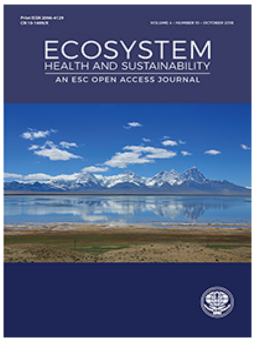

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Priority areas at the frontiers of ecology and energy

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ABSTRACT
The complexity of economic development and humanitarian crises means that energy science and technology should be involved in actions that address almost every major challenges of ecosystem health and sustainability. Energy is the engine of the world economy and the key to ecosystems' functioning, which also has a great impact on global warming. The energy crisis, environmental pollution, overuse of natural resources, water supply shortages, global climate disruption, and deteriorating ecosystems are major challenges to address in order to achieve the United Nations Sustainable Development Goals (SDGs). In light of the frontiers in energy sciences and disruptive innovation in eco-tech, we recognize the need to review and establish working mechanisms that identify and examine issues that are critical to future sustainable development, to offer advice to decision-makers in different social sectors (public and private), to secure a shared future for mankind, and to achieve shared prosperity and common interests through international communications and collaborations.

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Humanity's influence on the earth system is now so significant that a new geological epoch, the Anthropocene, has begun. We now live in a "full world." Human impacts, such as that of economic development on ecological life support systems, are increasingly complex and far-reaching. At the same time, the improvement of living standards places increasing demands on the planet's life support functions. In this "full" world, research, education, and policy need to shift their emphasis from isolated problems to the study of whole, complex, interconnected systems and the dynamic interactions between the parts, such as ecosystems and energy systems.

The complexity of economic development and humanitarian crises means that energy science and technology should be involved in actions that address almost every major challenge. These include fighting against poverty and hunger, providing renewable and sustainable energy, protecting the global environment and natural resources, accessing clean water and fertile land, and sustaining and sharing economic development and prosperity. In light of the frontiers in energy sciences and disruptive innovation in eco-tech, we recognize the need to review and establish working mechanisms that identify and examine issues that are critical to future sustainable development, to offer advice to decision-makers in different social sectors (public and private), to secure a shared future for mankind, and to achieve shared prosperity and common interests through international communications and collaborations. Thus, we were invited by the China Association for Science and Technology (CAST) to organize the CAST Frontier Forum on Ecology & Energy: Challenges and Opportunities (12–13 June 2018, Beijing, China).

The goals of this forum were to: (1) communicate advanced knowledge, in the fields of ecological science and energy technology, to policy makers for a more desirable, sustainable, and prosperous future for our planet; (2) provide strategic insights and solutions to the challenges and opportunities we are facing in ecology and energy via interdisciplinary, multidisciplinary, and trans-disciplinary approaches by leading scientists and engineers; (3) recognize the fundamental challenges and scientific issues that will impact human welfare and provide predictions for the scientific communities, industries, and societies; and (4) share ideas, development trends, risks, crises,

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All authors are listed in alphabetic order of their family names opportunities, and challenges in the field of ecology and energy in the interest of serving the scientific communities, governments, industries, and general public. Even though discussions at the CAST Frontier Forum on Ecology & Energy were mostly focused on the development of China as world's largest emerging economy, the identified trends and requirements have a more general character and address issues relevant both for other emerging economies and for fully developed, industrialized economies as well.

The energy crisis, environmental pollution, overuse of natural resources, water supply shortages, global climate disruption, and deteriorating ecosystems are major challenges to address in order to achieve the United Nations Sustainable Development Goals (SDGs). For example, according to the United Nations, a large proportion of wastewater is still released into the environment without being either collected or treated. This is particularly true in low-income economies, which, on average, treat only 8% of domestic and industrial wastewater, compared to 70% in high-income economies (Alvaredo et al. 2018). As a result, in many regions of the world, water contaminated by bacteria, nitrates, phosphates, and solvents is discharged into rivers and lakes. This water ends up in the oceans, where its negative impact on the environment and public health will fundamentally change the well-being of the earth's ecosystems.

To use China as an example, according to the national statistics, China discharges about 77.82 bn tons of wastewater from cities each year, with a treatment rate of 80.3%. There are another 19.7 bn tons of non-treated rural wastewater. It is estimated that each year about 4128 tons of total phosphorus and 82,560 tons of total nitrogen are discharged into watersheds. The total runoff could be 2250.5 bn m^3 per year in the wet season but only 461.0 bn m^3 per year in the dry season (Wang, Wang, and Jia 2016a). Without considering the surface runoff and agricultural pollution, the consistent discharge and reduced runoff have caused all the watersheds to become seriously polluted in the dry season, which further pollute the soil and impacts food safety. As the demand for food is projected to increase by 50% in the next 20 years, the usage of nitrogen fertilizer will increase by 200% and phosphorus by 80% (Tilman et al. 2002). Facing these challenges, China is making an effort to battle water pollution and increase the standard of wastewater treatment, thereby generating a new economy with a market volume of more than RMB 1000 bn (Wang, Huang, and Xie 2016b).

Rapid urbanization in China (from 22% in 1980 to 58% in 2016) generates 3.60 million tons of solid waste and about 900 thousand tons of toxic landfill leachate per day. Urbanization is increasing the risk of soil pollution through waste disposal and water pollution. More than 16% of China's agricultural lands face severe heavy metal pollution (Bai, Shi, and Liu 2014), and 36.3% of China's agricultural lands consist of soil classified as "unsafe," which is a serious threat to food security (Stephens, Jones, and Parsons 2018).

Energy is the engine of the world economy and the key to ecosystems' functioning, which also has a great impact on global warming. According to the United Nations, the world's energy needs will go up 60% by 2030 due to economic and population growth. On the other hand, based on the projected effect on insects, vertebrates, and plants, scientists urge to limit global warming to 1.5°C rather than 2°C (Warren et al. 2018). To confront global warming, "going renewable" is a sustainable long-term energy strategy, as it is declared political goal, for example, of Germany. In Germany, renewable energies have increased their production from 10 TWh in 1990 to 218.3 TWh in 2017. Nuclear energy has been reduced from 150 TWh to 76.3 TWh. Coal energy has been reduced from 310 TWh to 240.1 TWh (SBA 2018). Nonetheless, on a global scale urbanization will have a great impact on energy consumption that may overcompensate not sufficiently ambitious plans for the introduction of renewables. As China's urbanization increases 10%, the energy consumption of the 10% moving into cities increases by 83%, resulting in a total increase in the energy consumption by about 8% (Wang 2014).

An analysis of resource availability and potential bottlenecks in critical metals showed that the world's mining of cobalt, for the lithium-ion battery supply chain, has increased from 50 kt in 2002 to 125 kt in 2016 (Olivetti et al. 2017). There are risks associated with the geopolitical concentrations of cobalt, which can affect other industries in which the rapid growth of a materials-dependent technology disrupts the global supply of those materials. The geographically uneven distribution of resources is one issue affecting energy production. Poverty is another issue causing a CO_2 emissions gap, so the important issue is not population numbers but income level (Chiang et al. 2017). Based on Hubacek et al. (2017a, 2017b), people with daily incomes above 23 dollars (10% of the population) contribute 43% of the CO_2 emission, compared to the 3% contributed by those making less than 1.25 dollars a day (18% of the population).

Trends in energy supply and energy demand (IEA 2017a) could be listed as follows:

(1) Shift to emerging economies: More electricity capacity will be installed in 2040 than is installed today, 97% of the increase will be in non-OECD countries.
(2) Focus on renewable energy: From now until 2040, 60% of spending on new power plants will go toward renewable sources, and more

than 50% of all new energy generation will be renewable.

(3) Emphasis on efficiency: The energy demand of the increasing global economy expected to increase by 1/3, while the volume may increase by 150%.
(4) Urban-smart energy network: The fact that two-thirds of the world's energy is being consumed in cities presents a tremendous opportunity to "go smart."
(5) Digital transformation in smart energy: Investment in digital electricity infrastructure and software grew over 20% annually between 2014 and 2016, overtaking global investment in gas-fired power generation.

Global connectivity in information and communication technology across the economy, including in energy systems, is increasing rapidly, particularly in the developing world (IEA 2017b). Although every challenge is unique on a local, regional, or even global scale, global and regional collaborations will support, supplement, and fortify national policy-making toward the United Nations SDGs. Incorporating both biophysical and social dynamics makes these problems "wickedly complex" and impossible to address from within the confines of any single discipline. We are currently exceeding safe planetary biophysical boundaries (Rockström et al. 2009). GDP is growing, but rising inequality, loss of natural capital, and decreasing ecosystem services net out to stagnating improvements in overall quality of life and risks to sustainability (Costanza et al. 2014). The problems are well known. The solutions require new approaches.

To confront these complex challenges by focusing future development on the United Nations SDGs providing sustainable prosperity for all global citizens. The SDGs offer a detailed dashboard of 17 goals, 169 targets, and over 300 indicators. The SDG process provides an opportunity to trigger systemic change to build a sustainable future in an increasingly interconnected world. However, the SDGs by themselves provide loose guidelines, at best. There is still much additional work needed to elaborate the complex, dynamic interconnections between the goals; and the means-ends continuum toward an overarching goal and measures of progress toward that goal (Lu et al. 2015).

To achieve the SDGs, we need to shift from a narrow focus on GDP growth to a broader understanding and measurement of well-being – the integrated well-being of humans and the rest of nature. We recommend the following in order to accelerate this process for the benefit of the world:

Recommendations:

(1) **Focus on the ultimate goal of human and ecosystem well-being – the sustainable improvement of "quality of life."** This requires a better understanding of the trade-offs and synergies among all 17 SDGs and how they contribute to overall well-being – for example, reducing inequality to improve life in rural areas, ensuring universal access to clean energy, increasing productivity while decreasing environmental impact (Sovacool 2014), etc.
(2) **Create and use better measures of well-being to guide decision-makers at all levels**. This can build on previous work on the Genuine Progress Indicator, life satisfaction surveys, and ecosystem services assessments (Costanza et al. 2016) to ultimately create a new, hybrid *EcoCivilization Index (ECI)* applicable at multiple scales that can utilize emerging "big data," surveys, and forums.
(3) **Envision a future ecological civilization**. This utilizes public opinion surveys, deliberative forums, and creative media to engage the public in building alternative futures. This keeps the public informed about challenges for urban sustainability such as resource scarcity (water, soil, energy), climate change and its negative impacts, environmental pollution, habitat and species loss, ecosystem service and function degradation, landscape homogenization, and loss of agricultural land.
(4) **Enable systems thinking and integration**. This includes integrated modeling, life cycle assessment (LCA), and trans-disciplinary cooperation to bring together technical, environmental, and socioeconomic aspects, including energy, water, food, land use, community, and ethical considerations, to understand the trade-offs and synergies among the SDGs.
(5) **Accelerate the introduction of renewable energy and storage technologies**. This takes account of possible side effects, integration with ecosystems, and business models allowing for smooth transitions and ultimately for high renewable penetration, including storage and backup options (SDG 7, 11, 13).
(6) **Enable smart, clean, and flexible energy for all**. By leveraging digital transformation and investing in smart energy systems, including smart grids, we can improve energy efficiency, reduce GHG emissions, enable and enhance supply and demand-side management, and eliminate energy poverty (SDG 7, 11, 13).
(7) **Enable mobility systems that are attractive, convenient, affordable, and efficient for all**. For example, in China, pure battery electric power is the main force of market growth,

accounting for nearly 80% of the market share. With other emerging technologies, China could make transport more sustainable (SDG 11, 12).

(8) **Invest in research on scaleable breakthrough technologies and innovation to achieve the SDGs**. This includes organizing creative innovation hubs and summits, prizes, start-up grants, seed funding, and small business research initiatives to support emergent blockchain technologies, the internet of things, smart energy storage technologies, new reusable and recyclable materials, biomimicry, smart distributed energy and micro-grids, and renewable-energy-integrated buildings (SDG 9).

(9) **Significantly increase investment in nature-based solutions and environmental protection**. This includes air and water quality, solid waste management and landfill leachate treatment, soil reclamation and food security, ecosystem services protection and restoration, sponge cities, mine reclamation, coastal storm protection, and flood prevention (SDG 13, 14, 15).

(10) **Ensure food security and safety and resilient agricultural ecosystems**. This includes utilizing digital techniques to increase the efficiency of small-scale farming, improving sustainable and climate-smart output while preserving rural communities, food traceability/ingredient tracking, environmental impact labeling, rural water conservancy, etc. (SDG 2, 3).

(11) **Foster sustainable living through education and practice**. This includes utilizing a range of print, film, and other media to communicate sustainable practices, and set up guidelines for sustainable consumption and public behavior (SDG 4,12).

(12) **Implement full cost accounting and auditing**. Carbon trading, pollution fees, LCA, ecological risk assessment, ecosystem compensation payment, etc. to internalize externalities (SDG 13, 14, 15).

Disclosure statement

No potential conflict of interest was reported by the authors.

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