In the balance: The social costs and benefits of PV

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ABSTRACT
For more than a decade, the growth in PV markets surpassed expectations. Then, in 2012, the European market declined for the first time compared with the previous year. As policymakers' support for PV hesitates over the costs to society of this technology, it is timely to take an overview of the social costs and benefits, also referred to as the 'external costs', of PV electricity. In this article, these costs are put into perspective vis-à-vis those associated with conventional electricity-generating technologies. The external costs of electricity can be broken down into: 1) the environmental and health costs; 2) the costs of subsidies and energy security; and 3) the costs for grid expansion and reliability. Included in these costs are the increased insurance, health, social and environmental costs associated with damages to health, infrastructure and environment, as well as tax payments that subsidize producers of electricity or fuels, their markets and the electricity infrastructure. A life cycle assessment (LCA) of the environmental impact is used in the quantification of the associated environmental and health costs. Because the environmental footprint of PV electricity is highly dependent on the electricity mix used in PV module fabrication, the environmental indicators are calculated for PV electricity manufactured using different electricity mixes, and compared with those for the European electricity mix (UCTE), and electricity generated by burning 100% coal or 100% natural gas. In 2012$, coal electricity requires 19–29¢/kWh above the market price, compared with 1–1.6¢/kWh for PV manufactured with 100% coal electricity. The sum of the subsidies, avoided fossil-fuel imports and energy security, and the economic stimulation associated with PV electricity deployment, amounts to net external benefits. Integrating high penetrations of renewables, with the same reliability as we have today, appears to be fully feasible and within the cost horizons of the current activities of system operators.

Background

PV modules convert sunlight into electricity and operate for decades without emitting any greenhouse gases at all. But energy, with its associated carbon footprint, is intrinsic to the materials used to produce a PV module. In addition, energy (usually including a significant amount of conventional electricity) is directly used in PV module manufacturing and installation, as well as in its de-installation and recycling at the end of its life. This energy, which is invested in a PV module over its lifetime, is usually 'paid back' by the energy generated over about one year's operation of that module ('energy payback time'), or roughly 1/25th of the module's lifetime. A life cycle assessment (LCA) of a PV module considers the energy use, greenhouse gas emissions and other environmental impacts of the module from the manufacturing phase, through installation and operation, to the end-of-life and recycling stage.

One might fully accept the idea that a PV module does not emit greenhouse gases over its operation, but wonder whether it really makes sense for society to invest money and energy to switch from mostly conventional electricity production to a much greater amount from renewables. Given the current state of the world, it is urgent to address both the emission of greenhouse gases and the economy. It is therefore instructive to analyze what the costs and benefits are for society in opting for PV electricity, or electricity from renewable energy sources in general, as compared with conventional electricity-generating technologies. Costs which are not included in the market price of a saleable item are called 'external costs'. For electricity, external costs can be categorized into: 1) environmental and health costs; 2) costs associated with subsidies and energy security; and 3) costs for grid expansion and reliability. Included in these costs are the increased insurance, health, social and environmental costs associated with damage to health, infrastructure and the environment, as well as tax payments that subsidize producers of electricity or fuels, their markets and the electricity infrastructure.

In this article, an LCA of the environmental impact of PV electricity is presented and compared with that of conventional electricity. Because the environmental footprint of PV electricity is highly dependent on the electricity mix used in PV module fabrication [1], the environmental indicators are calculated for PV electricity manufactured using different electricity mixes, and compared with those for the European electricity mix (UCTE) and electricity generated by burning 100% coal or 100% natural gas. The environmental indicators are then used to quantify the associated environmental and health costs. The recent monetarization of these impacts is discussed, and compared with the findings of earlier studies.

Next, the global energy subsidies in 2011 and the energy subsidies in Germany over the past decades are reviewed. The amounts spent on subsidies to stimulate renewable energy deployment are compared with the savings on fossil fuel imports, and other economic effects of a stimulated industry sector. The security of a renewable energy supply is also explored.

Finally, the costs for grid expansion and grid reliability are considered. There are various motivations for grid expansion, some of which are not related to renewable energy generation. While a cost analysis of grid expansion is beyond the scope of this article, an examination of a current grid development plan suggests that a new estimate, with the interests of the future electricity mix and market in mind, may be required. Some recent studies are included to put into perspective the costs for achieving a very reliable electricity supply with a high penetration of renewable energy sources.

Wafer thickness	180μm
Cell size	156mm × 156mm
Module size	60 cells
Glass	single
Frame	yes
Roof mounting	Schletter
Inverter	2.5kW
Module efficiency	14.4%
Degradation	0.7%/yr
Performance ratio	0.8
Lifetime	30yrs
Irradiation	1700kWh/m^2/yr

Table 1. Key parameters associated with a PV system.

Methods

An LCA evaluates the environmental impact of a product or service over its lifetime. This analysis follows the guidelines set out in the international standard ISO 14040, which describes the principles and framework for LCA, as well as the methodology for LCA of PV electricity by the IEA [2]. The software used in this analysis is Simapro 7.3 with the ecoinvent 2.2 database, and the ReCiPe method for calculating a range of environmental indicators [3]. The carbon footprint is a measure of the emissions of greenhouse gases (in kg of CO_2 equivalents), effective over a period of 100 years, using the GWP100a method as defined by the Intergovernmental Panel on Climate Change (IPCC) in 2007 [4].

Data and key parameters

In order to calculate the environmental impact of 1kWh electricity over the lifetime of the generation source, data are required for each stage in the life cycle. Most of the data are supplied by the ecoinvent database, one of the world's leading international databases for life cycle studies. A kWh of electricity generated by coal or natural gas, or produced with the European electricity mix, can be readily calculated using the ecoinvent database. However, recent (2011) data on the energy and material use and processing of PV modules are not yet available in the ecoinvent database. This set of data has been compiled at ECN and was used to calculate the environmental profile of currently available PV modules. The key parameters of typical polysilicon PV modules manufactured in 2011 are given in Table 1.

A 12.4kWp PV system, mounted on-roof, with cabling and inverter, is taken as a typical PV system for a small to mid-size commercial enterprise. Electricity directly from the module is considered to be comparable to electricity from the power plant.

The environmental profile of electricity from three different PV modules is calculated: 1) one fabricated using electricity produced by 100% coal generation in European (UCTE) power plants; 2) another one manufactured using the average European (UCTE 2000) electricity mix (47% conventional thermal, 37% nuclear, 16% hydro); and 3) a third one made using hydropower in the production of the silicon feedstock, and natural gas electricity in the manufacturing of the cell and module. The manufacturing techniques, based on recent (2011) processes, of the three PV modules are in every other way identical. The environmental profile of natural gas electricity and the UCTE electricity mix is also calculated, and all the results are normalized to electricity generated with coal, in order to put them into perspective. The electricity from hard coal, natural gas and the UCTE mix is representative of average European plants in 2000 or 2001, as specified in the ecoinvent 2.2 database. In 2008 the UCTE mix consisted of 56% thermal (a mix of coal and gas technologies), 28% nuclear, 10% hydro and 7% other renewable energy sources.

Environmental impact

Greenhouse gases and air pollutants

Roughly 30% of the CO_2 emissions in Europe and the USA [5] are contributed by the power sector and are a major cause of global warming. These emissions lead to changes in the climate, including more frequent and more energetic weather events, rises in sea level, river flooding, heat waves and droughts, as well as changes in agriculture [6].

> "Roughly 30% of the CO_2 emissions in Europe and the USA are contributed by the power sector and are a major cause of global warming."

The air pollutant emissions by 1kWh electricity from multicrystalline silicon PV modules (19, 38 or 39g CO_2 eq) compared with electricity derived from burning gas (620g CO_2 eq), coal (1020g CO_2 eq), and the UCTE mix (506g CO_2 eq) are shown in Fig. 1. The emissions of greenhouse gases contributing to climate change (kg CO_2 eq) from PV modules manufactured with 100% coal electricity are double those from PV modules manufactured with hydro power and natural gas electricity, but are still 96% less than the emissions of electricity generated by coal. Coal electricity is also a leading cause of mercury emissions that may be inhaled or ingested by humans, causing neurological damage and contributing to the human toxicity indicator. Non-methane volatile organic compounds (NMVOCs) are organic compounds (e.g. benzene) that typically have compounding long-term health effects. Many are carcinogens. Particulate matter is suspended in air as an aerosol, and is associated with lung cancer and respiratory disease. Emissions of sulphur oxides lead to acid rain, which affects the biology of soil and vegetation and accelerates degradation of buildings and structures. The emissions calculated here are the average emissions of UCTE coal plants in 2000. Between 2000 and 2006, SO_2 emissions have decreased on average by ~40% in up-to-date coal plants, but 70% of coal plants in Europe are over 20 years old [7,8].

The results for the formation of photochemical oxidants and particulates and for terrestrial acidification follow the same pattern: the PV module made using hydro and natural gas electricity produces electricity with only ~2–3% of the impact per kWh of coal. The PV modules made with UCTE electricity (~50% fossil fuel) and with 100% coal electricity have twice the impact of the cleaner PV module (~6–7.5% of coal electricity). Electricity generated with natural gas provides 60% of the greenhouse gas emissions of coal, 36% of the volatile organic compounds (VOC), 15% of the particulates and 14% of the acidification. UCTE electricity presents the same level of human toxicity as coal electricity, but only 50% of the greenhouse gas emissions, 42% of the VOCs, 50% of the particulates and 47% of the acidification.

The UCTE electricity mix consists of almost a third nuclear generation, which is the reason for the high level of human toxicity in Fig. 1 and for the much greater amount of ionizing radiation in Fig. 2.

Water depletion and eutrophication

Water depletion and eutrophication (Fig. 3) are two critical issues for water management, now and in the future. Water depletion is a measure of the water withdrawn for use, and accounts for the water intake (which may damage ecosystems), the consumption (which reduces water availability) and the discharged water (which may present water quality issues). The eutrophication, or the accumulation of reactive nitrogen in the environment, is a leading cause of water quality impairment, and a serious threat to the health of marine systems. Both coal and, to a lesser extent, natural gas contribute to marine eutrophication. Water depletion for coal electricity is calculated to be 2682 litres/MWh, which is consistent with recent estimates for pulverized coal plants [9]. UCTE electricity uses 4300 litres/MWh, and natural gas, 2114 litres/MWh. The water demand of the thermal generation of electricity using coal or natural gas dwarfs the demand of PV electricity (575 litres/MWh for PV fabricated with coal or UCTE, and 474 litres/MWh for PV made with gas and hydro).

> "Although PV plants require some water over the life cycle, they offer the advantage of requiring little or no water for operation."

During recent warm, dry summers (2003, 2006 and 2009), several thermoelectric (fossil fuel and nuclear) plants in Europe were forced to reduce production because of a lack of cooling water. Recent analysis shows that the electricity supply from thermoelectric plants is vulnerable to climate change [10]. Although PV plants require some water over the life cycle, they offer the advantage, in terms of energy security, of requiring little or no water for operation.

Transformation of land

The transformation of natural land, as well as the occupation of urban and agricultural land, is large for hard coal because of the mining and infrastructure. Electricity from natural gas requires about three times as much transformation of natural land as coal or UCTE electricity as a result of the requirements for gas pipelines (Fig. 4).

Compared with coal electricity (per kWh), PV uses 86–89% less water, occupies or transforms over 80% less land and presents ~95% lower toxicity to humans; it also contributes 92–97% less to terrestrial acidification, 97–98% less to marine eutrophication and 96–98% less to climate change.

Monetarization of health and environmental impacts

The external costs of electricity have been discussed in political

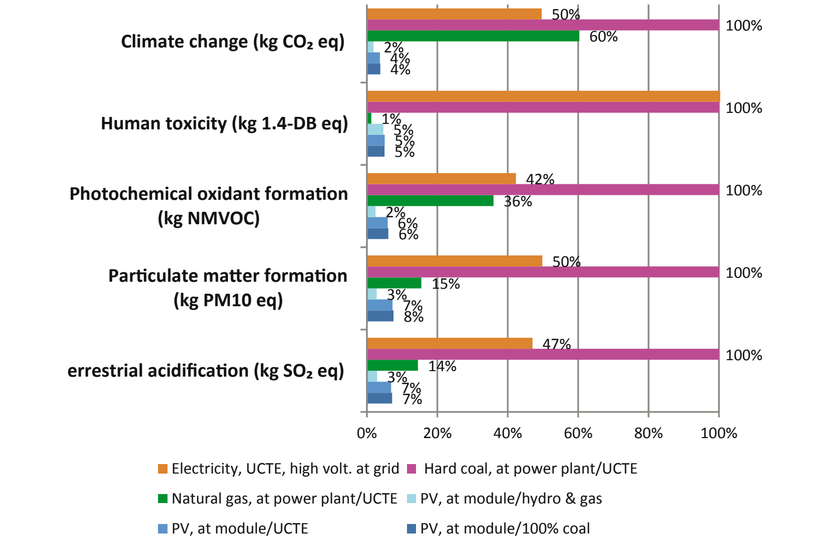

Figure 1. Comparison of air pollutant emissions of electricity produced by PV, natural gas, and the UCTE mix, at power plant, relevant to climate change (kg CO_2 eq), human toxicity (kg 1.4 dichlorobenzene (DB)), reactive organic pollutants (kg non-methane volatile organic compounds (NMVOCs)), and atmospheric particulate matter loading (kg of particulate matter smaller than ~10µm (PM10)), normalized to the impacts of hard coal electricity.

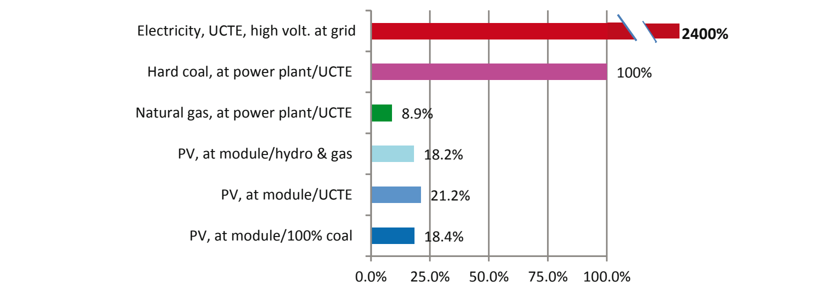

Figure 2. Comparison of the ionizing radiation emitted over the life cycle of various electricity generation sources.

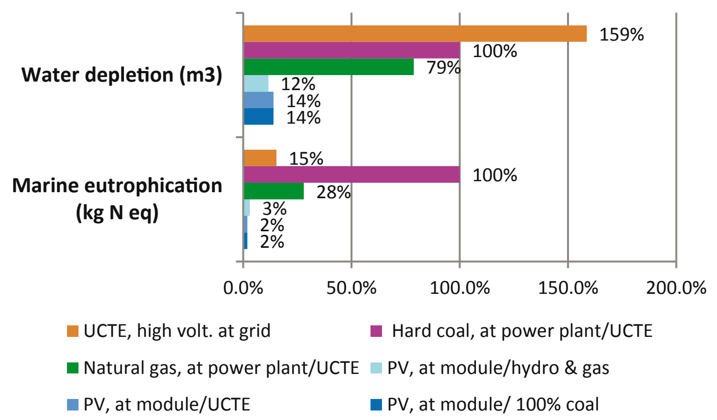

Figure 3. Comparison of water depletion and marine eutrophication by various electricity generation sources.

and scientific contexts for about 20 years. A very comprehensive, though finally inconsistent and incomplete, exercise quantifying energy-related externalities in Europe was done in the ExternE project [11], which continued through the NEEDS and CASES projects. The most recent (2010) set of results from the early methodology of ExternE estimates the total external costs for coal between 2.5 and 3¢/kWh (2008$) [12]. A more recent (2011) appraisal of these costs, carried out by Epstein et al. [13] at Harvard's School of Public Health, valued the environmental and health costs of coal electricity in the range of 18–27¢/kWh (2008$). This disparity of a factor of ten arises out of three fundamental differences in the bases of the evaluations: 1) the value placed on human morbidity; 2) the adequacy of the medical evaluation of the health and environmental damage; and 3) the appropriate and updated valuation of climate change. ExternE uses a much lower valuation (~50%) of human life than Epstein, who uses the value of statistical life most commonly used by the US Environmental Protection Agency. ExternE also uses outdated estimates of health and environmental impacts. Epstein gives a more complete epidemiology of air pollution, including particulates, and of the toxicity of heavy metals, such as mercury, relying on recent medical studies.

Finally, ExternE and its successors put an incredibly low value on the impact of climate change: an effective social cost of carbon of €2/tonne CO_2 [11]. The idea behind putting a price on CO_2 emissions was to stimulate industry and utilities to invest in clean electricity. When the price of CO_2 plummeted to €4/tonne last year, E.on CEO Johannes Teyssen proclaimed that the CO_2 market was a failure [13]. At this price, coal power plants are the most competitive, and even gas power plants can no longer stay in business [14]. E.on has also called for a minimum CO_2 price to be set, so that the market can begin to function as intended. The absolute minimum carbon price is considered to be about €20/tonne, as evidenced by the UK's carbon 'floor' price, the minimum CO_2 price set by the UK government in April 2013, with the plan that it will go up to €35/tonne by 2020 [15,16]. For the social cost of carbon, Epstein [13] uses values of US$30/tonne (€23/tonne) or US$100/tonne (€78/tonne) (low and high in Table 2).

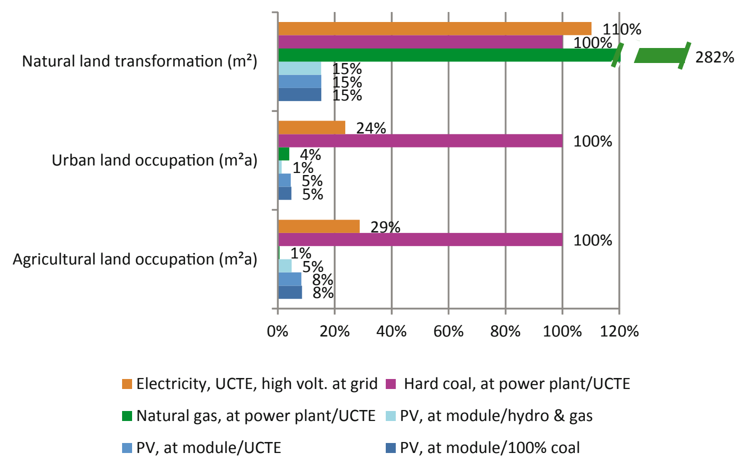

Figure 4. Land occupation and transformation for electricity (kWh) from PV, natural gas and coal, and the UCTE mix.

Before 2006, external cost studies of electricity did not take into account the magnitude of the costs of climate change. Then Nicolas Stern [17] changed that with his report stating that, if no action is taken, climate change will cost annually between 5–20% of the global GDP. A 2011 study, based on the social cost of carbon in Stern's work (US$85/tonne CO_2), estimated the cost of the impact of global greenhouse gas emissions to be US$4.5 trillion in 2008 (8% of GDP), with an expected rise to US$28.6 trillion in 2050 [18].

> "Climate change is contributing to the frequency and magnitude of extreme weather events, causing the losses from these events to steadily grow."

A validation of the increased valuation of climate change costs is the observation by the insurance industry in recent years that climate change is contributing to the frequency and magnitude of extreme weather events, causing the losses from these events to steadily grow. In 2012 the ten costliest natural catastrophes worldwide amounted to US$131bn in losses [19]. Total losses from natural catastrophes worldwide are approaching US$1 trillion annually, as contrasted with a norm 30 years ago of less than US$400bn/year [14]. The IPCC states in a 2012 report [20]: "Loss estimates

Category	Coal [¢/kWh] Low	Coal [¢/kWh] High	% impact of PV	PV/coal [¢/kWh] Low	PV/coal [¢/kWh] High
Climate change	3.15	10.55	3.8	0.12	0.40
Human toxicity	4.69	6.08	5	0.23	0.30
NMVOC+PM+SO_2	9.31	9.31	6.9	0.64	0.64
Land+AML	0.45	0.61	15	0.07	0.09
Coal transport	0.09	0.09	5	0.00	0.00
Total	17.69	26.64		1.07	1.44

Table 2. Monetarization of the environmental and health impact of 1kWh of electricity from coal compared with 1kWh of electricity from a PV module manufactured with 100% coal electricity, as per Epstein et al. [13]. Categories include: non-methane volatile organic compounds (NMVOCs) + particulate matter (PM) + sulphur oxide emissions (SO_2), and land transformation + abandoned mine lands (AML).

are lower bound estimates because many impacts, such as loss of human lives, cultural heritage, and ecosystem services, are difficult to value and monetarize, and thus they are poorly reflected in estimates of losses. Impacts on the informal or undocumented economy as well as indirect economic effects can be very important in some areas and sectors, but are generally not counted in reported estimates of losses." The estimate of roughly half a trillion dollars for the cost of extreme weather reveals that the order of magnitude for the costs of climate change must be at least in the trillions of dollars annually, which is consistent with Epstein et al., but not with the earlier methodology.

The methodology for costing damages from global warming is still evolving but the trend clearly indicates that climate change is much more expensive than originally thought. Indeed, insurers are currently re-evaluating their risk and business models in order to accommodate the new 'normal' of climate change events [21].

By using the methodology of Epstein et al., the external environmental and health costs can be estimated for PV manufactured with 100% coal electricity. Because the lion's share of the environmental impact of PV is associated with the electricity used to produce it, it is more consistent to compare 1kWh of electricity generated from PV manufactured using 100% coal electricity with 1kWh of electricity generated from coal.

Epstein et al. [13] assign monetary values (¢/kWh) for each impact category associated with the life cycle of coal, summarized here in the 'coal' columns of Table 2. The relative impact of PV ('% impact of PV' in Table 2) is taken from the environmental indicators for PV as a percentage of those for coal, as reported in Figs. 1-4. If the monetarization of Epstein et al. [13] is used, an estimate of the external environmental and health costs for a PV module manufactured exclusively with 100% coal electricity may be determined. This leads to an estimate of less than 1.5¢/kWh for the environmental costs for a PV module manufactured with 100% coal electricity, compared with 18–27¢/kWh for electricity generated from coal (2008$).

Subsidies

As pointed out by Chang [22]: "Virtually all of today's rich countries used protectionism and subsidies to promote their infant industries … The computer, semiconductors, aircraft, internet and biotechnology industries have all been developed thanks to subsidized R&D from the US government." The energy sector, in both the USA and Europe, is no exception. It is important to look at subsidies across the energy sector to put into context subsidies for renewable energy sources in general, and for PV in particular.

The IMF estimates that subsidies for fossil fuels took US$1.9 trillion out of the global economy in 2011, or 2.5% of global GDP, on an annual basis [23]. The figure for directly subsidizing fossil fuel use in 2011 was US$523bn (or ~25% of the total), compared with US$88bn subsidies for all renewable energy sources [24]. The other ~75% is attributable to the accompanying costs of environmental, health and infrastructure damages paid by taxpayer money (Fig. 5).

One example of a national renewable energy source subsidy is the feed-in tariff associated with the German Renewable Energy Law (EEG), which stimulated the growth of PV installations so that in 2012 PV generated 5% of German electricity. The feed-in tariff is funded by electricity users (but not large industrial electricity users) through a surcharge that appears on their electricity bills. The proceeds go to renewable electricity 'producers', the majority of whom are residential customers. From its inception, the feed-in tariff was designed so that the assistance would taper off to zero as the feed-in tariff converged to the market price of electricity as a function of the market growth in renewable energy. Fig. 6 gives an overview of the subsidies paid out by the German government from 1970 to 2012 [25].

The contribution that German electricity users pay to subsidize renewable energy rose from 3.592ct/kWh in 2012 to 5.277ct/kWh in 2013, constituting an increase of 46.9%. For an average household (3,500kWh/yr), electricity customers are paying about €185 total (or €84/person) during 2013, to finance a cleaner society and a new business sector with the associated jobs [26]. According to Claudia Kemfert, the Director of the Energy, Transportation and Environment Unit at the German Institute for Economic Research in Berlin, the cost of renewable energy is really quite small, i.e. about 2.3% of the average household's consumption expenditure – a lot less than the high prices of gasoline and heating, since the price of fossil fuels has been rising and will continue to rise [27].

Federal Environment Minister Peter Altmaier (Christian Democratic Union) and Federal Economics Minister Philipp Rösler (Free Democratic Party) have brought attention to the

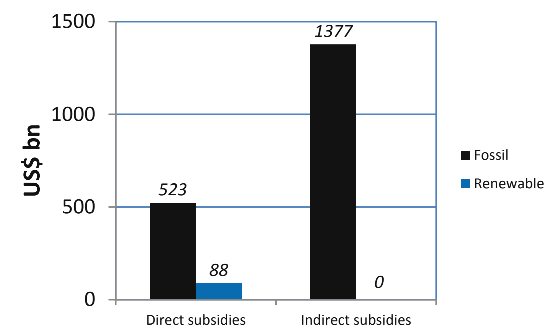

Figure 5. IMF statistics of annual global energy subsidies. The direct fossil fuel subsidies are concentrated in developing countries, while the indirect fossil fuel subsidies are predominately in the developed countries [19].

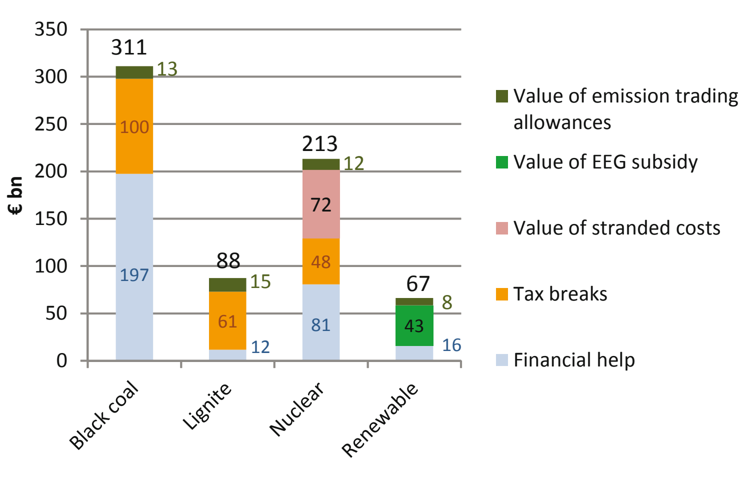

Figure 6. German government subsidies 1970–2012 in €bn (real) [21].

idea that the costs for the renewable energy transition are too high, and that renewable installations need to be slowed down significantly or stopped [28]. Altmaier has alarmed audiences with the claim that the energy transition will cost €1 trillion. However, economic analyses that take into consideration the cost of avoided fossil fuel imports, and avoided environmental damage among other related effects, do not substantiate the idea that renewable electricity is more expensive than fossil fuel electricity [29].

The main costs and benefits of the energy transition can be identified by looking at an economic analysis of the renewable energy expenditures for 2011, as shown in Fig. 7 [30]. In 2011 Germans paid, via the Renewable Energy Law, €11bn to install new renewable energy systems. For this price they received almost €60bn in economic and environmental benefits; in addition, 14,200 jobs were created in 2011, bringing the renewable energy employment to a total of 381,600 direct and indirect jobs (Fig. 7) [26].

Fuel imports and energy security

The political and economic potential risks and uncertainties of importing fossil fuels from outside Europe are continuously assessed in order to determine the security of Europe's energy supply (Fig. 8) [31]. A recent working paper of the European Commission discusses Europe's deteriorating security of energy supply [32]. "The EU currently imports more than 50% of its energy: more than 80% of the oil and more than 60% of the gas. If the current trends continue, import levels could reach more than 70% of the EU overall energy needs by 2030" [28]. The increased share of renewable energy will take some demand pressure off the fossil fuel supply, slowing down price escalation and increasing the EU's energy independence.

Compared with conventional energy, renewable energy is more economically and politically secure because fuel imports and dependencies are avoided, and the associated money does not leave the borders of the country. Furthermore, renewable deployment is associated with net job creation [33] – a stabilizing economic factor. Available studies show that job creation associated with renewable energy deployment is significant and occurs along the entire value chain, e.g. in manufacturing, sales, engineering, installation and administration. This means that countries which do not manufacture renewable energy products will still have a net job increase in the downstream parts of the value chain.

> "Compared with conventional energy, renewable energy is more economically and politically secure."

The costs that German society paid in 2011 through the EEG surcharge (€10.9bn) are almost balanced by the savings on fossil fuel imports alone (€7.1bn). The presence of renewable energy in the energy market brings down the cost of peak electricity (the merit order effect (€4.6bn)). Just these two factors more than offset the costs, and there is still a list of other benefits on top of that. Consequently, the net economic results of subsidies, fossil fuel imports and energy security are net external benefits.

Costs for grid expansion, control and balancing

In Fig. 7 (relating to the case of renewable energies in Germany in 2011), the costs for renewable energy (€10.9bn) include the direct renewable energy system costs (€10.6bn), electricity transaction costs (€0.3bn, or ~3% of the total costs) and the costs for control and balancing as well as grid expansion (most PV systems are connected to the low or medium voltage grid and do not require the kinds of additional transmission line that offshore wind requires).

Allocating the costs for grid expansion to PV, and to renewable energy sources in general, is complicated by several different factors. The ten-year plan of ENTSOE [34] sets out an ambitious and expensive blueprint for transforming Europe's transmission grid. The three motivations that it addresses are: 1) security of supply; 2) renewable energy integration; and 3) internal market integration, with the latter deemed the most important [34]. The security of supply aspect also relates to necessary upgrades to the ageing infrastructure, which were not performed over the past decades [35]. As there is little incentive in the liberalized energy market for investment in the common energy infrastructure, an investment shortfall has accumulated. The current need for investment in the electricity grid infrastructure because of insufficient investment in the past should not automatically be allocated to new electricity generators. Indeed, transparent and detailed information

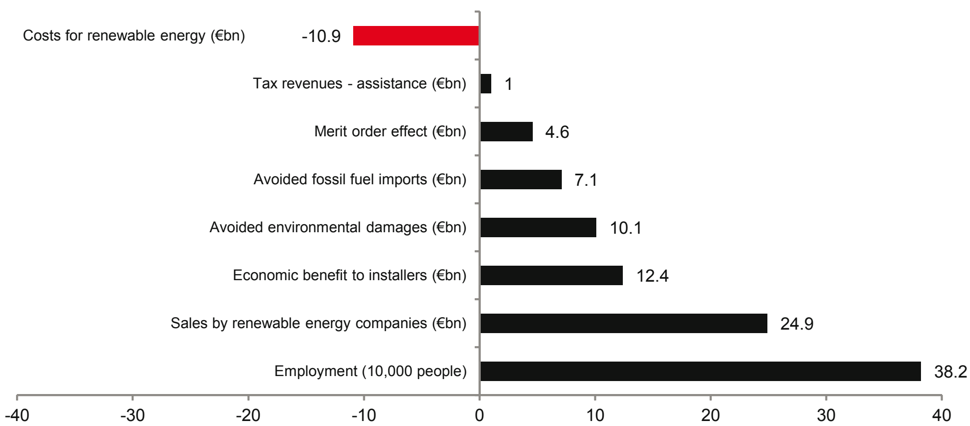

Figure 7. Economic analysis of the costs and benefits of the Renewable Energy Law in 2011, carried out by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. In 2011 14,200 more jobs were created, bringing the total number of renewable energy jobs to 381,600.

over what costs are really necessary in terms of infrastructure should be put out in the public domain. Furthermore, this information should be separated from the costs for a market structure whose benefit to customers is debatable.

ENTSOE's development plan currently allocates more than 60% of the investments to internal market integration in accordance with, and building on, the current energy market design [31]. However, the energy market is currently designed for conventional generators, and is against flexible renewable generators [36]. Considering that the energy market will need to evolve with the inevitable increase of renewables, the large investment in this energy market design should not be accepted without question.

Questions have been raised about the costs (which include the costs for balancing and reserve capacities) for assuring the reliability of integrating large amounts of renewables. Recent studies [37,38] demonstrate that the same high level of reliability as at present can be achieved on an hourly basis throughout the year, for the estimated electricity demand for the year 2050, with more than 50% renewable generation (TWh); this 'transition' scenario would offer savings of US$83bn over 40 years compared with the 'business as usual' (BAU) scenario. Those studies also demonstrate that the idea that 'every MW of renewable capacity requires a MW of fossil fuel generation capacity to back it up' is a misconception. The transition scenario requires 20% extra capacity, whereas 30% extra capacity is required by the BAU scenario.

The US National Renewable Energy Laboratory (NREL) has also produced a study which shows that balanced electricity from 80% renewables is feasible for the USA in 2050 [39]. The cost was found to be comparable to other possible energy scenarios (including combinations of renewable, nuclear and low-emission fossil fuels).

The experiences of system operators such as the Xcel Energy subsidiary Public Service Company of Colorado (PSCo) and the Electric Reliability Council of Texas (ERCOT) are also relevant. PSCo has had well over 50% wind at times, and ERCOT has over 10GW wind. ERCOT's calculations for the total cost of integrating wind in 2011 came out to about US$0.50/MWh, or a modest ~1.3% of the energy value [40]. ERCOT explains that its efficient dispatch of wind is a result of state-of-the-art forecasting, five-minute dispatch intervals, the advantages of a large geographic area, and the ability to use 'non-spinning reserves' to cover the risk of insufficient generating capacity [35]. 'Non-spinning reserves' means that they can obtain electricity by turning on generation sources with a fast start-up, or by balancing imports and exports to retain more electricity to cover demand.

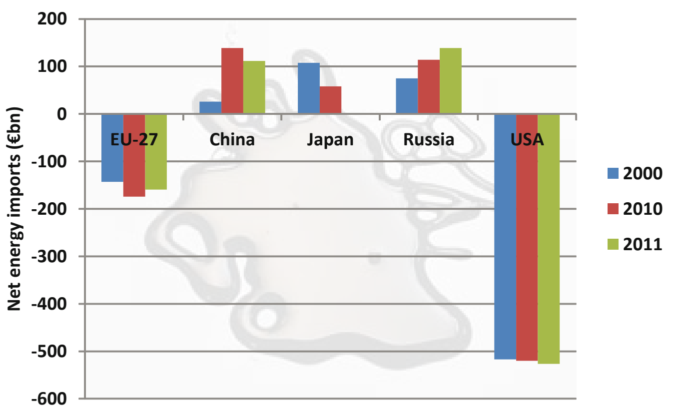

Figure 8. EU-27 and the USA dependency on imports of coal, lignite, oil and gas (2011 data for Japan were not available).

This kind of flexible, short-interval dispatch is what is necessary for low-cost integration of large penetrations of renewable energy sources. In February 2013 the California Independent System Operator (CAISO) and PacifiCorp (a utility ranging over six western states in the USA) signed a memorandum of understanding to create an energy imbalance market in 2014. This will create the sort of market structure for enabling flexible, short-interval dispatch. NREL anticipates that this market will save US$150–300m per year over current operations, as well as allowing low-cost integration of a high percentage of renewables [41,42].

Instances of high penetrations of renewables are increasingly occurring in Europe. Redes Energéticas Nacionais (REN), Portugal's grid operator, reported that 70% of the country's electricity was generated by renewable energy sources in the first quarter of 2013 [43].

The cost of integrating renewables clearly depends on the abilities of the system operator to operate flexibly, with short-interval dispatch, and to share reserve generation across a broader region. It may be that many system operators have to update their operations to rise to the inevitable challenge of high penetrations of renewables; the solutions some utilities and operators have found to achieve this apparently come with cost savings, rather than cost burdens. Detailed cost pictures for integrating renewables necessarily depend upon the system operator, and this is beyond the scope of this paper. However, the adaptation to the future electricity supply based on very large penetration of renewables appears to lie within the choice of business model and operations of the system operators.

Renewable energy is a solution for mitigating the deteriorating energy supply, for bringing down greenhouse gas emissions, for avoiding the economic drain of importing fossil fuels from third countries, and for stimulating the creation of jobs. Integrating high penetrations of renewables, with the same reliability as we have today, appears to be totally feasible and within the cost horizons of current operations. It therefore does not need to be considered an external cost burden for distributed renewable generators.

Conclusions

The social, economic and environmental value of PV specifically, and renewable energy in general, is especially relevant today. Two indicators, one social and one environmental, are emblematic for the state of the world in 2013: income inequality and the atmospheric level of CO_2. The first indicator is highlighted in the World Economic Forum's 2013 Global Risk Report. Severe income disparity, or inequality of wealth and income, is identified as one of the direst risks in 2013, and a symptom of the continued stress on the global economic system [44]. The OECD also recently published a report showing that the first three years of the financial crisis markedly increased income inequality worldwide: from 2007 to 2010 the inequality in income from work and capital increased as much as in the previous twelve years [45]. That report cautions that, given the current sluggish recovery, with less spending capability of the middle classes, this trend may spiral downwards.

The social and economic benefits of investing in renewable energy, and PV specifically, include not having to send increasing sums of money for fossil fuels to third countries, which increases energy security and creates jobs and renewable energy products and markets, as well as lower wholesale electricity prices. The costs paid in 2011 by German society through the EEG surcharge (€10.9bn) are almost balanced by the savings on fossil fuel imports alone (€7.1bn). The presence of renewable energy in the energy market brings down the cost of peak electricity on account of the merit order effect (€4.6bn). These two factors alone more than offset the costs, and there is additionally a list of other benefits on top of that. The combination of subsidies, avoided fossil fuel imports and energy security therefore results in net external benefits.

"Switching to renewable energy sources is the single most effective measure that can be taken to slow the acceleration of CO_2 levels in the atmosphere."

The second indicator – the atmospheric level of CO_2 – has just passed the 400ppm mark; CO_2 added to the atmosphere and oceans stays around for thousands of years. Thus climate changes forced by CO_2 depend primarily on cumulative emissions, making it progressively more and more difficult to avoid further substantial climate change [46]. Switching to renewable energy sources is the single most effective measure that can be taken to slow the acceleration of CO_2 levels in the atmosphere. As Ralph Keeling [43], from the Scripps Institute of Oceanography, says: "It mainly comes down to how much we continue to rely on fossil fuels for energy." PV electricity contributes 96–98% less greenhouse gases than electricity from 100% coal, and 92–96% less compared with the European electricity mix. Furthermore, compared with coal electricity, PV electricity over its lifetime uses 89–86% less water, occupies or transforms over 80% less land, and presents ~95% lower toxicity to humans; it also contributes 92–97% less to terrestrial acidification and 97–98% less to marine eutrophication. The economic consequences are expressed as the environmental and health external costs, which, for a PV module manufactured with 100% coal electricity, is 1–1.5¢/kWh compared with 18–27¢/kWh for electricity from coal (2008$). In 2012$, coal electricity requires an extra 19–29¢/kWh, compared with 1–1.6¢/kWh for PV manufactured with 100% coal electricity. For households this is yet another economic burden that may be avoided by using renewable electricity.

The final reservations about integrating high amounts of renewable energy into the grid appear to be resolvable, as more and more evidence mounts showing that it is indeed feasible to do so. Integrating high penetrations of renewables, with the same reliability as we have today, appears to be totally feasible and within the cost horizons of current operations of the system operators. It therefore does not need to be considered an external cost burden for distributed renewable generators. If the goal of policymakers is to improve the health and welfare of society, then they need not hesitate in supporting PV and other renewable energy sources.

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References

[1] De Wild Scholten, M. 2011, "Environmental profile of PV mass production: Globalization", *Proc. 26th EU PVSEC*, Hamburg, Germany.

[2] IEA 2011, "Methodology of life cycle assessment for photovoltaic electricity", Report IEA-PVPS T12-03:2011 [http://www.iea-pvps.org/fileadmin/dam/public/report/technical/rep12_11.pdf].

[3] Goedkoop, M. 2012, "ReCiPe 2008", Report for the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM) [http://www.lcia-recipe.net/].

[4] Working Group I 2007, "Global warming potentials", Contribution to the fourth assessment report of the Intergovernmental Panel on Climate Change [http://www.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-2-5.html].

[5] Eurostat 2011, "Energy, transport and environment indicators" [http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-DK-11-001/EN/KS-DK-11-001-EN.PDF].

[6] European Environmental Agency 2012, "Climate change, impacts and vulnerability in Europe 2012" [http://www.eea.europa.eu/publications/climate-impacts-and-vulnerability-2012].

[7] Ito, O. 2011, "Emissions from coal fired power generation", IEA Workshop on High Efficiency, Low Emissions Coal Technology Roadmap [http://www.iea.org/media/workshops/2011/cea/Ito.pdf].

[8] Drake, F.-D., "Investment in coal-fired power generation", IEA/NEA Joint Workshop on Power Generation Investment in Liberalized Electricity Markets [https://www.oecd-nea.org/ndd/investment/session3/Drake.pdf].

[9] Martin, A.D. 2012, "Water footprint of electric power generation: Modeling its use and analyzing options for a water-scarce future" [http://sequestration.mit.edu/pdf/AnnaDelgado_Thesis_June2012.pdf].

[10] van Vliet, M. 2012, "Vulnerability of US and European electricity supply to climate change", *Nature Climate Change*, Vol. 2, pp. 676–681.

[11] Krewitt, W. 2002, "External costs of energy – Do the answers match the questions? Looking back at 10 years of ExternE", *Energy Policy*, Vol. 30, pp. 839–848.

[12] Markandya, A., Bigano, A. & Porchia, R. (Eds.) 2010, *The Social Costs of Electricity*. Northampton, MA, USA: Edward Elgar Publishing.

[13] Epstein, P. et al. 2011, "Full cost accounting for the life cycle of coal", *Ann. N.Y. Acad. Sci.*, Vol. 1219, pp. 73–98.

[14] Chestney, N. 2012, "POLL-analysts cut EU, UN carbon forecasts" [http://www.pointcarbon.com/news/reutersnews/1.2087144].

[15] Pilita Clark, P. & Tighe, C. 2013, "UK business attacks EU carbon move", *Financial Times* (April 17) [http://www.ft.com/intl/cms/s/0/652c2932-a77d-11e2-9fbe-00144feabdc0.html#axzz2XEEkWTDp].

[16] HM Revenue & Customs 2013, "Carbon price floor" [http://www.hmrc.gov.uk/climate-change-levy/carbon-pf.htm].

[17] Stern, N. 2006, "Stern review: The economics of climate change", Executive Summary [http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/media/4/3/Executive_Summary.pdf].

[18] United Nations Environment Programme Finance Initiative & Principles for Responsible Investment 2011, "Universal ownership: Why environmental externalities matter to institutional investors" [http://www.unpri.org/files/6728_ES_report_environmental_externalities.pdf].

[19] Munich Re Touch 2012, Annual Statistics [http://www.munichre.com/touch/naturalhazards/en/natcatservice/annual_statistics.aspx].
[20] IPCC 2012, "Summary for policymakers", in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, Field, C.B. et al. (Eds.). Cambridge and New York: Cambridge University Press, pp. 3–21 [http://ipcc-wg2.gov/SREX/images/uploads/SREX-SPM_FINAL.pdf].
[21] McHale, C. & Leurig, S. 2012, "Stormy future for U.S. property/casualty insurers [https://www.ceres.org/resources/reports/stormy-future/view].
[22] Chang, H-J. 2011, *23 Things They Don't Tell You about Capitalism*. London: Penguin Books.
[23] IMF 2013, "Energy subsidy reform: Lessons and implications" [http://www.imf.org/external/np/pp/eng/2013/012813.pdf].
[24] IEA 2013, "Tracking clean energy progress 2013" [http://www.iea.org/publications/TCEP_web.pdf].
[25] Greenpeace & BWE 2012, "Was Strom werklich kostet" [http://www.greenpeace-energy.de/uploads/media/Stromkostenstudie_Greenpeace_Energy_BWE.pdf].
[26] German Federal Ministry for Family Affairs, Senior Citizens, Women and Youth 2004, "Families in Germany, facts and figures" [http://www.bmfsfj.de/RedaktionBMFSFJ/Broschuerenstelle/Pdf-Anlagen/Brosch_C3_BCre-Familie-im-Spiegel-englisch,property=pdf,bereich=,sprache=de,rwb=true.pdf].
[27] Hockenos, P. 2013, "The battle over electricity" [http://energytransition.de/2013/04/the-battle-over-electricity/].
[28] Enkhardt, S. 2013, "Germany: Severe renewable energy cuts planned" [http://www.pv-magazine.com/news/details/beitrag/germany--severe-renewable-energy-cuts-planned_100010216/#ixzz2Sb82NmzK].
[29] Green Budget Germany 2013, "Die Kosten der Energiewende – Wie belastbar ist Altmaiers Billion?" [http://www.foes.de/pdf/2013-03_Kurzanalyse_Energiewendekosten_Billion.pdf].
[30] Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2012, "Renewable energy sources in figures – National and international development" [http://www.erneuerbare-energien.de/fileadmin/Daten_EE/Dokumente__PDFs_/broschuere_ee_zahlen_en_bf.pdf].
[31] Eurostat 2012, "Energy, transport and environment indicators" [http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-DK-12-001/EN/KS-DK-12-001-EN.PDF].
[32] European Commission Staff Working Paper 2012, "Renewable energy: A major player in the European energy market", 271 final [http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SWD:2012:0149:FIN:EN:PDF].
[33] International Renewable Energy Agency (IRENA) 2012, "Renewable energy – Jobs status, prospects & policies" [http://www.irena.org/DocumentDownloads/Publications/RenewableEnergyJobs.pdf].
[34] ENTSOE 2012, "Ten-year network development plan 2012", p. 48 [https://www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2012/].
[35] European Commission 2011, "Connecting Europe: The energy infrastructure for tomorrow" [http://ec.europa.eu/energy/mff/facility/doc/2012/connecting-europe.pdf].
[36] Neuhoff, K. 2011, "Opening the electricity market to renewable energy: Making better use of the grid" [http://www.diw.de/documents/publikationen/73/diw_01.c.375862.de/diw_econ_bull_2011-01-4.pdf].
[37] Vitolo, T. et al. 2013, "Meeting load with a resource mix beyond business as usual", *Synapse Energy Economics*, April 17 [http://www.civilsocietyinstitute.org/media/pdfs/20130417Meeting%20Load%20with%20a%20Resource%20Mix%20Beyond%20Business%20as%20Usual%20-%20FINAL.pdf].
[38] Keith, G. et al. 2011, "Toward a sustainable future for the U.S. power sector: Beyond business as usual 2011" [http://www.synapse-energy.com/Downloads/SynapseReport.2011-11.CSI.BBAU-2011.11-037.pdf].
[39] NREL 2012, "Renewable electricity futures study" [http://www.nrel.gov/analysis/re_futures/].
[40] Ahlstrom, M. 2013, "A market perspective on forecast value", WindLogics [http://www.uwig.org/slcforework/Ahlstrom-Session1.pdf].
[41] Baak, J. 2013, "CAISO and PacifiCorp agreement paves way for lower cost solar integration" [http://www.renewableenergyworld.com/rea/news/article/2013/02/caiso-and-pacificorp-agreement-paves-way-for-lower-cost-solar-integration].
[42] Milligan, M. et al. 2012, "Examination of potential benefits of an energy imbalance market in the Western interconnection", NREL Report [http://www.westgov.org/PUCeim/documents/drftNRELba.pdf].
[43] REN 2013, "Renewables supply 70% of domestic consumption of electricity in Q1" [http://www.ren.pt/media/comunicados/detalhe/renovaveis_abastecem_cerca_de_70__do_consumo_nacional_de_eletricidade_no_1__trimestre/?culture=en-GB].
[44] World Economic Forum 2013, "Global risks 2013" [http://www3.weforum.org/docs/WEF_GlobalRisks_Report_2013.pdf].
[45] OECD 2011, "Crisis squeezes income and puts pressure on inequality and poverty" [http://www.oecd.org/els/soc/OECD2013-Inequality-and-Poverty-8p.pdf].
[46] National Oceanic and Atmospheric Administration (NOAA) 2013, "Carbon dioxide at NOAA's Mauna Loa Observatory reaches new milestone: Tops 400 ppm" [http://research.noaa.gov/News/NewsArchive/LatestNews/TabId/684/ArtMID/1768/ArticleID/10061/Carbon-Dioxide-at-NOAA%e2%80%99s-Mauna-Loa-Observatory-reaches-new-milestone-Tops-400-ppm.aspx].

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