)[6] and the United States[7,8]. The uncertainty of local external costs is reasonably small, whereas that associated with global costs is much larger[6] (4–140 euros per tonne of CO_2). We therefore carried out a sensitivity analysis of situations with global costs ranging from zero to 250 euros per tonne CO_2.

We have examined three situations (see supplementary information), each corresponding to a different problem of cost minimization and subject to two constraints: the estimated energy demand of Italy in 2010 (353 terawatt-hours) should be satisfied; and each energy-production technology should not exceed a maximum feasible quota (estimated on the basis of physical constraints, the current state of technology and its predicted progress[2]). The three problems of cost minimization correspond to: minimizing only the sum of production costs (business as usual, BAU); minimizing total social costs (MSC; that is, the sum of industrial and external costs of energy production); and minimizing only production costs, with the further constraint that the Kyoto Protocol must be satisfied (BAU + Kyoto). The target set for Italy is a 6.5% reduction in GHG emissions with respect to 1990 levels. Here, as we are considering only electricity generation, the BAU + Kyoto scenario does not require Italy as a whole to satisfy the Kyoto protocol, but merely constrains the electricity sector to cut its GHG emissions by 6.5%.

If we use the average global external cost calculated by the ExternE[6] study (30 euros per tonne CO_2), we obtain the results shown in Fig. 1. The BAU situation implies much higher external costs than the other two, not only in terms of uncertain global costs, but also in the much more certain local costs. Both MSC (which happens to satisfy the Kyoto Protocol) and BAU + Kyoto require large quotas of gas, which has a high combustion efficiency and lower emission of pollutants such as NO_x and SO_2, which are responsible for most local external costs. MSC, however, uses far less coal. We also carried out a sensitivity analysis for MSC (see supplementary information) and found that the value of shares in the different technologies would not change markedly, but that increasing global external costs would cause a shift from gas towards renewable sources and co-generation.

The estimated balance of BAU + Kyoto against BAU is a 17% reduction in GHG emissions, 1,829 million euros saved in reducing external costs (local, 1,068 million; global, 761 million), and a cost of 308 million euros in increased industrial outlay. However, if the cost of GHG reduction is smaller in the electricity sector than in those responsible for the remaining two-thirds of emissions, the industrial costs of compliance with the Kyoto Protocol for Italy might be more than three times those shown here.

The economic costs of global warming cannot be accurately estimated and may never be[9]. However, even accounting only for local external costs, together with production costs, to identify energy strategies, compliance with the Kyoto Protocol would imply lower, not higher, overall costs. Also, reducing local and regional air pollution is sufficient reason to cut coal combustion, which is the single worst GHG source from a global perspective.

Whatever decision-makers believe about climate change, they should make changes to their power-generation strategies now. Active energy-conservation policies, which are not considered here, might further increase social benefits without harming economies[10]. We conclude that any delay in reducing GHG

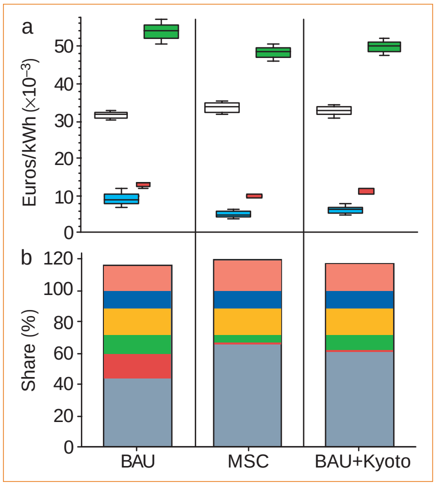

Figure 1 Annual costs of one kilowatt-hour of electricity in Italy and the shares of technologies for three different cost situations (see text). Box plots were obtained by considering the range of estimated costs for each technology (see supplementary information). Values in **a** represent: white, industrial costs; blue, local external costs; red, global external costs; green, total costs. Values in **b** represent: grey, gas; red, liquid fossil fuel; green, solid fossil fuel; yellow, renewable sources; blue, imported (nuclear); pink, co-generation. Of Italy's enery requirements, 11.3% is produced abroad (mainly nuclear energy imported from France and Switzerland). Shares of the technologies total more than 100%, because part of the energy is co-generated, which reduces external costs. With respect to the 'business as usual' (BAU) situation, compliance with the Kyoto Protocol implies a 3.1% increase in industrial costs but a 35% reduction in external costs — a net saving of 1.5 billion euros per year (8.8% of the total BAU cost). The saving in the 'minimize total social costs' (MSC) situation is 2 billion euros, or 11.7% of the total BAU cost.

emissions is not justified.

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Supplementary information is available at http://www.nature.com or as paper copy from the London editorial office of *Nature*.

Supplementary Information - The economic benefits of the Kyoto Protocol

The general structure of the optimisation problems we have solved is as follows

$$\begin{aligned} &Min\ f(C(x)/\theta) \\ &x_{min} \leq x \leq x_{max} \\ &0 \leq g(x) \leq \alpha \end{aligned}$$

where $f(C)$ is a suitable function of the costs to be considered in the specific problem (BAU, MSC, BAU+Kyoto), x is the vector of decision variables (namely, TWh/yr contributed by each production technology to satisfying the electricity demand), θ is the vector of parameters (such as different costs per kWh for the different technologies) defining the objective function f, while $x_{min} \leq x \leq x_{max}$ and $0 \leq g(x) \leq \alpha$ are the constraints. More precisely, the first set of bounds "$x_{min} \leq x \leq x_{max}$" defines the technological constraints for the decision variables with x_{max} being the maximum feasible quotas estimated for each technology as of 2010 and x_{min} being the minimum quotas (e.g., hydroelectric power plants that are currently operational will still be operational in 2010). The second set of bounds "$0 \leq g(x) \leq \alpha$" defines additional constraints, which are functions of the decision variables; it always includes the mandatory constraint that the sum of the decision variables be equal to 353 TWh/yr, which is the electricity demand for Italy in 2010. This demand has been estimated from the results of many extensive studies carried out by the largest electricity producer in Italy[1] (ENEL), the Italian Oil Association (Unione Petrolifera), the government[2], the research institution Ente Nazionale Energie Alternative (ENEA), and other researchers[3]. Also, this second set of constraints may contain ceilings to emissions to satisfy the Kyoto protocol (in the BAU+Kyoto scenarios).

The function f is built by summing up all the costs: in BAU and BAU+Kyoto it includes only the discounted (10%) and annualised investment costs, the cost of fuel and the operating costs, while in MSC it comprises the external costs too. A more complete account of the methodology is given by De Paoli and Lorenzoni[4]. Information on the constraints, the industrial and local external costs, and the emissions is reported in Table 1.

As for external costs, we have adopted the definition of the *ExternE* project. Global External costs are those due to GHG. As they are affected by a great level of uncertainty, *ExternE* has decided to account separately for global external costs and "non-global" external costs, which are referred to as "local". So, "local" external costs are all those due to causes different from Global Climate Change. As a consequence, local external costs do not necessarily have to be very localized geographically, even though they mostly reflect damages occurring within Italy. In fact, the Ecosense software package used in *ExternE* implements both a small scale air pollution model (ISC) and a regional air quality model (the Harwell Trajectory Model) to compute diffusion of pollutants at the European level. In Table 1 we report, for each technology, the average local external cost per unit of energy produced and its range of variation as estimated from the comprehensive work by De Paoli and Lorenzoni[4].

To generate the box and whiskers plots shown in Figure 1 of the main text we have used a Monte-Carlo approach. In fact, to account for uncertainty in the cost estimates, we have fitted beta distributions to data on industrial and local external costs. Then, we have drawn industrial and local external costs at random from the beta distributions and solved the corresponding optimisation problems (via Linear Programming) 1000 times, while keeping the global external cost set to 30 Euros per tonne of CO_2. The corresponding shares of each kind of power-production technology are shown in Table 2. It is interesting to note that in general the shares are much less sensitive to changes in the cost estimates than the corresponding values of the objective function *f*. The largest variations are for the use of gas and oil in the BAU scenario. To test for the significance of differences in the costs shown in Figure 1 of the main text we have used a randomisation test. All the pairwise differences of industrial, external and total costs turn out to be significant ($P = 95\%$).

As the global external costs are most uncertain we have run a sensitivity analysis for the solution of the MSC problem with the cost per tonne of CO_2 ranging between 0 and 250 Euros and the other costs set to their averages. The results are reported in Figure SuppInf. If we set the global external cost to zero, MSC is equivalent to minimising the sum of the industrial costs and the local external costs alone. Even in this case the MSC scenario implies lower total costs than BAU, with a net saving of about 918 million Euros per year, as the increase of industrial costs (+548 million Euros) is more than compensated by the decrease of local external costs (-1466 million Euros). Further analysis shows that in both MSC and BAU+Kyoto scenarios net savings with respect to BAU are larger and larger (in percentage and in absolute value) for increasing anticipated damages of global climate change, as the decrease of total external costs always largely overcompensates the higher industrial costs required to shift toward cleaner technologies. As for the share of different technologies, MSC implies a strong shift towards gas even when global external costs are set to zero, as reported in Figure SuppInf. The share of renewable sources equals 16.6%, that of cogeneration 17.9% and both do not change appreciably as long as the global external cost per tonne of CO_2 is lower than 30 Euros. For larger costs per tonne of CO_2, the importance of cogeneration increases to 20%, the share of renewables reaches 23.6% while that of gas decreases to 59.6%.

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Table 1 Feasible production quotas, costs and GHG emission for each technology of electricity generation in Italy. Green: renewables, red: oil, blue: gas, black: coal.

Technology	**Annual production** [TWh]		**Local External Costs** Average (Min-Max) [10^{-3} Euro/kWh]	**Industrial Costs** Average (Min-Max) [10^{-3} Euro/kWh]	**CO_2 emission** [g/kWh]
	Min	Max			
Hydro - big, existing power plants (>10 MW)	36.3	36.3	3.6 (3.1-9.3)	13.9	0
Hydro – small, existing power plants (<10 MW)	9.4	9.4	2.6 (2.1-3.1)	18.1	0
Hydro - new, small power plants (<10 MW)	0	8.7	2.6 (2.1-3.1)	69.7 (43.9-103)	0
Geothermal	4	5.5	1.5 (0.5-6.7)	74.9 (62-108)	440
Solid Waste	4	6.7	12.4 (2.6-18.1)	93.0 (62-160)	510
Wind power	1.5	5.0	1.5 (0.5-2.1)	77.5 (54.2-108)	0
Biomass	3	15.0	(11.9 (0.5-19.6)	98.1 (77.5-136.9)	0
Biogas	0.43	1.0	0.0	47.5 (43.9-67.1)	0
Photovoltaic	0.0054	0.2	1.5 (1.0-2.1)	433.8 (261-568)	0
Oil (Rankine cycle)	0	62.2	20.7 (11.9-71.3)	29.4	700
Co-generation from oil-derived feedstocks	3.5	3.5	9.3 (3.1-9.3)	29.4	530
Natural Gas – Repowering	91	130.0	5.7 (0.5-13.9)	32.5 (24.3-41.3)	360
Natural Gas - Combined Cycle. New power plants	0	42.0	5.7 (0.5-13.4)	34.1 (25.8-47.0)	350
Natural Gas, big power plants with co-generation	25.6	32.0	2.6 (0.5-8.8)	35.1	312
Natural Gas, medium power plants with co-generation	15.5	28.0	2.8 (0.5-8.8)	38.7	313
Natural Gas, small power plants with co-generation	2	10.0	3.1 (0.5-8.8)	46.5	325
Gas Turbines not using natural gas , existing power plants	8	8.2	10.3 (5.2-15.5)	49.1	660
Integrated Tar Gasification Combined Cycle	9.1	12.0	6.2 (2.1-11.9)	46.5	779
Coal (Rankine cycle)	0	25.0	25.8 (2.6-51.6)	22.7	930
Coal (Combined heat-recovery cycle with co-generation)	5	6.4	5.2 (2.6-7.7)	20.7	976
Coal (Combined heat-recovery cycle without co-generation).	1.5	2.0	5.2 (2.6-7.7)	12.9	1040

Table 2 – The resulting mix of technologies (average ± SD) for each scenario, as obtained by Monte-Carlo simulations in which we set the global external cost to 30 Euros per tonne of CO_2.

	BAU	MSC	BAU+Kyoto
Renewable sources	16.6±0.0 %	16.9±0.5 %	16.7±0.1 %
Gas	44.3±4.7 %	66.2±0.6 %	60.4±1.2 %
Oil	15.7±4.7 %	1.0±0.0 %	1.8±2.6 %
Solid Fossil Fuel	12.0±0.0 %	4.6±0.2 %	9.8±1.5 %
Import	11.3%	11.3 %	11.3%
Total	100.0 %	100.0 %	100.0 %
Co-generation	15.1±0.3 %	19.2±1.3 %	17.0±2.0 %

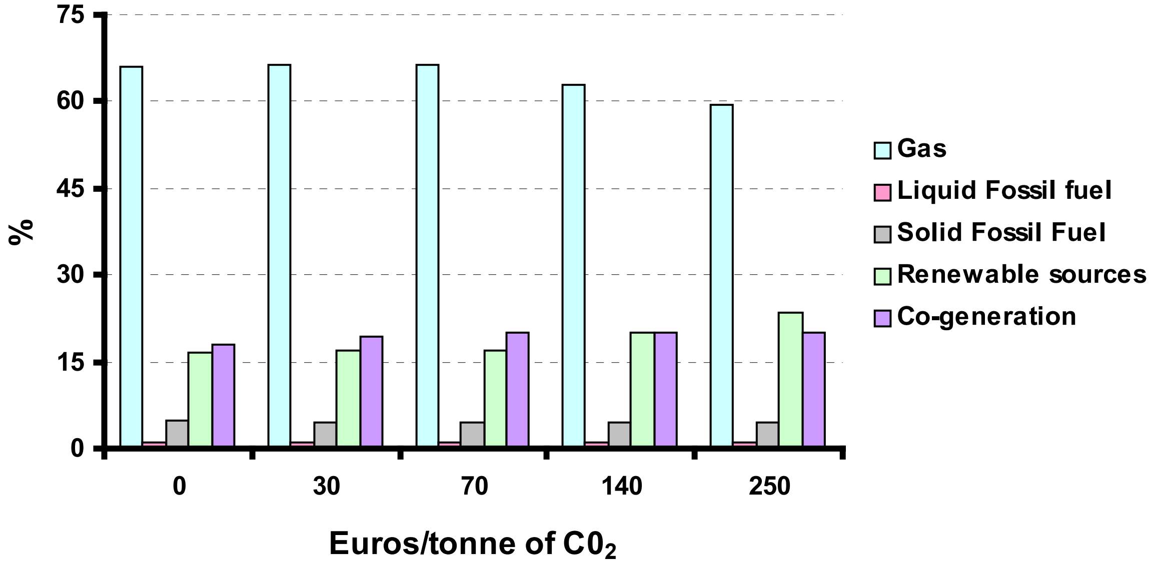

Figure legends - Supplementary Information.

Figure SuppInf Sensitivity analysis of the MSC scenario with respect to global external costs. For increasing costs, the best strategy is to favour first gas, then co-generation and finally, for high global costs, renewable sources.