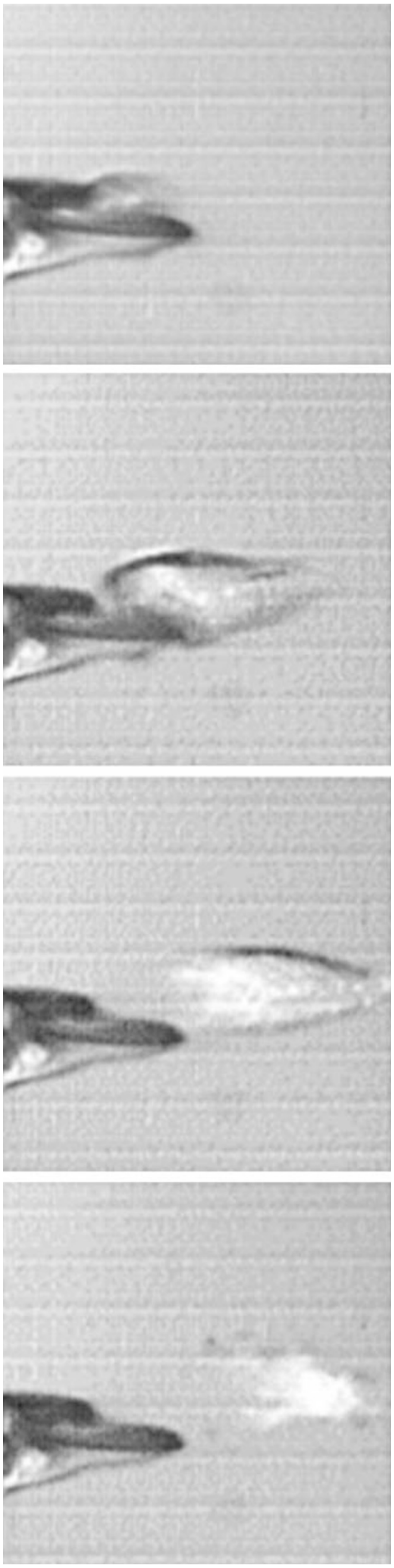

Figure 1 Side view of the tip of the snapper claw (left), showing the growth and subsequent collapse of the cavitation bubble, which produces a light flash and snapping sound. The light flash (not visible here) is indicative of the high temperature and pressure in the bubble interior at the point of collapse.

Snapping shrimp make flashing bubbles

The cavitation bubbles created by shrimp in stunning their prey have some surprising properties.

Snapping shrimp produce a loud crackling noise[1,2] that is intense enough to disturb underwater communication. This sound originates from the violent collapse of a large cavitation bubble generated under the tensile forces of a high-velocity water jet formed when the shrimp's snapper-claw snaps shut[3] (Fig. 1). Here we show that a short, intense flash of light is emitted as the bubble collapses, indicating that extreme pressures and temperatures of at least 5,000 K (ref. 4) must exist inside the bubble at the point of collapse. We have dubbed this phenomenon 'shrimpoluminescence' — the first observation, to our knowledge, of this mode of light production in any animal — because of its apparent similarity to sonoluminescence[5,6], the light emission from a bubble periodically driven by ultrasound.

To investigate this light-emission process, we positioned a snapping shrimp (*Alpheus heterochaelis*) in a seawater aquarium maintained at 20 °C and evoked a snap by gently stroking its snapper claw with a paintbrush. The sound pressure was recorded using a hydrophone in close proximity (1–3 cm) to the imploding bubble. The light emitted during the collapse was detected using a calibrated photodetector; all experiments were carried out in complete darkness.

The time course of the process is shown in Fig. 2a, b. The sound-pressure curve (Fig. 2a) consists of a small precursor signal, followed by an intense pressure peak at $t=0$ that results from the collapse of the cavitation bubble (Fig. 1). A flash of light coincides with this pressure peak (Fig. 2b). A second pressure peak, originating from the collapse of a cloud of bubble fragments in the wake of the water jet some 300 microseconds after the main pressure peak, coincides with a second, dimmer light flash.

The flash duration is extremely short — shorter than could be temporally resolved in our experiment (limit, 10 nanoseconds; Fig. 2c). In a range of 100 nanoseconds around, but mainly before, the main light peak, very dim flashes also occur, which may be due to emission of light from the tiny bubble fragments (Fig. 1). Such multiple light pulses have also been observed for cavitating laser-induced bubbles[7,8] and are associated with the non-sphericity of the collapse.

The total number of photons emitted from the hot bubble interior is up to 5×10^4, which is one to two orders of magnitude less than the sonoluminescence typical of a single collapsing bubble. Shrimpoluminescence cannot therefore be detected with the naked eye. Moreover, unlike sonoluminescence, the phenomenon is not repeated at a regular frequency, so there is no integration on the retina. A correlation of light intensity with sound intensity was not found in our set of 36 experiments with two different shrimp. We ascribe this to the uncontrolled way in which the asymmetric cavitation bubbles are created and then collapse.

The light emission associated with bubble collapse may not be biologically significant, but may instead represent a by-product of collapse, the shock wave from which is used to stun or even kill prey. But light emission is

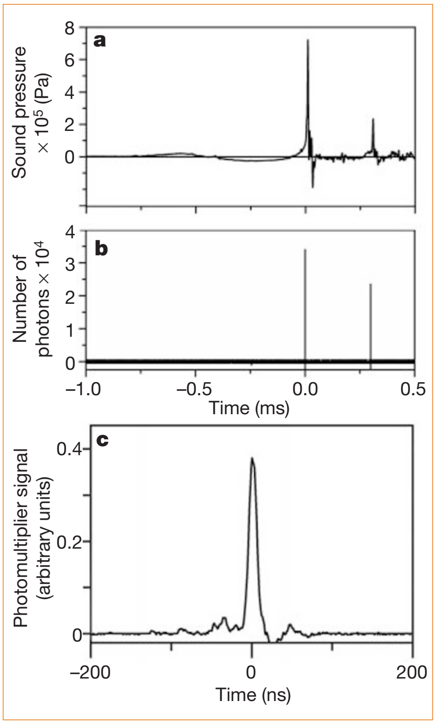

Figure 2 Sound and light from a snapping shrimp (*Alpheus heterochaelis*). **a,** Hydrophone signal and **b,** light emission from the snap of a shrimp. The principal light-emission event coincides with the bubble collapse at $t=0$. A second light flash coincides with the subsequent collapse of a cloud of bubbles, which is formed upon collapse of the principal bubble. **c,** Expanded view of the photomultiplier signal, showing the short pulse duration of 'shrimpoluminescence'. Within a range of 100 nanoseconds around the main peak, dimmer flashes of light are also evident; these may be due to emission of light from small bubble fragments formed during the violent collapse of the asymmetric cavitation bubble. Data analyses, R. M. Nelissen.

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

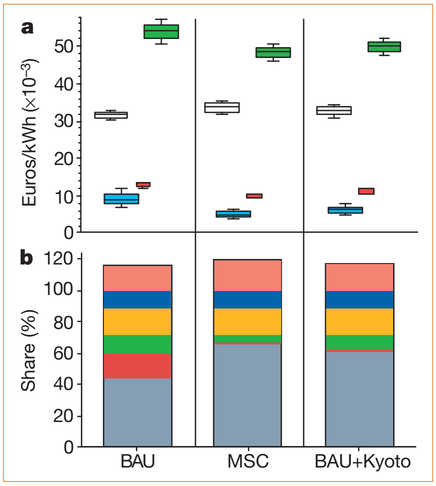

Figure 1 Annual costs of one kilowatt-hour of electricity in Italy and the shares of technologies for three different cost situations (see text). Box plots were obtained by considering the range of estimated costs for each technology (see supplementary information). Values in **a** represent: white, 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.