



Key role for nuclear energy in global biodiversity conservation

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Abstract: *Modern society uses massive amounts of energy. Usage rises as population and affluence increase, and energy production and use often have an impact on biodiversity or natural areas. To avoid a business-as-usual dependence on coal, oil, and gas over the coming decades, society must map out a future energy mix that incorporates alternative sources. This exercise can lead to radically different opinions on what a sustainable energy portfolio might entail, so an objective assessment of the relative costs and benefits of different energy sources is required. We evaluated the land use, emissions, climate, and cost implications of 3 published but divergent storylines for future energy production, none of which was optimal for all environmental and economic indicators. Using multicriteria decision-making analysis, we ranked 7 major electricity-generation sources (coal, gas, nuclear, biomass, hydro, wind, and solar) based on costs and benefits and tested the sensitivity of the rankings to biases stemming from contrasting philosophical ideals. Irrespective of weightings, nuclear and wind energy had the highest benefit-to-cost ratio. Although the environmental movement has historically rejected the nuclear energy option, new-generation reactor technologies that fully recycle waste and incorporate passive safety systems might resolve their concerns and ought to be more widely understood. Because there is no perfect energy source however, conservation professionals ultimately need to take an evidence-based approach to consider carefully the integrated effects of energy mixes on biodiversity conservation. Trade-offs and compromises are inevitable and require advocating energy mixes that minimize net environmental damage. Society cannot afford to risk wholesale failure to address energy-related biodiversity impacts because of preconceived notions and ideals.*

Keywords: climate change, fossil fuels, greenhouse gases, land use, pollution, sustainable energy

Un Papel Clave para la Energía Nuclear en la Conservación de la Biodiversidad Global

Resumen: *La sociedad moderna usa cantidades masivas de energía y el uso de éstas incrementa conforme la población y la riqueza aumentan. La producción de energías y su uso continuamente han tenido un impacto sobre la biodiversidad o las áreas naturales. Para evitar la normalidad con la que se depende del carbón, el petróleo y el gas en las próximas décadas, la sociedad debe encontrar una futura mezcla de energías que incorpore fuentes alternativas. Este ejercicio puede llevar a opiniones radicalmente diferentes sobre lo que un portafolio de energías sustentables puede implicar, así que se requiera de una evaluación objetiva de los costos y beneficios relativos de las diferentes fuentes de energía. Evaluamos el uso de suelo, emisiones, clima e implicaciones de costo de tres líneas argumentales publicadas pero divergentes sobre el futuro de la producción de energía, ninguna de las cuales fue óptima para todos los indicadores ambientales y económicos. Al usar un análisis de toma de decisiones con criterios múltiples, ordenamos a siete fuentes generadoras de electricidad (carbón, gas, nuclear, biomasa, hidrológica, eólica y solar) con base en costos y beneficios y evaluamos la sensibilidad de las clasificaciones a sesgos originados de ideales filosóficos contrastantes. Sin importar las ponderaciones, la energía nuclear y la eólica tuvieron la relación costo-beneficio más alta. Aunque el movimiento ambiental históricamente ha rechazado la opción de la energía nuclear, la tecnología de reactores de nueva generación que reciclan completamente los desechos e incorporan sistemas pasivos de*

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seguridad puede resolver las preocupaciones ambientalistas y debería ser entendido con mayor profundidad. Ya que no existen fuentes de energía perfectas, los profesionales de la conservación necesitan tener un enfoque basado en evidencias para considerar cuidadosamente los efectos integrados de la mezcla de energías sobre la conservación de la biodiversidad. Las compensaciones y los acuerdos mutuos son inevitables y requieren abogar por las mezclas de energía que minimicen el daño ambiental neto. La sociedad no puede permitirse el riesgo de un fracaso total en la señalización de impactos sobre la biodiversidad relacionados con la energía por causa de ideales y nociones preconcebidas.

Palabras Clave: cambio climático, combustibles fósiles, contaminación, energía sustentable, gases invernadero, uso de suelo

Introduction

Over the last few centuries, civilization has become a vast and ceaselessly expanding consumer of energy, delivered primarily by fossil fuels (>80%)—coal, oil, and natural gas. The latest compiled data from 2011 show that approximately 550 exajoules (1 EJ = 10^{18} J) of primary energy were consumed by the global economy in that year (IEA 2013). Yet given the mounting threat of greenhouse gas-induced climate change and the chronic health impacts and energy-security problems associated with a reliance on burning fossil fuels, it is imperative that we seek substitute forms of energy supply in coming decades (Kharecha & Hansen 2013). In 2011, for global electricity generation (80 EJ of final energy in 2011), hydroelectric dams supplied the largest nonfossil component (15.8%), followed by nuclear (11.7%), wind (2.0%), biomass (1.9%), and solar power (0.3%) (IEA 2013). The transportation, mechanized agricultural, and industrial sector demands remain, for now, almost completely satisfied by fossil fuels.

Forecasts point to a difficult transition (IPCC 2011). Energy use is set to continue to rise, driven largely by burgeoning demand for low-cost electricity in the developing world (Clarke et al. 2007). Moreover, extraction of a vast resource of environmentally damaging unconventional fossil fuels has begun (e.g., shale gas, tar sands, coal-seam gas) (Wigley 2011). Socioeconomic and technical momentum will make this trend toward cheap and readily available new fossil energy difficult to discourage and will require articulation of a well-planned, cost-competitive, and evidence-based alternative strategy (Mackay 2008; Nicholson 2012). If this energy future is to be relatively benign to nature, the costs and benefits of all competing energy forms will need to be carefully traded-off (Blees 2008). We argue that conservation professionals have a key role to play in this policy arena.

For the least direct harm to biodiversity, the best energy options are those that use the least amount of land and fresh water (in production or mining), minimize pollution (e.g., carbon dioxide, aerosols, heavy metals, and toxic chemicals), restrict habitat fragmentation, and have a low risk of accidents that have large and lasting regional impacts on natural areas (e.g., oil spills, dam-burst floods, radioactive fallout). Yet the indirect effects

of energy production are also critical. Conservation-friendly energy sources must also be cost-effective, reliable, and accessible relative to more environmentally damaging methods if they are to displace them.

We reviewed the links between energy supply and biodiversity conservation, considered the potential and problems of some of the most widely touted nonfossil-fuel alternatives (renewable and nuclear), and devised a basic framework that can be used to rank and balance energy options objectively. Our goal was not to be overly prescriptive; rather, we sought to show why and how conservation scientists could engage most effectively in the energy-policy debate and so yield the best outcomes for global biodiversity.

Intertwining of Biodiversity and Industrial Energy

Conservation biologists readily acknowledge that 2 of the principal drivers of terrestrial biodiversity extinctions are habitat degradation and loss—mainly via agricultural expansion, logging, urbanization, and pollution (Brook et al. 2008). Climate disruption, and its synergies with other extinction drivers, will also continue to worsen over centuries and so strongly influence future species distributions (Bellard et al. 2012). Thus, it follows that anything humanity can do to mitigate climate warming, energy-related pollution, and land-use changes that negatively affect species will ultimately benefit biodiversity. Given that energy production from fossil fuels—for electricity, transportation, and industrial processes—is the principal source of anthropogenic greenhouse-gas emissions, biodiversity conservation is intrinsically intertwined with how we source our energy (Wiens et al. 2011).

Cutting emissions is, however, only one aspect of the complex relationship between energy and biodiversity. For example, hydroelectricity dams are largely emissions-free after construction, but they can wreak havoc on local biodiversity through flooding and by obstructing migration (Dudgeon 2006). Globally, around 60% of the world's rivers were considered regulated in 2001; over 40,000 large dams (>100 have walls higher than 150 m) and their resulting reservoirs cover 500,000 km² (McAllister et al. 2001). Other renewable energy sources are also land hungry (Wiens et al. 2011). Biofuels and wind energy in particular require land area per unit energy

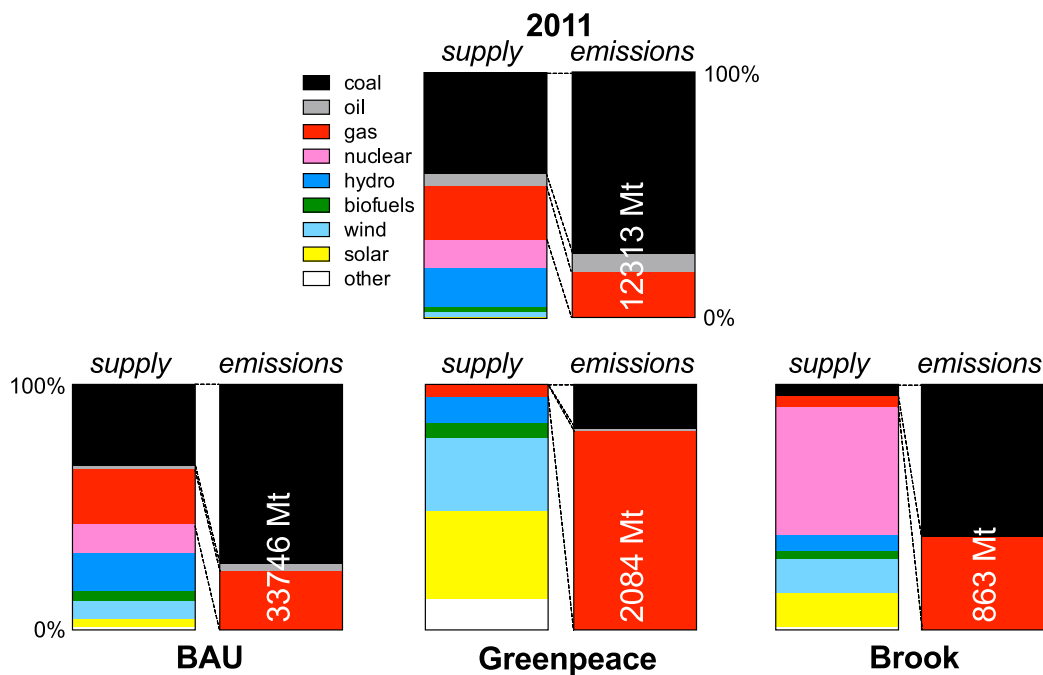


Figure 1. Comparison of energy-mix scenarios. (a) Global electricity production by source (expressed as proportions that sum to 1) and greenhouse-gas emissions by source in 2011 and (b–d) electricity use and greenhouse-gas emissions by source for 3 future scenarios: (b) a business-as-usual (BAU) scenario for the year 2035 from World Energy Outlook (2013), (c) the renewables-focused Energy [R]evolution scenario from Greenpeace (for 2050), and (d) the near-total decarbonization scenario (for 2060) from Brook (2012). In (a) total primary energy is 547 EJ (exajoules) and the electricity component of total primary energy is 22113 TWh (terawatt hours). This is forecast to rise to 77,000 TWh of electricity in 2060 in (c), so scenarios (a) and (b) were rescaled proportionally to meet this generation target. Emissions are expressed in megatonnes carbon-dioxide equivalents (Mt) and as a proportion of each type of fossil-fuel contribution; absolute emissions are in Fig. 2. ‘Other’ is geothermal, wave, and tidal energy production.

produced similar to hydroelectric dams (photovoltaic solar requires about 9 times less area per unit energy) (Supporting Information) (Pimentel & Pimentel 2007). Given that protected areas alone will be insufficient to safeguard biodiversity (Laurance et al. 2012), the conflict for space between energy production and habitat will remain one of the key future conservation issues to resolve.

The demand for cropland production has been increasing by around 3.4 million ha/year, partly to keep pace with world’s growing human population and consumption patterns (FAOSTAT 2009), which means that the additional burden of biofuel production could see increasingly larger areas commandeered for agriculture. For example, Stickler et al. (2007) estimate that 746 million ha of tropical forest are suitable for biofuel production (palm, soy, sugarcane) and if converted could provide 63% of global transportation fuel demand by 2030, releasing 443 Pg (1 Pg = 10^{15} g) of CO_2 (Wiens et al. 2011). Land clearing for biofuel production also increases emissions from forest clearance (Mason Earles et al. 2012), removing the sequestration services of high-carbon-density forests and soils and increasing opportunity costs for conservation by raising land prices (Luyssaert et al. 2008). Indeed, the conversion of forests

and peatlands to agriculture is responsible for about 15% of total human carbon emissions (Wiens et al. 2011).

Slowing the conversion and fragmentation of primary forests and other relatively unscathed natural areas for energy production, while minimizing greenhouse gas emissions, is therefore a primary target for conservation science. It follows that land-use intensification for food (and possibly biofuel) production could minimize conflicts between human needs and biodiversity conservation if one or more cheap, abundant, and low-emissions energy sources were available to replace fossil fuels and so provide the majority of human needs. Highly intensified (and thus land-sparing) forms of agriculture, such as greenhouses, vertical farms, and hydroponic facilities, require substantial inputs of artificial energy, synthesized nutrients, and desalinated water, which must be supplied by clean-energy sources to be considered sustainable and low impact.

Business as Usual and Alternative Energy Futures

The forecasting reported in the IEA (2013) *World Energy Outlook* projects an ongoing dominance of coal, oil, and gas for at least the next 5 decades, and only minor

mitigation policies have been implemented to date. This business-as-usual (BAU) with new-policies scenario (implementing already announced national energy plans) described by the International Energy Agency assumes ongoing energy-demand growth, due to increasing human population and affluence (Bradshaw & Brook 2014), with the greatest expansion coming from Asia and developing nations. Concomitant with this scenario is an enormous rise in greenhouse-gas emissions. The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2013) predicts global warming of 2.6–4.8 °C by 2081–2100 under the most emissions-intensive energy scenario (RCP8.5).

What might an alternative and more biodiversity-friendly future scenario look like? Although an almost infinite variety of future energy mixes is possible, most are implausible on the grounds of cost, technological maturity, capacity to operate at large scales, reliability, social acceptance, and the pragmatic need to manage infrastructure transitions incrementally (Smil 2010). For illustrative purposes, we refer to 2 alternative energy production scenarios that differ substantially from the BAU scenario but nevertheless have credibility (i.e., deemed plausible in the peer-reviewed literature): a high renewable-energy mix that excludes nuclear power and assumes massive gains in energy efficiency that leads to a lower overall demand (Greenpeace 2012) and an energy mix with a large nuclear-energy contribution, smaller contributions from a mix of renewables and fossil fuels, and carbon capture and storage (Brook 2012). The proportional energy breakdowns (in terms of electricity generation) and resulting greenhouse-gas emissions for these 3 scenarios are shown in Fig. 1. All 3 scenarios assume ongoing and substantial improvements in end-use efficiency.

We standardized the most biodiversity-relevant impacts of these scenarios to the same total global electricity demand for valid cross-scenario comparison (Fig. 2) and plotted land area occupied by production infrastructure (power plants, wind and solar farms, hydroelectric dams, etc.) and mining for fuel (but not for construction materials); resultant greenhouse-gas emissions generated from energy production only; estimates of the amount of climate warming by mid-century (IPCC 2013) based on the midpoint forecast of the closest-matching representative concentration pathways (RCP8.5 for the BAU scenario and RCP2.6 for the 2 alternatives); and the annualized system cost of the 3 scenarios. Given the impossibility of integrating all potential effects of energy production on biodiversity, we used land displacement as a surrogate of broad-scale impacts on habitat. We ignored the difficult-to-quantify embodied greenhouse-gas emissions from the full life cycle of an energy-production facility. We used estimates by the U.S. Energy Information Administration of the 2018 levelized cost of electricity of different sources (price per unit of electricity delivered integrated over the

whole life cycle of the production plant). The levelized cost includes capital, fuel, operations and maintenance, grid management, and waste disposal and management.

Depending on the preference given to the various criteria in Fig. 2, any of the 3 scenarios might be considered the best, although a scenario with low land use and carbon footprint that is also economically competitive arguably achieves the most balanced and realistic outcome for biodiversity conservation. To understand these trade-offs, it is necessary to focus on the individual components of these energy mixes.

Energy-Source Compromises

Given that there is currently no ideal commercialized energy source—one that is simultaneously low-cost, low-impact, zero-carbon emissions, nonpolluting, completely safe, found everywhere, and always available on demand—we are left to weigh various environmental and socioeconomic compromises. In the energy-analysis literature, this is formally done using a multicriteria decision-making analysis (MCDMA) framework, as described in Hong et al. (2013b). This method can be used for comparative integrated assessments across a range of quantitative and qualitative metrics with varying units or scales. It can also incorporate preferences by assigning different a priori weightings to indicator criteria.

In the MCDMA, we assigned ranks across alternative energy sources to various sustainability indicators (e.g., volume of greenhouse gases emitted, expense, land use) and summed across all indicators. Weightings were then used to bias the results of the rankings objectively in favor of different a priori positions (e.g., a focus on economic competitiveness or an emphasis on biodiversity benefits such as small land and carbon footprints). The integrated result was strongest for nuclear energy, with wind also competing well, whereas traditional combustion sources of energy such as biomass and coal were ranked as least sustainable (Table 1). The sustainability indicators we used in this illustrative MCDMA are only a subset of all possible factors (which might also include direct impacts on wildlife, freshwater consumption, use of rare embodied materials, specific chemical or aerosol outputs), but these are sufficient to show the trade-offs inherent in energy options and do not lead to a single, obviously best choice.

Nuclear Energy in Focus

An outcome of the MCDMA that might surprise many is how well nuclear energy emerged from these overall ranked-and-weighted comparisons. Given the hostility toward nuclear fission by most environmental NGOs (e.g., Greenpeace's energy plan described in the previous section rejects outright any use of nuclear), we decided to focus more deeply here on the pros and cons of this

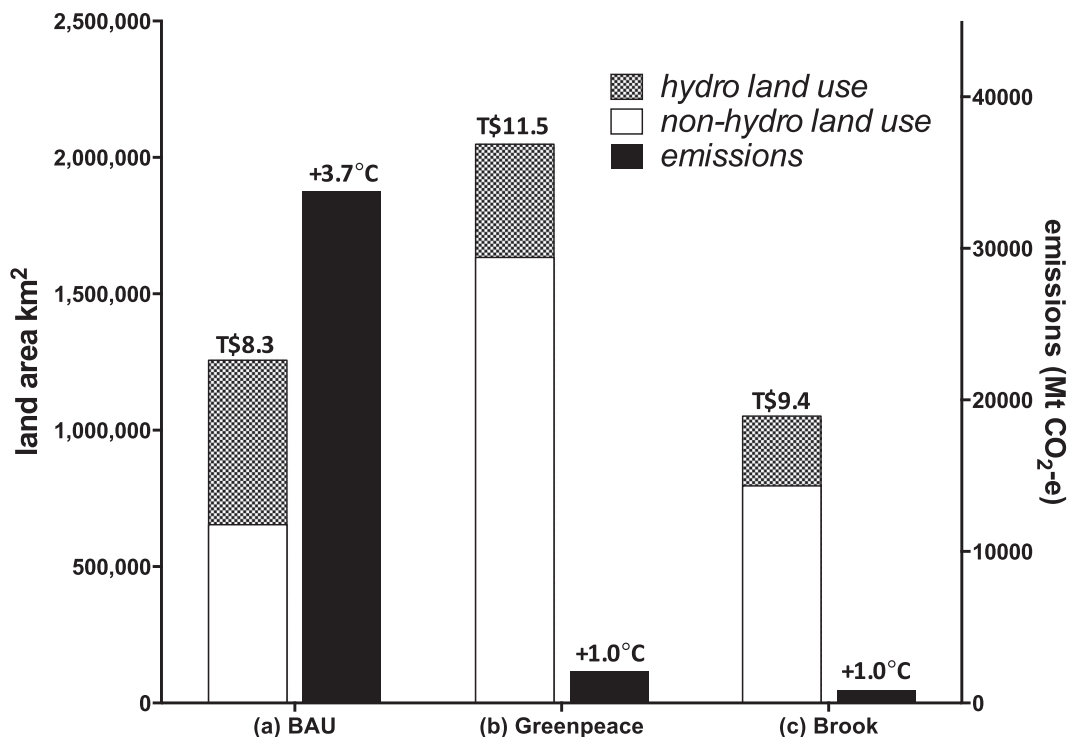


Figure 2. Land area converted for energy production (hatched and white bars), annualized cost of total electricity generation (above bars, US\$ trillions, T\$), greenhouse-gas emissions (black bars), and forecast increase in late 21st century global temperature (above bars) associated with 3 future energy-mix scenarios, standardized for comparison to meet the same total energy demand of 77,000 terawatt hours (based on large-scale electrification to cover stationary electricity, transportation, industrial and agricultural energy sectors): (a) business-as-usual (BAU), high fossil-fuel dependence (based on the World Energy Outlook [IEA 2013]); (b) high renewables, excluding nuclear (Greenpeace 2012); and (c) high nuclear, medium renewables (Brook 2012). See Fig. 1 for energy mixes. Scenarios and details of input values and underpinning calculations are in Supporting Information.

particularly contentious energy option. For completeness, in the Supporting Information we also provide a more detailed contrast among other best performers arising from the MCDMA—natural gas, wind, and solar.

Nuclear-power advocates have fought an enduring battle to present this energy source as clean, safe, and sustainable. Today, a mix of lingering myths and half-truths continue to influence people's thinking on nuclear power (Blees 2008), whereas proponents of other low-carbon energy-production types typically do not admit to the difficulties of large-scale use of these technologies (Trainer 2012). Common qualms about nuclear energy are that uranium supplies will soon run out, long-lived radioactive waste needs isolation for 100,000 years, large amounts of greenhouse gases are produced over the full nuclear cycle, development is too slow and costly, and large-scale deployment increases the risk of nuclear war. Crises such as the one at the Fukushima Daiichi nuclear plant (a 1960s vintage reactor) in Japan in 2011, triggered by a massive earthquake and tsunami, amplified people's concerns (Hong et al. 2013b). Yet, given the urgency of the global environmental challenges we must deal with

in the coming decades, closing off our option on nuclear energy may be dangerously shortsighted.

In 2010, nuclear energy was used to generate commercial electricity in 31 countries, provided 74% of total supply in France, and contributed 2,628 terawatt hours (TWh; IEA 2013). Based on life-cycle emissions intensities for nuclear (20 t CO₂-e TWh⁻¹) and coal (>1,000 t CO₂-e TWh⁻¹) power, this is an effective saving of at least 2.4 billion tons of carbon dioxide annually, as well as avoidance of a toxic brew of heavy metals, black carbon, sulfates, and numerous other aerosols (Kharecha & Hansen 2013). Foregoing nuclear power therefore means overlooking an already large global contributor to low-carbon electricity, especially given its use as a direct substitute for coal. Currently, only hydroelectricity displaces more fossil-fuel energy than nuclear power (3,490 TWh), but it is geographically dependent on the distribution of waterways.

Nuclear power is deployed commercially in countries whose joint energy intensity is such that they collectively constitute 80% of global greenhouse-gas emissions. If one adds to this tally those nations that are actively planning

Table 1. Per terawatt hour (TWh) data for key sustainability and economic–environmental impact indicators associated with 7 electricity generation options and relative ranks^a of the energy source.

Indicator (per TWh)	Coal		Natural gas		Nuclear		Biomass		Hydro		Wind (onsbore)		Solar (PV)	
	value	rank	value	rank	value	rank	value	rank	value	rank	value	rank	value	rank
GHG emissions (t CO ₂) ^b	1,001,000	7	469,000	6	16,000	3	18,000	4	4,000	1	12,000	2	46,000	5
Electricity cost (\$US) ^c	100.1	4	65.6	1	108.4	5	111	6	90.3	3	86.6	2	144.3	7
Dispatchability ^d	A	1	A	1	A	1	B	4	B	4	C	6	C	6
Land use (km ²) ^e	2.1	3	1.1	2	0.1	1	95	7	50	6	46	5	5.7	4
Safety (fatalities) ^f	161	7	4	5	0.04	1	12	6	1.4	4	0.15	2	0.44	3
Solid waste (t)	58,600	7	NA	1	NA	1	9,170	6	NA	1	NA	1	NA	1
Radiotoxic waste ^g	mid	6	low	3	high	7	low	3	trace	1	trace	1	trace	1
Weighted Rank ^h		6.0		2.0		1.3		6.7		3.3		2.3		5.3

^aEnergy source with the lowest environmental or economic impact for a given indicator (e.g., greenhouse-gas emissions, cost of electricity, etc.) is assigned a rank of 1, whereas the worst performing of the 7 energy sources is assigned a rank of 7. Ties are given the same rank. All calculations and supporting data behind this table are detailed in the Supporting Information.

^bIncludes production-related and life-cycle-embodied emissions.

^cLevelized cost of electricity, includes cost amortization for long-term waste management and plant decommissioning for nuclear energy.

^dCategorical rating of capacity and availability to deliver electricity on demand.

^eFor fuel mining and generating footprint.

^fDeaths from accidents, excluding chronic health problems.

^gCategorical classification of the volume of the radiotoxic waste stream.

^hAverage of 3 multicriteria decision-making analysis scenarios with multiplicative weightings applied to the indicator ranks: (1) no weighting = 1 × multiplier for all ranks; (2) economic

rationalist = 1 × land use, solid waste, and radioactive waste, 2 × cost and dispatchability, and 0.5 × greenhouse gas emissions and safety; and (3) environmentalist = 1 × safety, solid

waste and radioactive waste, 2 × greenhouse gas emissions and land use, and 0.5 × cost and dispatchability. Weightings are arbitrary but illustrative of typical viewpoints.

nuclear deployment or already have scientific or medical research reactors, this figure rises to over 90% (Brook & Lowe 2010). As a consequence, displacement of fossil fuels by an expanding nuclear-energy sector would not lead to a large increase in the number of countries with access to nuclear resources and expertise. Nuclear weapons proliferation is a complex political issue, with or without commercial nuclear power plants, and is under strong international oversight (Blees 2008).

Today, over 70 so-called generation III reactors are under construction, including 29 in energy-hungry China (www.world-nuclear.org/info/Current-and-Future-Generation/Nuclear-Power-in-the-World-Today), attesting to its price competitiveness with other energy sources in the appropriate economic and regulatory environments (Nicholson et al. 2011). In terms of future costs and build times, the standardized, compact, passive-safety blueprints of next-generation nuclear power plants (generation IV small modular reactors)—designed to be built in assembly-line factories and shipped as complete units to a site—have the potential to be transformative in an industry that has, in the past, been plagued by regulatory ratcheting and legal challenges against one-off designs (Cohen 1990). France, which built 59 large reactors in 22 years (1978 to 1999) to alleviate its oil dependence, using generation II standardized designs, is a real-world illustration of what can be achieved quickly with nuclear deployment under favorable sociopolitical circumstances (Mackay 2008). To date, there have been no accidents or deaths at any of the French plants, despite nuclear power providing >75% of the nation's electricity supply for decades.

In terms of accidents and hazardous waste, to demand zero incidents and no waste is to ask the impossible of any energy technology, given the possibility of beyond-design-basis events, and this position ignores the trade-off involved in fixing other major environmental problems with extremely high probabilities attached (see next section). Further, based on a hard-nosed assessment of fatalities per unit of energy generated, nuclear power has historically ranked relatively well (Table 1). Yet, there are technological solutions for improved nuclear safety and waste management that hold great promise. For instance, although government reports and the media hardly ever mention so-called fast reactors, these have the potential to provide vast amounts of clean, reliable electricity, as well as heat for industrial processes and desalination. A technology developed between 1964 and 1994 at the U.S. Government's Argonne and Idaho National Laboratories, the integral fast reactor (IFR), uses over 99% of the nuclear fuel, leaves only a small amount of waste that decays to below background levels of radiation within 300 years (see Fig. 3 fuel-cycle diagram), shuts itself down automatically, and cools itself indefinitely if the control systems fail or the operators abandon the facility (Hannum 1997). The IFR technology in particular also

counters one of the principal concerns regarding nuclear expansion—the proliferation of nuclear weapons—because its electrorefining-based fuel-recycling system cannot separate weapons-grade fissile material (Till & Chang 2011). The production of such material requires either specialist uranium-enrichment facilities or dedicated short-cycle reactors associated with large (highly visible) aqueous chemical processing infrastructure—neither of which are required for the IFR's pyroprocessing-based, closed-fuel cycle (Blees 2008) (Fig. 3). As an added benefit, the large-scale deployment of fast reactor technology would result in all of the nuclear-waste and depleted-uranium stockpiles generated over the last 50 years being consumed as fuel (Fig. 3).

The IFR, and other generation IV designs that use thorium (Hargraves 2012), offer a realistic future for nuclear power as a major source of sustainable, carbon-free energy for global civilization; there are sufficient fuel resources to last for millions of years (Lightfoot et al. 2006). At present, uranium remains cheap and policies for treating actinide wastes (e.g., direct geological disposal vs. recycling) are in limbo in most countries. However, if nuclear power were to be deployed on a large scale, such recycling would become essential.

For many countries—including most high energy-consuming nations in East Asia and Western Europe with little spare land and already high population densities—the options for massive expansion of renewable energy alternatives are heavily constrained (Trainer 2010; Hong et al. 2013a). But making a case for a major role for nuclear fission in a future sustainable energy mix does not mean arguing against energy efficiency and renewable options. Under the right circumstances, these alternatives might also make important contributions (Mackay 2008; Nicholson 2012). Ideally, all low-carbon energy options should be free to compete on a fair and level playing field against a range of sustainability criteria, as exemplified in Table 1, so as to maximize displacement of fossil fuels (one of the key goals for effective biodiversity conservation). Ultimately, as the urgency of climate-change mitigation and land sparing mounts and requirements for sustainable growth in developing economies and replacement of ageing infrastructure in the developed world come to the fore, pragmatic decisions on the viability of all types of nonfossil-fuel energy technologies will have to be made on a nonprejudicial basis.

Energy Trade-Offs and the Big Conservation Picture

The alternative energy futures we contrasted—namely those rejecting or embracing nuclear power to replace the bulk of today's reliance on fossil fuels—are only 2 possible pathways among many different plausible permutations. Our goal was not to promulgate any particular energy mix; rather, we used concrete examples to

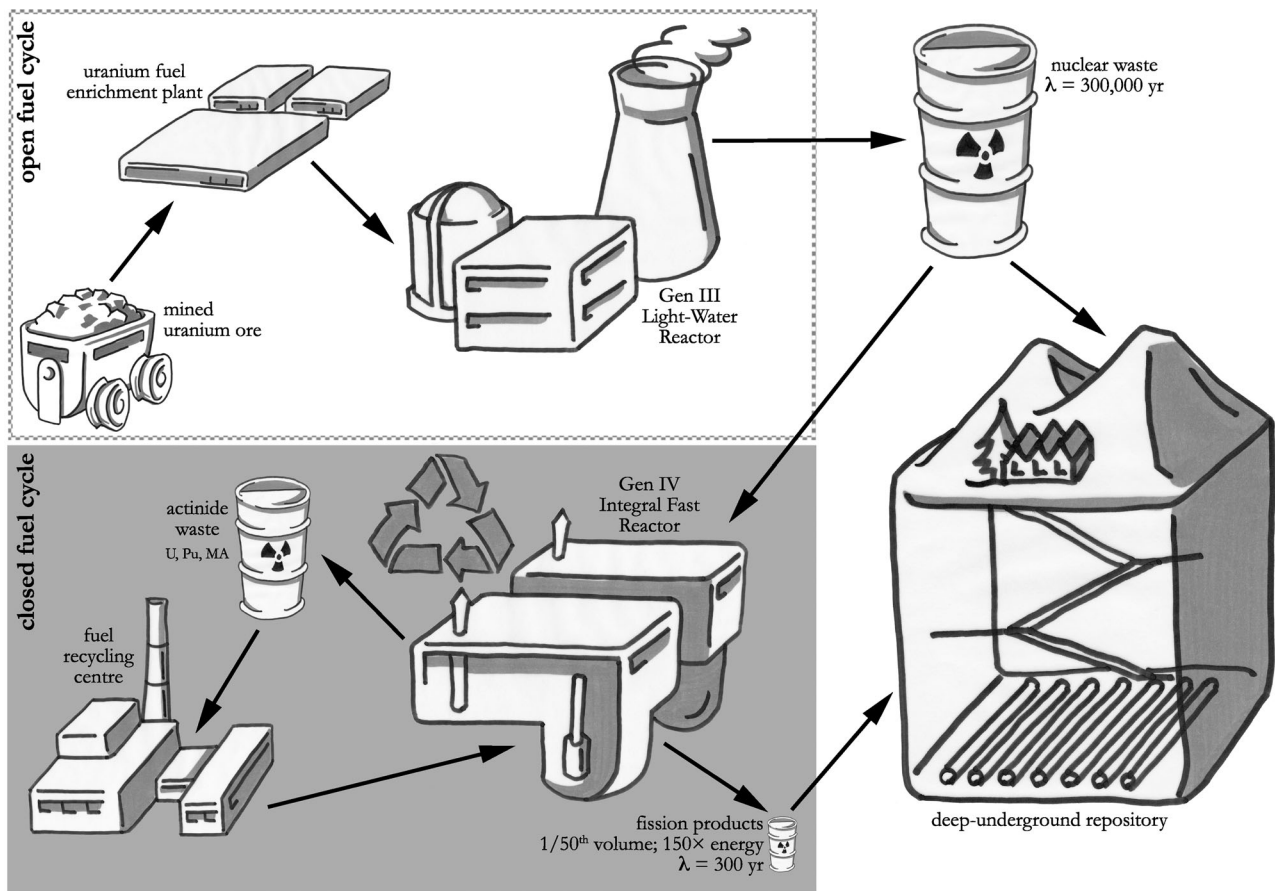


Figure 3. Open and closed nuclear fuel cycles. Today's typical open fuel cycle (top) follows these steps: yellowcake ore is mined; uranium is extracted, enriched, and fabricated into oxide fuel rods; fuel rods are run through a water-cooled-and-moderated generation III thermal nuclear reactor to generate electricity for approximately 18 months; and used fuel (with radioactive actinides and fission products) is cooled, stored, and eventually disposed of in a deep, long-term underground geological repository. A closed fuel cycle (bottom) greatly improves sustainability and lessens environmental impacts of nuclear fission by converting the used thermal-reactor fuel (and depleted uranium left over from enrichment) into metal fuel and then recycling this repeatedly through a liquid-metal-cooled fast neutron reactor. Over many cycles, this allows extraction of about 150 times more energy from the uranium and results in a far more compact waste stream with a radiotoxic lifespan of a few centuries, instead of hundreds of millennia (abbreviations: U, uranium; Pu, plutonium; MA, minor actinides; λ , radiotoxic half-life).

demonstrate that conservation biologists should apply similar, objective approaches to rank all the relevant criteria before supporting or rejecting a particular technology. Least faith triumph over evidence, rejecting any given energy source requires finding an alternative and considering the full spectrum of its environmental and societal implications.

From a biodiversity-centric standpoint, conservation professionals also need to consider carefully the energy sources they will support in terms of how many species they are willing to lose. In other words, conservation professionals should be asking themselves what minimum criteria should be met for the choice of global energy supply in terms of biodiversity persistence (e.g.,

considering just how bad climate disruption will get and how much more land area will be cleared) and what is their maximum tolerance for failure to achieve those goals (Brook & Bradshaw 2012). Can we afford to play Russian roulette with biodiversity because of preconceived notions and ideals?

Idealized notions of a preferred energy supply without a sound assessment of risk (i.e., a probabilistic analysis of how likely we are to avoid a BAU scenario and its ensuing problems) are exactly the sorts of obstacles we encounter daily when attempting to convince society why it should value and protect biodiversity. Just as our discipline has matured from measuring how human endeavor harms biodiversity to one attempting to answer questions

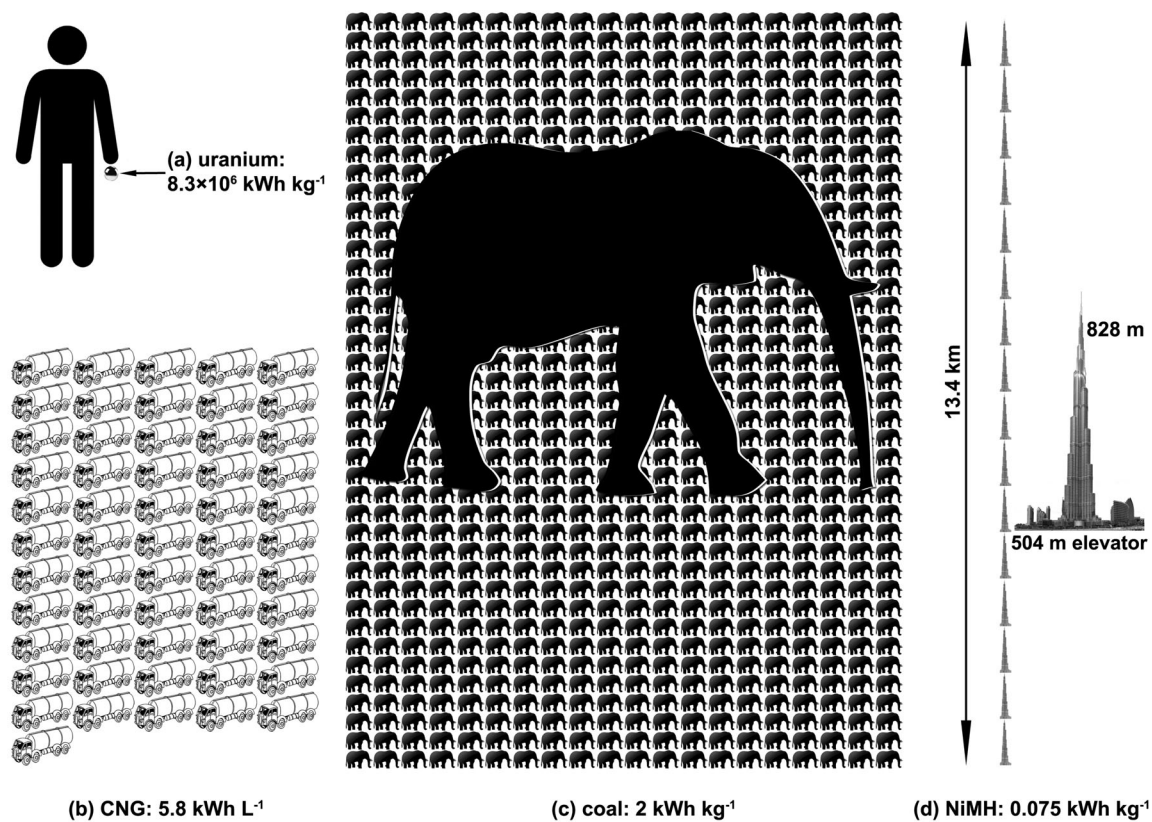


Figure 4. Comparative energy density of fuels: (a) uranium, (b) compressed natural gas (CNG), (c) coal, and (d) nickel-metal-hydride (NiMH) chemical batteries (standard type used in electric vehicles) required to supply or store approximately 220 kWh of electricity equivalent per day for 80 years (enough to service all lifetime needs for lighting, heat, transport, food production, manufacturing, etc. of a developed-world citizen). Total electrical energy embodied is calculated as 6.4 million kWh. Mass-to-volume relationship is uranium = 780 g or 40.7 cm^3 (golf-ball sized); compressed natural gas = $56 \times 20,000\text{-L}$ tanker trucks; coal = 3,200 t or $4,000 \text{ m}^3$ (approximately 800 elephant equivalents); NiMH battery = 86,000 t (elevator-sized battery as tall as the service shaft for 16 Burj Khalifa sized super skyscrapers). Supporting data and underpinning calculations are in the Supporting Information.

pertaining more to the implications of its loss and what we can do to restrict it, so too must we develop our scientific appraisal of world energy production.

A pertinent piece of information (Fig. 4) suffices to illustrate the relative impacts of 4 types of energy supply and dispatchable storage (as distinguished from instantaneous power generation): the average developed-nation human will use about 6.4 million kWh of energy (not just electricity) over his or her lifetime. This is equivalent to the energy stored in a 780 g (40.7 cm^3) golf-ball-sized lump of uranium; 56 20,000-L tanker trucks of compressed natural gas; about 3,200 t ($4,000 \text{ m}^3$, or about 800 elephant equivalents) of coal; or, if the storage capacity required for electricity generated from renewables is considered, a 86,000 t elevator-shaft-dimensioned battery over 13 km high (Fig. 4). The size of the battery is equivalent to 16 of the elevator shafts built to service the world's tallest building (the Burj Khalifa super skyscraper in Dubai) stacked on top of one another. These

energy-density comparisons for storage are telling and increase in importance when considering the additional components of emissions (e.g., burning 800 elephants worth of coal would release approximately 12,000 t of carbon dioxide into the atmosphere) and land use (e.g., mining required for materials to construct the massive NiMH battery required to store intermittent wind or solar energy).

Future of Energy Production

Fossil fuels have supplied most of society's energy demand since the Industrial Revolution. Yet with the mounting problems of climate change, pollution, security, and dwindling supplies, we now face the need for a near-total transformation of the world's energy systems. We have provided a short critical overview of the challenges and trade-offs in—and potential solutions for—completely decarbonizing our energy supplies

while meeting the growing need for increased prosperity in the developing world. Of the limited options available, next-generation nuclear power and related technologies, based on modular systems with full fuel recycling and inherent safety, hold substantial yet largely unrecognized prospects for being a principal cure for our fossil-fuel addiction, yet nuclear power still has an undeservedly poor reputation in the environmental community. Solving the energy problem has broader implications: it will not only help mitigate climate change, it will also avoid destructive use of natural and agricultural landscapes for biofuels and diffuse energy generation and thus allow societies to reduce their environmental footprint by sparing land and resources for biodiversity conservation.

Based on an objective and transparent analysis of our sustainable energy choices, we have come to the evidence-based conclusion that nuclear energy is a good option for biodiversity conservation (and society in general) and that other alternatives to fossil fuels should be subjected to the same cost-benefit analyses (in terms of biodiversity and climate outcomes, as well as sociopolitical imperatives) before accepting or dismissing them. We conclude that large-scale nuclear power—as a route to an electrified, oil-, gas- and coal-free economy—offers a positive way forward because it provides a low-risk pathway to eliminating the fossil-fuel dependencies, global energy poverty, and wealth imbalances that rank among the major forces driving today's biodiversity crisis. At the very least, nuclear power needs to be considered seriously, alongside renewable sources of energy such as wind and solar power, in any robust sustainable energy mix for the future.

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Supporting Information

An explanation of how to compare alternative energy sources on an equal basis, definitions of *power* and *energy*, and a detailed description of the methods behind the figures and tables (Appendix S1), a summary of cost and land use of fossil fuel, nuclear, and renewable-energy systems (Appendix S2), supporting calculations for Table 1 (Appendix S3), data and modeling for Fig. 1 (Appendix S4), details on the land use and cost calculations for Fig. 2 (Appendix S5), and supporting data and calculations underpinning Fig. 4 (Appendix S6) are available online. The authors are solely responsible for

the content and functionality of these materials. Queries, other than the absence of material) should be directed to the corresponding author.

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