cesses), but for these three photocatalyzed reactions, quantum yields of >>1 were observed, indicative of radical-chain processes being dominant.

Care must be taken not to extrapolate these findings to all photoredox reactions. Instead, they are likely to be case-dependent (*11*, *12*). Mechanistic studies concerning photocatalyst quenching dynamics with luminescence quenching and transient absorption spectroscopy have played an important role in elucidating the elementary steps in catalyst-substrate interactions (*13*). Other mechanistic considerations, such as catalyst deactivation, have been studied with reaction-progress kinetic analysis (*14*). Collectively, these techniques provide the powerful tools necessary to probe the intricate mechanisms inherent in these catalytic systems. Further advancement of mechanistic understanding will have a tremendous impact on the development of novel transformations, the optimization of existing reactions, and the design of more effective photocatalysts. ■

"Collectively, these techniques provide the powerful tools necessary to probe the intricate mechanisms inherent in these catalytic systems."

REFERENCES AND NOTES

1. C. Chatgilialoglu, A. Studer, Eds., *Encyclopedia of Radicals in Chemistry, Biology and Materials* (Wiley, Weinheim, Germany, 2012).
2. D. M. Schultz, T. P. Yoon, *Science* **343**, 1239176 (2014).
3. J. J. Douglas, J. D. Nguyen, K. P. Cole, C. R. J. Stephenson, *Aldrichim. Acta* **47**, 15 (2014).
4. C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.* **113**, 5322 (2013).
5. A. Juris *et al.*, *Coord. Chem. Rev.* **84**, 85 (1988).
6. M. A. Cismesia, T. P. Yoon, *Chem. Sci.* 10.1039/C5SC02185E (2015).
7. G. M. Burnett, H. W. Melville, *Chem. Rev.* **54**, 225 (1954).
8. S. Lin, M. A. Ischay, C. G. Fry, T. P. Yoon, *J. Am. Chem. Soc.* **133**, 19350 (2011).
9. M. A. Ischay, M. E. Anzovino, J. Du, T. P. Yoon, *J. Am. Chem. Soc.* **130**, 12886 (2008).
10. D. A. Nicewicz, D. W. C. MacMillan, *Science* **322**, 77 (2008).
11. H. Ismaili, S. P. Pitre, J. C. Scaiano, *Catal. Sci. Technol.* **3**, 935 (2013).
12. M. Majek *et al.*, *Beilstein J. Org. Chem.* **10**, 981 (2014).
13. N. A. Romero, D. A. Nicewicz, *J. Am. Chem. Soc.* **136**, 17024 (2014).
14. J. J. Devery III *et al.*, *Chem. Sci.* **6**, 537 (2015).

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ENERGY

King Coal and the queen of subsidies

The window for fossil fuel subsidy reform is closing fast

By **Ottmar Edenhofer**

Coal is the most important energy source for the Chinese economy (see the photo). Other rapidly growing economies in Asia and Africa also increasingly rely on coal to satisfy their growing appetite for energy. This renaissance of coal is expected to continue in the coming years (*1*) and is one of the reasons that global greenhouse gas (GHG) emissions are increasing despite the undisputed worldwide technological progress and expansion of renewable technologies (*2*). The implications for long-term GHG emissions are serious because, once installed, a coal power plant will emit for decades. Fossil fuel subsidies support investments in coal capacities around the globe and thereby threaten the achievement of climate change mitigation goals. Targeted reform of these subsidies could yield benefits for climate change mitigation as well as other development objectives.

The existing global energy infrastructure already commits 729 gigatons of CO_2 ($GtCO_2$) of future cumulative emissions over its lifetime. Aims to limit global temperature increase to 2°C allow for a total of 1000 $GtCO_2$ to be released into the atmosphere. If only one-third of currently planned coal capacity is installed successfully, an additional 113 $GtCO_2$ emissions are committed, nearly depleting the budget allowed by such mitigation targets (*3*).

Over the past year, many nations have made commitments to reduce their domestic GHG emissions. The U.S. government has announced plans to reduce emissions in the power sector by 32% below 2005 levels in 2030 through its Clean Power Plan (*4*). The Chinese government pledged that its emissions would peak in 2030 and has plans to increase the installed capacities of renewables and nuclear power substantially in the next decade (*5*). The Chinese emission target is sufficiently vague to prevent a precise evaluation of emission reductions. But even if China and the United States are successful in reducing their domestic emissions, worldwide emissions are expected to continue to rise. After all, a reduction in coal demand in one region reduces world market prices, incentivizing an increasing demand in other regions (*6*).

What explains this renaissance of coal? The short answer is the relative price of coal. The price of coal-based electricity generation remains much lower than that of renewable power when the costs of renewable intermittency are taken into account.

As a result of technological progress and economies of scale, the costs of generating electricity from wind and solar power have declined substantially. Wind generation now costs 70 US$ per megawatt-hour (MWh) on average, and geographically favorable sites can compete with the costs of coal-fired power (~50 US$/MWh). Solar photovoltaic projects have reached 80 US$/MWh and within a few years can also be expected to match the costs of coal generation (*7*, *8*). However, the costs of intermittency of wind and solar add an additional markup of about 30 US$/MWh (*9*) in cases where these technologies are deployed on a large scale as a result of increasing backup capacity requirements. Because of these additional costs, coal becomes more attractive for investors than renewable sources in many countries. In addition, coal is increasingly traded on the world market, dashing the hopes of many concerned with climate change that coal is only economically viable for a few countries with large domestic endowments (*1*).

At the same time, finance ministers around the globe subsidize fossil fuels, mostly by enabling the sale of these fuels on the domestic market below world market prices. In 2013, these pretax subsidies amounted to about 550 billion US$ worldwide (*10*). Energy subsidies are often believed to mainly support low-income households, but this belief is not well supported. Energy subsidies are typically captured by rich households in low-income countries and do little to support the poor. In all regions, the poorest 20% of the population received less than 8% of the benefits of the subsidies, whereas more than 40% of the subsidies were captured by the richest 20% (*11*).

Well-designed fossil fuel subsidy reform has considerable potential to raise the financial means necessary to reduce poverty. As a

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Coal renaissance. Rapidly growing economies, including China, increasingly rely on coal for cheap energy, jeopardizing efforts to reduce fossil fuel use worldwide. In this image, workers haul coal to barges in Fengjie for delivery to power plants downriver.

PHOTO: © BOB SACHA/CORBIS

recent study has shown (*12*), if current fossil fuel subsidies were to be redirected to investments in basic infrastructures over the next 15 years, substantial strides could be made in reducing poverty. This includes universal access to clean water in about 70 countries, to improved sanitation in about 60 countries, and to electricity in about 50 countries (out of roughly 80 countries that do not yet have universal access). Such investments would also increase the long-term growth prospects of poor economies.

The lion's share of pretax fossil fuel subsidies is targeted at oil consumption in the Middle East, North Africa, and Asia. At first glance, it would thus seem that subsidies are not instrumental in driving the renaissance of coal. However, this would be a premature conclusion: King Coal and the queen of subsidies are involved in a complex marriage, as shown by a recent International Monetary Fund (IMF) report on energy subsidies (*13*).

The IMF report suggests that fiscal spending is an incomplete and even misleading metric for fossil fuel subsidies: The nonpricing of adverse external effects such as GHG emissions, premature deaths through local air pollution, increased congestion, and other adverse side effects of vehicle use must also be taken into account. These subsidies also discourage investments in low-carbon alternatives such as energy efficiency, renewable energies, or natural gas infrastructure, which generate less or none of these externalities. In addition, the fiscal costs of subsidies must be financed by some combination of higher public debt, higher tax burdens, and crowding out of potentially productive public spending on health, education, and infrastructure.

A key insight from the IMF report is that posttax energy subsidies (which would include a price on the aforementioned externalities) are higher than the pretax subsidies by a factor of almost 10. The IMF calculates that the full social costs of fossil fuel consumption in 2013 amounted to 4.9 trillion US$ globally. A second major insight from their calculation is that coal receives about 60% of the total posttax subsidies. This implies that one ton of CO_2 receives, on average, more than 150 US$ in subsidies (with 32 $GtCO_2$ emitted by the global energy sector in 2013). The report convincingly shows that the mispricing of fossil fuels will contribute to an ongoing renaissance of coal over the coming decades.

The window of opportunity for successful price reform is rapidly closing. As many quickly growing countries continue to invest in coal-fired plants, they lock in carbon-intensive infrastructure, which substantially increases the costs of future emission reductions. Getting prices right before this infrastructure is built is essential. If the opportunity to correct the distortion in fossil fuel pricing is missed, climate policy is in peril.

The social costs of fossil fuel subsidies may not be obvious to the public and might even be masked for finance ministers. The upside of this debate is that adopting a more rational approach to fossil fuel pricing would increase overall welfare, provide fiscal gains for governments, and allow for new strategies to finance sustainable development that would particularly benefit the poor. These incentives arise from a purely self-interested national perspective, without the need to wait for a global climate agreement to come to fruition. At the same time, bold national actions to align fossil fuel prices with their true social costs could also remove important barriers for carbon pricing and hence become a major boost for international climate diplomacy. ■

REFERENCES

1. J. C. Steckel, O. Edenhofer, M. Jakob, *Proc. Natl. Acad. Sci. U.S.A.* **112**, E3775 (2015).
2. International Energy Agency (IEA), World Energy Outlook Special Report 2015: Energy and Climate Change (2015); www.iea.org/publications/freepublications/publication/weo-2015-special-report-energy-climate-change.html.
3. C. Shearer, N. Ghio, L. Myllyvirta, T. Nace, *Boom and Bust: Tracking the Global Coal Plant Pipeline* (Coalswarm, Sierra Club, 2015); http://action.sierraclub.org/site/DocServer/Coal_Tracker_report_final_3-9-15.pdf?docID=17381.
4. U.S. Environmental Protection Agency, Clean Power Plan for Existing Power Plants (2015); www2.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants.
5. White House, U.S.-China Joint Announcement on Climate Change (2014); www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change.
6. H. McJeon *et al.*, *Nature* **514**, 482 (2014).
7. IRENA, *Renewable Power Generation Costs in 2014* (International Renewable Energy Agency, Abu Dhabi, 2015).
8. Intergovernmental Panel on Climate Change, Working Group III, O. Edenhofer *et al.*, Eds., *Special Report on Renewable Energy Sources and Climate Change Mitigation* (Cambridge Univ. Press, Cambridge, 2011).
9. L. Hirth, F. Ueckerdt, O. Edenhofer, *Renew. Energy* **74**, 925 (2015).
10. IEA, World Energy Outlook 2014 (IEA, Paris, 2014).
11. F. J. Arze del Granado, D. Coady, R. Gillingham, *World Dev.* **40**, 2234 (2012).
12. M. Jakob, C. Chen, S. Fuss, A. Marxen, O. Edenhofer, *Nat. Climate Change* **5**, 709 (2015).
13. D. Coady, I. Parry, L. Sears, B. Shang, *How Large Are Global Energy Subsidies?* IMF working paper (2015); www.imf.org/external/pubs/ft/wp/2015/wp15105.pdf.

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