Ecological stewardship will be the guiding scientific principle for new avenues of inquiry.

Science and Engineering Research That Values the Planet

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The recognition that human activity is transforming the planet, both in intended and dramatically unintended ways, has led to the development of a new field of research—sustainability science. Widely discussed essays (e.g., Clarke, 2002; Kates et al., 2001; Kennedy, 2003; McMichael et al., 2003; Swart et al., 2002), special issues of premier journals (NAS, 2003), and extensive websites (FSTS, 2005) are now devoted to defining sustainability and identifying useful modes and topics for research. Building on this foundation, we now have a tremendous opportunity to advance a new global scientific research paradigm—the generation and implementation of sustainability science. One important lesson emerges very clearly from this body of work—only by posing the question of sustainability explicitly and, where necessary, repairing the damage humans have caused to the biosphere, can we begin to understand how humans can prosper without degrading the planet.

In a seminal treatise on science policy, Vannevar Bush (1945) wrote that, "applied research invariably drives out pure [research]," to the detriment, in his view, of the national capacity for innovation. The subsequent separation

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of basic and applied research shaped the evolution of science and engineering research for decades and was a point of departure for E.F. Schumacher (1973) and the "appropriate technology" movement, a precursor of sustainability science that involved identifying important but neglected issues for scientific study. This approach, dubbed "mundane science," (Kammen and Dove, 1997), involves projects that combine pragmatic and goal-oriented applied research with potential advances in basic science (Stokes, 1997). The growing recognition of the value of supporting interdisciplinary research and the emergence of sustainability science are continuations of the intellectual evolution of the interaction between science and society.

The scientific recognition of the reality of global environmental change (Hansen et al., 2005), the political awareness of the need to act now to address greenhouse gas emissions (Kennedy, 2005), and the increasing disparities between the lives of the poor and the wealthy provide an opportunity for galvanizing global action to place sustainability science at the forefront of educational, research, and career-development agendas. The next step toward putting sustainable science into action is recognizing that, with ecological stewardship as a guiding scientific principle, entirely new avenues of inquiry are possible.

At this moment in history, this message has the potential to transform research careers and make sustainability a theme that researchers, public officials, and civil society can all embrace. The World Conference on Physics and Sustainable Development, held in Durban, South Africa, in October and November 2005, provided a forum for showcasing opportunities for the co-evolution of basic research and social advances (SAIP, 2005).

Currently attention, debate, and a trans-Atlantic division are focused on how to provide meaningful, long-term aid and assistance to Africa. To highlight a potential solution, we present two cases of sustainable science, engineering, and action in developing nations that advance both science and sustainable human and ecological communities.

The Energy-Health-Ecology Nexus

Household use of solid fuels is one of the leading causes of death and disease in developing countries throughout the world—particularly among women and children (Smith et al., 2004). Over the past decade, a series of studies has been conducted of programs to design and disseminate more efficient, safer household stoves *and* to develop and implement sustainable forestry and fuel (often charcoal) production practices in Africa. As Figure 1 shows, combined attention to both stove and forestry programs can lead to dramatic simultaneous improvements in human health, ecological sustainability, and local economic development (Kammen, 1995).

The Kenya study showed that transitions from wood and dung fuels burned in simple stoves to charcoal burned in improved stoves reduced the frequency of acute respiratory infections

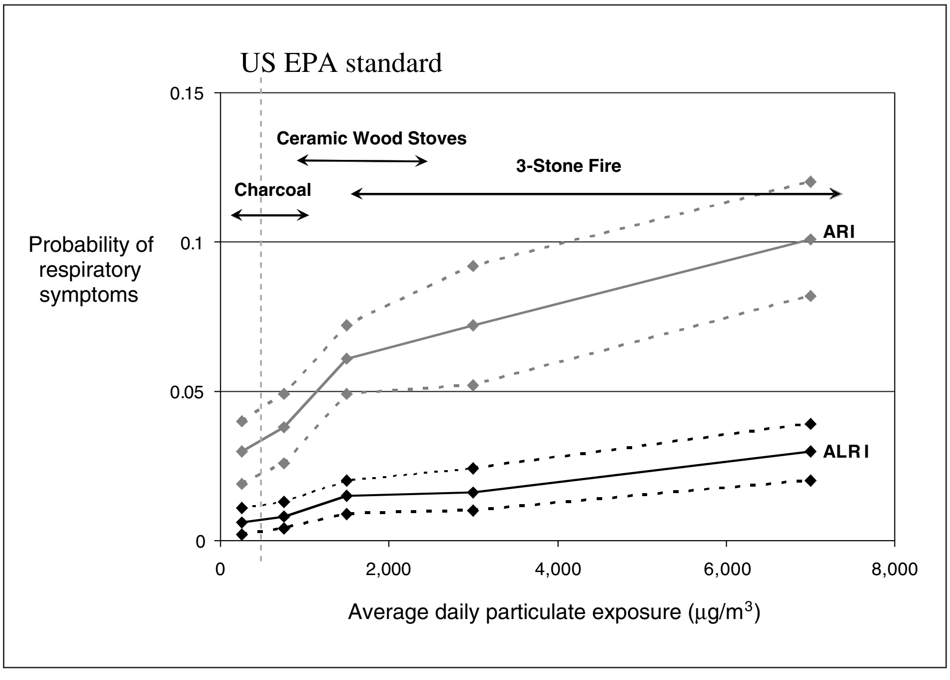

FIGURE 1 The exposure-response graph from a six year, 500 person, exposure and stove intervention study in Kenya. The vertical axis shows the percentage of time subjects participating in biweekly health examinations exhibited ARI or acute lower respiratory illness (ALRI) symptoms. The EPA particulate exposure standard of 200 $\mu g/m^3$ for PM_{10} (particles with diameters of less than 10 microns) is indicated by the dotted vertical line, which forms a lower bound for the exposure range observed in the Kenya project. The stove and fuel combinations indicate exposure ranges. Adapted from Ezzati and Kammen, 2001.

(ARI) by a *factor of two*. This is a tremendous impact on ARI, the most common illnesses reported in medi-cal exams in sub-Saharan Africa. Comparatively simple materials and design modifications to household stoves are now known not only to improve energy efficiency, but also to reduce particulate and greenhouse gas emissions (Bailis et al., 2005).

These benefits can be achieved at exceptionally low cost, just a few dollars per life saved, and have the added benefit of mitigating atmospheric carbon, at just a few dollars per ton of carbon (Ezzati and Kammen, 2002). By contrast, carbon today trades for roughly $30/ton on the London exchange, a price that reflects only the impact of greenhouse gases. By making the dissemination and use of improved cookstoves a component of a comprehensive Africa-assistance strategy, both local health and development needs *and* global environmental protection could be addressed with great economic efficiency.

The project in Kenya led to a number of unanticipated advances in "basic science." The high pollution concentrations observed in rural African homes—as much as 100 times higher than those observed in the urban areas of many industrialized nations—provided a laboratory for examining the epidemiology of exposure-response in a pollution regime that had not been studied before (Ezzati and Kammen, 2001). These studies have greatly extended the cutting-edge epidemiological work being done largely in developed nations (Rich et al., 2005).

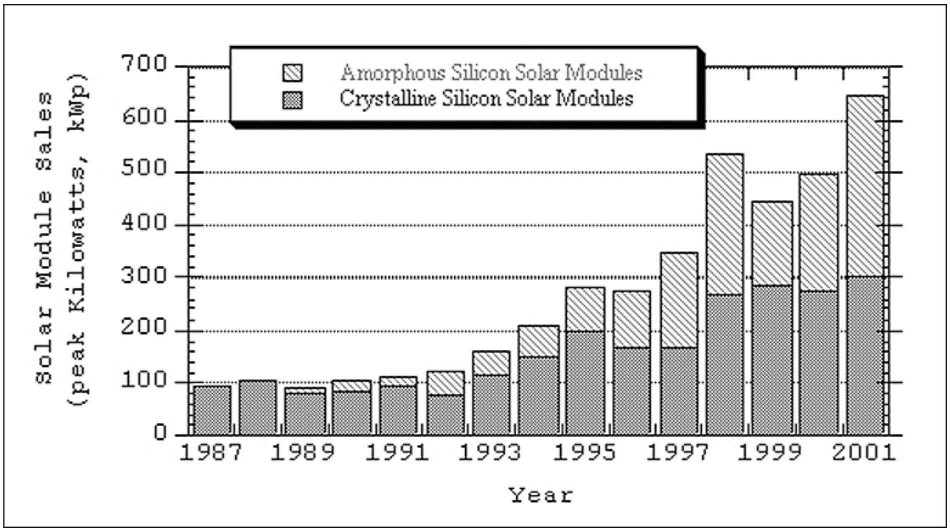

FIGURE 2 Sales of solar modules from 1987 to 2001 in Kenya showing the dramatic increase in sales of amorphous silicon (a-Si) solar cells. The average system size is less than 25 Wp, and current annual sales exceed 30,000 individual solar electric home systems. A substantial fraction of crystalline silicon (c-Si) module sales are for institutional systems that are funded primarily through donor aid programs. Sources: ESDA, 2003; Hankins, 2000; Hankins and Bess, 1994.

Solar Electricity Markets in Developing Nations

Household solar photovoltaics (PV) have emerged as the leading alternative to grid-based rural electrification in many developing countries. In Kenya, 30,000 PV systems are sold annually, making it a global leader, per capita, in sales of residential renewable energy systems (Figure 2). Advances in amorphous silicon (a-Si) PV technology, which led to the development of small, low-cost a-Si PV modules, played a critical role in the emergence and growth of the Kenyan solar market (Hankins, 2000; Jacobson, 2004).

A key aspect of these advances involved minimizing the initial light-induced Staebler-Wronski degradation of a-Si modules, a poorly understood materials issue with significant implications for low-cost solar cells. The power output of a-Si solar modules typically decreases by 15 to 40 percent during the first few months of exposure to solar radiation due to Staebler-Wronski degradation. Better quality brands have lower degradation levels (Staebler and Wronski, 1977; Su et al., 2002), and after the initial period of degradation, the power output stabilizes. Figure 3 shows degradation curves for two different brands of a-Si modules, showing that the initial power output of some brands drops significantly more than others. The rated power of most reputable brands of a-Si PV modules corresponds to the final, stabilized power output under standard test conditions of 1,000 W/m^2 and 25°C.

A second important design issue has been the development of cost-effective sealant materials and methods of preventing delamination. Water intrusion can lead to outright module failure, and the actual power output of modules with significant delamination is often reduced to less than 10 percent of the nameplate power rating. Figure 4 shows water-induced delamination in an a-Si module caused by low-quality seals. A number of a-Si manufacturers have developed highly effective sealing techniques, but a few brands continue to have water-intrusion problems.

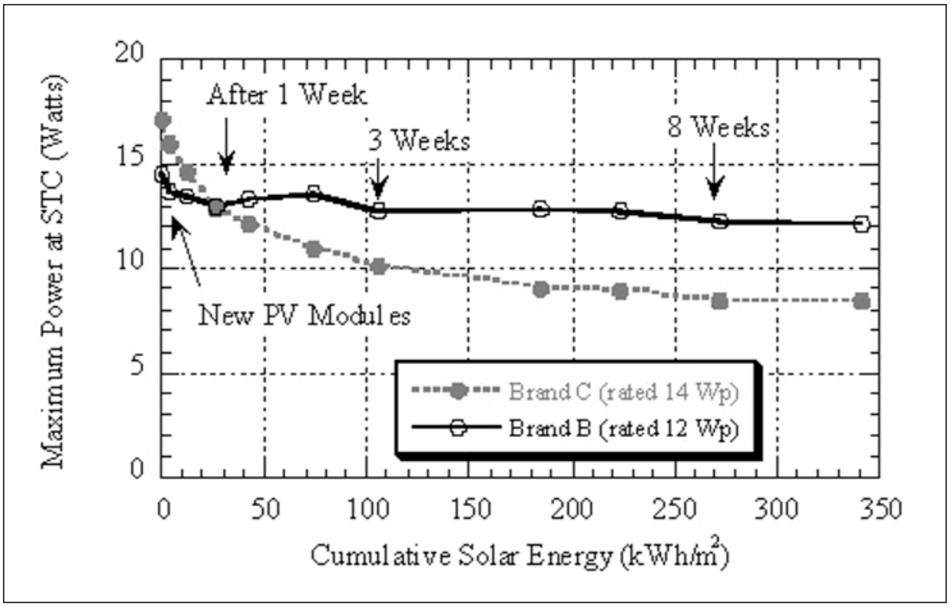

FIGURE 3 Performance of two brands of a-Si solar modules during the first few months of exposure to solar radiation showing substantial differences in light-induced Staebler-Wronski degradation for the two brands. The power output of the Brand C module, although initially higher than its 14W power rating, drops far below its nameplate rating after several months in service. By contrast, the performance of the Brand B module stabilizes near the 12W rating. Note that these results are from 2000 and do not reflect recent improvements for Brand C (shown in Figure 5). Source: Jacobson et al., 2000.

These advances have been important for the PV industry as a whole, but have been especially significant for rural electrification with solar energy in developing countries. In contrast to laboratory and commercial rivalries over which company produces the most thermodynamically efficient solar cells, the firms that manufacture a-Si PV modules for markets in developing countries have focused on lower efficiency but significantly less expensive products (Green et al., 2005). The resulting 12 to 20W a-Si PV modules now available in Kenya and elsewhere cost 50 percent less than comparable crystalline silicon (c-Si) PV modules, and are, by far, the best-selling solar products in the region.

The dissemination of a-Si PV technology in Kenya has not, however, been without complications. In an extensive market survey (Figure 5), we found that, although most manufacturers produce high-quality products, one prominent brand performed well below its advertised levels. A previous study in 1999 showed a similar pattern, although for a different brand. Thus, the successful deployment of new technology requires market institutions that ensure quality and protect the public interest. The combination of technical studies of solar equipment performance and analyses of Kenyan market development, socio-cultural dynamics, and regulatory policy has led to progress toward eliminating low-performing products from the market, as well as insights into institutional aspects of renewable energy market development (Acker and Kammen, 1996; Duke et al., 2002; Jacobson, 2004; Kammen, 1995).

Making Sustainable Science the Norm

The first step in making sustainable science the norm is to demonstrate that, once funding and a research/action team have been assembled, these projects are no more difficult than traditional research projects. To be effective, however, projects must be neither exclusively in the academic or laboratory setting, nor entirely in the sphere of nonprofit organizations or local governments. To take maximum advantage of both the emerging science and the implementation capacity for sustainability, we must demonstrate support in each of the disciplines involved, both through actions and funding priorities.

Second, we must make sustainability science a basic precept of teaching in secondary schools, colleges, and postgraduate studies. Pre-college students have already demonstrated a tremendous aptitude for working in interdisciplinary areas. We must nurture and reward

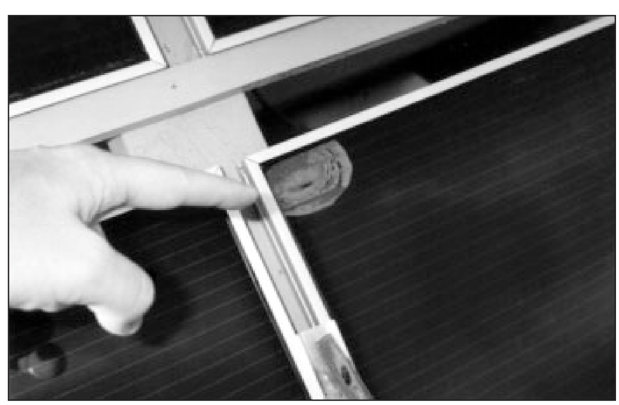

FIGURE 4 Water-intrusion-related delamination in a Brand D a-Si PV module. The actual power output of this 14W rated module was less than 1W.

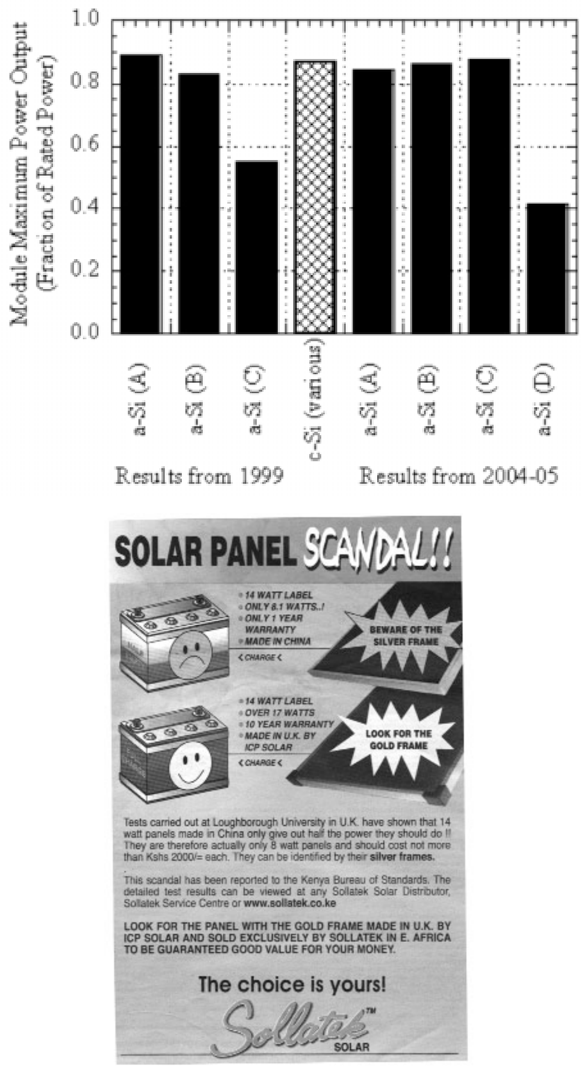

FIGURE 5 Average stabilized maximum power output results from 1999 and 2004–2005 for a-Si solar modules sold in Kenya. Aggregate test results for several brands of c-Si modules are included for comparison. Note that, although most a-Si brands have power output levels similar to the more expensive c-Si modules, some brands perform well below their advertised power ratings. The 1999 test results are based on field measurements of 130 a-Si modules and 17 c-Si modules. The 2004–2005 results involved 20 a-Si modules randomly selected from Kenyan retail shops. The presence of low-performing brands has led to considerable acrimony in the Kenyan solar industry, as indicated in the "Solar Scandal" advertisement from a local newspaper. Following the release in Kenya of the 2004–2005 results, the market presence of Brand D dropped. Source: Jacobson and Kammen, 2005.

this interest with courses in junior high schools, high schools, and colleges on energy, the environment, and the social drivers of resource degradation. In the United States, the Upward Bound Math-Science Program (DOEd, 2005) and Summer Science Program (2005) are models that could be adapted to the theme of sustainability science.

The launch of Sputnik in 1957 initiated an unprecedented mobilization of U.S. science and technology, a lesson in the power of a use-inspired drive to innovate. The Yale Environment Survey found overwhelming interest in energy and environmental sustainability (Yale University, 2005). Contrast that interest with the results of the 3rd International Mathematics and Science Study (TIMSS), in which American secondary school students ranked 19th out of 21 countries in both math and science (NRC, 1997). The TIMMS authors concluded that science and mathematics education in the United States lacked direction, vision, and motivation. Sustainability science could give science, mathematics, and engineering education renewed meaning and immediacy, with paradigm-changing possibilities in both developed and developing nations.

Third, we could establish sustainability awards—modeled after the Ashoka Innovators Awards (2005), the Ansari X Prize (X Prize Foundation, 2005) for the launch of a space vehicle, and the Ashden Awards (2005) for sustainable energy. These awards would bring together partners from developed and developing nations in academia, industry, civil society, and government and would encourage groups to take action on critical sustainability projects. Ideally, sustainability awards, jointly sponsored by private foundations and state or federal governments, would take advantage of the diversity of perspectives and skills that interdisciplinary, international teams would bring together.

Finally, we must address the principal weakness in the economies of many poor nations—a lack of capacity to compete in the global marketplace. Debt forgiveness for impoverished countries in Africa and elsewhere is laudable (Sachs, 2005), but it has already been criticized by African leaders who have noted that aid alone is not a panacea. Estimates of the percentage of overall economic growth from innovation in science and technology, virtually all in industrialized nations, are as high as 90 percent (Solow, 2000). Developing economies would be energized by dramatically increased investment in indigenous innovation. A natural way to do that would be to reward investments in science and technology capacity for sustainable development with additional debt relief or more favorable trade arrangements. This is a perfect time for the G8 to adopt this plan and assist all nations to invest in environmentally conscious innovation.

Acknowledgements

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