EcoWISE.
Innovative Approaches to Socio-Ecological Sustainability

Varenyam Achal
Abhijit Mukherjee
Editors

Ecological Wisdom Inspired Restoration Engineering

Springer

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EcoWISE (Ecological wisdom inspired science and engineering) series aims to publish authored or edited volumes that (1) offer novel perspectives and insightful reviews, through the lens of ecological wisdom, on emerging or enduring topics pertaining to urban socio-ecological sustainability research, planning, design, and management; (2) showcase exemplary scientific and engineering projects, and policy instruments that, as manifestations of ecological wisdom, provide lasting benefits to urban socio-ecological systems across all temporal and spatial scales; or (3), ideally, coalesce (1) and (2) under a cohesive overarching framework. The series provides a forum, the first of its kind, for the broad international community of scholars and practitioners in urban socio-ecological systems research, planning, design, and management.

Books in the EcoWISE series will cover, but not be limited to, the following topical areas:

- Transdisciplinary studies of ecological wisdom, *ecophronetic* practice research, complex adaptive systems, traditional ecological knowledge (TEK), urban resilience, global climate change, urbanization, phronetic social science, and sustainability science;
- Ecological sciences for and practices in ecosystem rehabilitation, habitat reconstruction, landscape restoration, sustainable agroecology, permaculture, architecture, landscape and urban planning and design, resource conservation and management, disaster management, urban flood control and management, and low impact development;
- Benchmarks for sustainable landscape and urban planning and design (e.g., the Sustainable SITES Initiative [SITES], Leadership in Energy & Environmental Design [LEED]);
- Engineering science, technology and policy for environmental restoration (e.g., river, lake, hazardous waste sites, brown fields), low CO_2 emission, wastewater and soil treatment, renewable energy, urban green infrastructure and building materials.

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Preface

Ecological wisdom inspired science and engineering (EcoWISE) offers novel perspectives and insightful research and reviews, through the lens of ecological wisdom, on emerging or enduring topics pertaining to urban socio-ecological sustainability research, planning, design, and management. It was first proposed during the *1st International Symposium on Ecological Wisdom for Urban Sustainability* on October 17–18, 2014, in Chongqing, China, by Prof. Wei-Ning Xiang, and reiterated during *2nd International Symposium on Ecological Wisdom for Urban Sustainability*, November 17–20, 2016, held at the University of Texas at Austin. Following this conference, "Ecological Wisdom Inspired Restoration Engineering" took shape of a book and attracted contributions from authors from all around the world.

Ecological Wisdom Inspired Restoration Engineering is one of first two edited books in the EcoWISE book series. It is focused on learning and adapting EcoWISE in restoration engineering through theories, hypotheses, policies, practical understandings, and case studies. Understanding nature's processes is a prerequisite for prudent human actions to sustain the healthy functioning of a habitable earth. The book aims to (1) provide a guide for the readers seeking to understand and build sustainable urban socio-ecological systems by restoration technologies coming from ecological wisdom and (2) explore ecological wisdom principles from various perspectives pertaining to ecological restoration.

There are 14 chapters in this book. Chapter "Development of Environmentally Sustainable Materials" examines environmentally sustainable materials from a standpoint that might be said to be deeply ecological as it advocates for the increased use of sustainability metrics in assessing evaluations of materials' greenness. Construction industry is facing big problem in achieving sustainability. Approaching from the ecological wisdom perspective, microbial strategies are providing promising strategy to achieve green building materials. Popularly investigated strategies are listed as biocementation, biomasonry, biorepair, and bioconsolidation (Chapter "Overlooked Strategies in Exploitation of Microorganisms in the Field of Building Materials"). In Chapter "Microbially Induced Calcite Precipitation (MICP) for Soil Stabilization," biogrout is explained as environmentally friendly alternate to chemically based grouting materials in improving the engineering properties of soils. Chapter “Utilization of Microbially Induced Calcite Precipitation for Sand Solidification Using *Pararhodobacter* sp.” shows how a bacterium, *Pararhodobacter* sp. contributed to the application of a new technique for sand improvement using biostimulation, while Chapter “Effect of Plant-Derived Urease-Induced Carbonate Formation on the Strength Enhancement of Sandy Soil” presents the research on plant-derived urease using crude extract of watermelon (*Citrullus lanatus*) seeds in improving sand specimens with potential in controlling soil liquefaction.

In order to save carbon emission and reduce environmental impact, making an effective use of straw fibers in concrete is no doubt a significant step toward low carbon and sustainable construction in the era of rapid economic growth and industrialization in China. It is explained in Chapter “Material Properties of Agriculture Straw Fibre-Reinforced Concrete”, a chapter that focused on advance knowledge on the mechanical characteristics of agricultural straw fiber reinforced concrete (ASFRC) in improving its compressive and tensile performance. Aiming for a clean future through smart technology in construction, Chapter “Agro-Industrial Discards and Invasive Weed-Based Lignocelluloses as Green Building Materials: A Pertinent Review” delineates the viability potential and hurdles in the path of using agro-industrial discards and invasive weed-based lignocelluloses in building materials.

There are various environmental and social problems such as pollution, difficulties in food and water supply, poverty or homelessness, faced by modern city, where specific ecosystem services offer structural solutions. Structural integrating ecosystem services in the built-up urban space can solve major urban environmental and social problems to improve urban sustainability and revitalize degraded urban areas. Chapter “Integration of Ecosystem Services in the Structure of the City is Essential for Urban Sustainability” shows that nature-based solution management differs from technological management and provides ecosystem services in any restoration project. Chapter “Integrated Blue and Green Corridor Restoration in Strasbourg: Green Toads, Citizens, and Long-Term Issues” provides perspectives on several ecosystem services, including supporting services (habitat for amphibians), regulating services (water quality enhancement), and cultural services (urban landscape greening) from ecological, engineering, and sociological points of view. Further, brownfields are challenging problem, especially in industrial and post-industrial cities in many countries. In Chapter “The Role of Ecological Wisdom in Brownfields Redevelopment in China,” ecological wisdom is synthesized and integrated from other countries where brownfield redevelopment is studied and applied to deepen the current understanding of brownfield redevelopment. Chapter “Ecological Wisdom-Inspired Remediation Technology for Aquaculture Water Quality Improvement in Ecological Agricultural Park” investigates ecological wisdom-inspired remediation technology for the improvement of aquaculture water quality in ecological agricultural park of Shanghai, China. In addition, wetlands are significant for the development of resources and environmental protection in the city of Shanghai and discussed in Chapter

"Wetlands Restoration Engineering in the Metropolitan Area." The management of wastewater being generated from domestic, industrial, and agricultural sources is also a big issue worldwide. Chapter "Modern and Emerging Methods of Wastewater Treatment" employs the principle of ecological wisdom in designing new treatment strategies and also to strengthen the available natural treatment methods in order to achieve the goal of sustainable water development. The concept of ecological wisdom also guides us to look for alternative to improve crop production and soil health to enhance sustainable agricultural production (Chapter "The Role of Microbes to Improve Crop Productivity and Soil Health").

I wish to express my appreciations to the multidisciplinary team of authors for wonderful scientific contribution to this book. We are very grateful to Prof. Wei-Ning Xiang (the Founding Editor in Chief of the Springer Nature EcoWISE book series) for his insightful comments and for accepting this book to be a part of the EcoWISE book series. Thanks to Ms. Xiaoli Pei from Springer Nature and her production team for supporting us constantly during the editorial process. It is intended that this book will serve as a useful resource for environmental engineers, biotechnologists, civil engineers, researchers, and graduate students in these areas. On behalf of all the authors, I firmly believe that the knowledge and wisdom in this book will greatly enhance the EcoWISE enterprise's effort to resolve various environmental issues under the beacon of ecological wisdom.

We hope you like reading this book.

Shanghai, China Varenyam Achal

Contents

Prologue

Ecological Wisdom: Genesis, Conceptualization, and Defining Characteristics

EcoWISE

Ecological practice is the action and process that humans involuntarily engage themselves in the aim to bring about a secure and harmonious socio-ecological condition that serves human beings' basic need for survival and flourishing. It is the most fundamental and arguably primordial practice. *Homo sapiens* has been engaging in over thousands of years of coevolution with nature and falls into one or any combination of the following categories—ecological planning, design, construction, restoration, and management.

From ecological practice, humans acquired a distinctive master skill par excellence, *ecological wisdom*, that enables them to address and act well on intractable socio-ecological issues that are crucial to their survival and flourishing. While manifesting itself in a myriad of ecological and landscape projects and public policy instruments that has been beneficent to both humans and other residents on the earth, this invaluable intellectual asset of ecological wisdom continues to evolve in the contemporary society of unprecedented socio-ecological transformations, inspiring advancement in modern science, and stimulating technological and engineering innovations for the greater good. Ecological wisdom inspired science and engineering (EcoWISE, for brevity) is therefore the emerging transdisciplinary field of scholarly inquiry that seeks novel insights, deliberately through the lens of ecological wisdom, into contemporary socio-ecological issues, and aims to develop innovative, prudent, and efficacious scientific and engineering solutions. The Springer Nature EcoWISE book series provides a forum, the first of its kind, for the international community of scholars and practitioners to collectively advance this worthy enterprise.

The book series aims to publish authored or edited volumes that (1) offer novel perspectives and insightful reviews, through the lens of ecological wisdom, on emerging or enduring topics pertaining to ecological practice and research; (2) showcase exemplary scientific and engineering projects, and policy instruments that, as manifestations of ecological wisdom, provide lasting benefits to socio-ecological systems across all temporal and spatial scales; or (3) ideally, coalesce (1) and (2) under a cohesive overarching framework. The series is intended to serve the broad international community of scholars and practitioners in socio-ecological practice and research.

Integral to EcoWISE are the questions pertaining to the genesis, conceptualization, and defining characteristics of ecological wisdom: What is it? Where does it come from? What defining characteristics does it have? In the following sections, I shall explore these three questions.[1]

Ecological Wisdom

There are three ways in which the scholarly construct of ecological wisdom is defined (for recent and succinct reviews of various definitions, see Liao and Chan 2016, pp. 111–112; Wang et al. 2016). As described chronologically below, they derive from different etymologies and reflect varied intellectual traditions.

Ecological Wisdom as an Ethical Belief: *Ecosophy*

In a 1973 essay on the main characteristics of the deep ecology movement, Norwegian ecological philosopher Arne Naess coined the term *ecosophy*, by combining the ancient Greek words *ecos* (household place) and *sophia* (theoretical wisdom), to represent an individual's own personal "philosophy of ecological harmony or equilibrium (between human and nature—the author)" (Naess 1973, p. 99). Despite his intention to use this term "to mean ecological wisdom or wisdom of place" (Drengson and Devall 2010, p. 55), no formal articulation was made until 16 years later. In a 1989 essay entitled *From ecology to ecosophy, from science to wisdom*, he inaugurated the fused nexus of ecological wisdom and *ecosophy* with a strong proclamation that for humans "to live on Earth enjoying and respecting the full richness and diversity of life-forms of the ecosphere, … [e]co-wisdom (ecosophy) is needed" (Naess 1989, p. 185).

Along with this *ecosophical* line of reasoning, there was a strikingly parallel development in a noncognate context and with no direct intellectual contact. In a

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[1] Drawing primarily on Chinese and English literature owing to my linguistic capabilities, this synthesis is inevitably limited in its scope and thus subject to expansion.

1996 seminal Chinese book *On ecological wisdom* (《生态智慧论》, *sheng tai zhi hui lun*), Chinese philosopher Zhengrong She (佘正荣) coined the term 生态智慧 (*sheng tai zhi hui*), in a way similar, yet unrelated, to Naess', by combining the Chinese words 生态 (ecological) and 智慧 (wisdom). He defined ecological wisdom as *ecohumanism* with the following proclamation (She 1996, pp. 3–4)[2]: "At the transitional juncture from the industrial to ecological civilization, human beings must supplant the anthropocentric humanism with ecohumanism. A tripartite worldview that blends seamlessly ecological sciences, ecological ethics, and ecological aesthetics, ecohumanism is the ecological wisdom human beings need, and can guide the contemporary human beings through the jungle of industrial civilization toward the bright future of ecological civilization."

Acknowledging that "ecological wisdom is the wisdom for living and survival that is rooted in and developed through the primordial process of human adaptation to the environment" (She 1996, p. 2),[3] he posited that the ecological philosophies (i.e., *ecosophies*, as defined by Naess) of some of the greatest thinkers in human history, including those of Laozi, Aldo Leopold, Aurelio Peccei, Holmes Roston III, Arnold Joseph Toynbee, and Zhuangzi, are but archived individual convictions drawing on collective *ecosophical* beliefs (Ibid. p. 3).[4]

This collective perspective of *ecosophy* deviates from the "whole personal view" (Drengson and Devall 2010, p. 56) of Naess'. According to Canadian philosopher Alan Drengson and American sociologist Bill Devall, Naess believes that "[s]ince there is an abundance of individuals, languages, cultures, and religions, there will be an abundance of *ecosophies*." (Ibid.) To differentiate, "[e]ach person's *ecosophy* can be given a unique name, possibly for the place they live, or for something to which they feel strongly connected." Exemplifying this individual's personal view are Naess' "*Ecosophy* T" (Drengson and Devall 2010, pp. 56–57) and Chinese ecological aesthetician Xiangzhan Cheng's "*Ecosophy* C" (2013).

Ecological Wisdom as a Dual Ability: *Ecophronesis*

In a 2017 article entitled *Ecological philosophy and ecological wisdom*, Chinese ecological philosopher Feng Lu (卢风) defined ecological wisdom as the dual human ability to make ethically and politically sound judgment and to take ensuing

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[2] "人类在从工业文明向生态文明转变的历史关头,必须超越人类中心主义的价值观,形成一种使生态规律、 生态伦理和生态美感有机统一的新的价值观。这就是生态人文主义的价值观。生态人文主义是当代人类所需要的生态智慧, 它将引导人类安全地走向未来的生态文明。"

[3] "生存智慧来源于生物对环境的适应, 因而生存智慧实质上就是生态智慧。对环境的适应是一切智慧最原始和最深刻的根源。"

[4] "生态哲学给人类提供了一些深刻的生存智慧。但是这并不是说, 在现今的生态哲学中已经达到了尽善尽美的生存智慧, 也不是说在生态哲学出现之前就没有产生过相当深刻的生态智慧。事实上, 在东方古代的文化传统中就产生过非常深刻的生态直觉 (智慧—作者), 这些生态直觉 (智慧) 对于当代人类生态观的发展和完善具有十分重要的价值。"

prudent actions in particular circumstances of ecological practice (Lu 2017, p. 278; p. 285).[5] This human ability approach to wisdom definition has its intellectual root in Aristotelian conception of *phronesis* (i.e., practical wisdom; for a recent and succinct review of Aristotelian *phronesis*, see Xiang 2016, pp. 54–55). It is in fact the philosophical underpinning of a 2016 essay on ecological practical wisdom by American geographer and planning scholar Wei-Ning Xiang (Xiang 2016). In a way similar to that employed by Naess and She, Xiang coined the term *ecophronesis*, by combining two ancient Greek words *ecos* and *phronesis*, to represent ecological practical wisdom which he defined as “the master skill par excellence of moral improvisation to make, and act well upon, right choices in any given circumstance of ecological practice” (Xiang 2016, p. 55). Here, Xiang noted the term *skill* is used as an uncountable mass noun synonymous with the term *ability* (as in “the skill”) [Ibid.].

Despite the nascent coinage of *ecophronesis*, both the term and the *ecophronetic* line of reasoning it represents are indeed, according to Xiang, an *ex post* recognition of and a revered tribute to an outstanding group of human beings throughout history (Xiang 2016, p. 59). *Ecophronimoi* are the people of ecological practical wisdom whose master skill par excellence of *ecophronesis* enabled them to be successful in challenging circumstances of ecological practice (Ibid.). Among the prominent *ecophronimoi* are the Chinese ecological planner and engineer Li Bing (480 BC–221 BC) and his colleagues of many generations who collectively designed, built, and sustained the Dujiangyan irrigation system (256 BC to present) in Sichuan, China (Needham et al. 1971, p. 288; Xiang 2014, pp. 65–66), and the American ecological planner and educator Ian McHarg (1920–2001) and his colleagues who planned and developed the town of the Woodlands in Texas, the USA, in the 1970s (McHarg 1996, pp. 256–264; Xiang 2017a; Yang and Li 2016). Their *ecophronetic* practices of stellar quality have brought lasting benefits to the people and other living communities in the areas the projects serve, and clearly achieved the paramount level of “doing real and permanent good in this world” (Xiang 2014, p. 65).

Ecological Wisdom as a Cohesive Whole of *Ecophronesis* and *Ecosophy*

In his 2016 essay on *ecophronesis*, Xiang made the observation that not only are *ecophronesis* and *ecosophy* so profoundly linked, but the connection between them is indeed integral to *ecophronesis*. He noted that in the instances of prudent and successful ecological practice throughout human history, like those of aforementioned Dujiangyan irrigation system and the Woodlands, *ecophronimoi*’s mastery and execution of improvisational skill were mindfully bound by a moral covenant with nature, and inspired and informed by the human beings’ enlightened

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[5] “生态智慧是在生态学和生态哲学指引下养成的判断能力、直觉能力和生命境界 (涵盖德行)。生态智慧与人的生命和实践‘不可须臾离’” (卢风, 2017, p. 285).

self-interest (Xiang 2016, pp. 57–58).[6] This union of improvisational ability and moral commitment is what American planning scholar John Forester calls "moral improvisation" (Forester 1999, pp. 224–241). It is with this very master skill par excellence of moral improvisation that *ecophronimoi* became capable of being "doubly responsible" (Nussbaum 1990, p. 94) in any particular instance of ecological practice—honoring commitments and upholding principles, on the one hand, and attending specific circumstantial particulars, on the other (Xiang 2016, p. 58).

This observation corroborates Xiang's argument that as an *ex post* and long overdue recognition of a reverable human virtue in ecological practice, the scholarly construct of ecological wisdom is incomplete and unbalanced in the absence of either *ecosophy* or *ecophronesis* (Xiang 2016, p. 58). It provides support for his proposal, as depicted symbolically in Eq. (1)[7] (Xiang 2017b), that both *ecosophy* and *ecophronesis* should be juxtaposed at the core of ecological wisdom (Xiang 2016, p. 53).

$$\text{Ecological wisdom} = \text{ecosophy} + \text{ecophronesis} \tag{1}$$

This *ecophronetic* line of reasoning for "the *ecophronesis-ecosophy* nexus of ecological wisdom" (Xiang 2016, p. 58) finds supporting arguments in Naess' work on *ecosophy*. In the 1989 essay aforementioned, Naess argued that the ethical belief of *ecosophy* is a source of inspiration and guidance for both action and research. "[N]ot a philosophy in the academic sense" (Naess 1989, p. 187), he wrote, "[a]n articulated *ecosophy* includes an attempt to outline *how to inhabit the Earth* conserving her long range, full richness and diversity of life as a value in itself (Ibid. p. 186)." As such, "[w]ithin the framework of Ecosophy research enters primarily as 'action research'" that is "subordinated to practical policies," (Ibid. p. 188), and aimed at "the derivation of particular prescriptions (that are) adapted to particular situation." (Ibid. p. 187) The practical orientation of *ecosophy* and contextual characterization of *ecosophical* research Naess articulated here manifest in his own work on Ecosophy T and the Apron Diagram, and are readily evident throughout his later writings (for a succinct review, see Drengson and Devall 2010).

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[6] Human beings' enlightened self-interest is a term used in environmental virtue ethics that serves the same *ecosophical* function as Naess' *ecosophy* does—it is an ethical belief of the ecological harmony between human and nature (Cafaro 2001, pp. 3–5). According to Xiang (2017, p. 56), under the premise that there exists a relationship of human-nature reciprocity, "it states plainly that it is in human beings' self-interest—ethical, moral as well as material—to respect and appreciate the intrinsic value of all living and non-living beings on the earth; and that human beings' own flourishing, at individual and collective levels, should be conceived and pursued in ways that both sustain and depend on the flourishing of the entire 'more-than-human whole' of which humans are part." As "such nonanthropocentrism is a part of wisdom" (Cafaro 2001, p. 15) that is widely shared by people from around the world and across generations, including Naess (see his 1986 essay, p. 72), I use it here as a collective *ecosophy*.

[7] In delivering this keynote speech in Chinese, Xiang presented the equation as 生态智慧=生态哲思+生态实践智慧. A copy of the PowerPoint presentation is available from the author upon request.

An Embracing Definition of Ecological Wisdom

At the point where the *ecosophical* and *ecophronetic* lines of reasoning converges, Xiang posited in a 2017 speech (2017b), emerges a definition of ecological wisdom that embraces *ecophronesis* and *ecosophy* into a cohesive whole. One such definition he initially presented (Ibid.) is further elaborated below.

> Ecological wisdom is the master skill par excellence of moral improvisation for and from ecological practice; it enables a person, a community, or an organization to make ethical judgment and take circumspect actions in particular circumstances of ecological practice; it is a cohesive whole of the *ecosophical* belief in the relationship of human-nature reciprocity and the *ecophronetic* ability to make, and act well upon, contextually and ethically right choices.

This definition highlights two defining characteristics of ecological wisdom—the ability in ecological practice to achieve the ideal of the unity of moral knowledge and virtuous action, and the ability to conduct preeminent ecological practice research.

Ecological Wisdom as the Ability to Achieve the Unity of Moral Knowledge and Virtuous Action

Fine hundred years ago, Chinese Neo-Confucian philosopher Wang Yangming (王阳明, 1472–1529) coined the term *the unity of knowledge and action* (知行合一, *zhī xíng hé yī*) to designate a state of moral ideal that he believes "exists for all (humans)" (Ching 1976, p .68) and can be achieved through and in practice (Ibid. p. 72). In this state of moral ideal, ethical knowledge (*i.e.*, knowledge of the good) and virtuous action (*i.e.*, action to do the good) are only two words describing the same one effort; as such, one acts spontaneously yet virtuously upon deep moral convictions (Ibid. pp. 68–69).[8] Similar ideas are also found in Aristotle's thinking over two millennia ago. "For Aristotle," wrote Canadian political scientist David Tabachnick, "to be 'ethical' was more than simply knowing right from wrong, but also meant the capacity to act upon that (moral—author) knowledge." (Tabachnick 2013, p. 32).

Ecological wisdom as defined above enables a person, a community, or an organization to achieve Wang's ideal state of the unity of moral knowledge and virtuous action (for brevity, thereafter, *the unity of knowledge and action*), and to meet the Aristotelian ethical standard. As a master skill par excellence of moral improvisation, it activates and amplifies the action-guiding function of *ecosophical*

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[8] It should be noted that, according to Julia Ching, a Canadian philosopher and a word leading Wang Yangming scholar, for Wang Yangming, "…just as true knowledge is always knowledge of virtue, true action should always be virtuous action. 'The unity of knowledge and action' is primarily a moral ideal rather than a principle of epistemology." (Ching 1976, p. 66) Unfortunately, by many with good intentions it has been mistaken as a principle of epistemology (Dong 2013).

belief such that the ethical knowledge of the good serves as a moral benchmark for one's sound judgment and virtuous action in particular circumstances of ecological practice (Xiang 2016, p. 56). The ensuing outcomes, in the form of ecological plans, designs, construction and restoration projects, and management policies, are thus simply tangible manifestations of the knowledge of the good, and exemplified by, among others, the aforementioned Dujiangyan irrigation system and the Woodlands. This process of activating and realizing one's *ecosophical* belief is analogous to, if not the same as, *zhì liáng zhī* (致良知)—extending and realizing one's innate conscience (i.e., knowledge of the good) through virtuous actions in practice—a process that, according to Wang Yangming, leads to *the unity of knowledge and action.*[9]

In a 2003 essay, Chinese philosopher Mingying Deng proposed the concept of *eco-conscience* (生态良知, shēng tài *liáng zhī*) and defined it as a coalesced nexus of "the consciousness of being part of a more-than-human whole; the sense of moral goodness of one's own conduct, intentions, or character; and a feeling of ethical obligation to do right or be good in the best interest of the more-than-human whole." (Deng 2003, p. 86).[10] *Eco-conscience* such defined is comparable to the *ecosophy* component of ecological wisdom (section "Ecological Wisdom as a Cohesive Whole of *Ecophronesis* and *Ecosophy*") with a shared belief in the relationship of human-nature reciprocity. A subtle difference is that *eco-conscience*, or conscience by and large, is often regarded as an innate quality of every human being [i.e., "the innate knowledge of the good" (Zhang 2017, p. 341)], while *ecosophy* is not reportedly so.[11] The difference can nevertheless be omitted here and now since even Wang Yangming himself makes no distinction between conscience and moral knowledge in his conception of *zhì liáng zhī* (Ching 1976, p. 67). As such, it suffices to say that ecological wisdom, through activating, extending, and realizing *eco-conscience* (*zhì* shēng tài *liáng zhī*, 致生态良知) or *ecosophical* belief grounded in eco-conscience, is capable of empowering a person, a community, or an organization to achieve Wang's state of moral ideal of *the unity of knowledge and action* in ecological practice and thus to become ethical by the Aristotelian standard.

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[9] "致吾心良知之天理于事事物物，则事事物物皆得其理矣。致吾心致良知者,致知也。事事物物皆得其理者，格物也。是合心与理为一者也。" (王阳明《王阳明全集》卷二《传习录中.答顾东桥书》, 上海古籍出版社, 1992).

[10] "(生态良知) 是指人类自觉地把自己作为生物共同体的一员，把自身的活动纳入生物共同体的整体活动， 并在此基础上形成的一种维持生物共同体和谐发展的深刻的责任感以及对自身行为的生态意义的自我评价能力。" (邓名瑛, Deng 2003, p. 86).

[11] More investigation is requested into the relationships between eco-conscience and *ecosophy*. In the writings on *ecosophy*, authors (Naess, Drengson, Deval, and Cheng, among others) predominantly treated *ecosophy* as a belief of environmental ethics with no articulation to eco-conscience. In a 2017 essay, on the other hand, Chinese ecological philosopher Xuezhi Zhang posited that one's achievement of the ideal moral state of *the unity of human and nature* is grounded in eco-conscience and speculated whether eco-conscience could integrate environmental ethics (2017, p. 342). However, no rigorous investigation into the relationships has been found in the literature.

Ecological Wisdom as the Ability to Do Preeminent Ecological Practice Research

In addition to activating the action-guiding function of *ecosophical* belief or *eco-conscience*, e*cophronesis* in the scholarly construct of ecological wisdom is capable of empowering scholar-practitioners and practitioners to do outstanding research for ecological practice.

Scholar-practitioners are scholars who are engaged in use-inspired basic research for practice (i.e., *practice research*) in Pasteur's quadrant and dedicated to generating *new* knowledge that is *useful* to practitioners (Xiang 2017, pp. 2243–2244). Common to all scholar-practitioners who have done outstanding ecological practice research, like McHarg, is their *ecophronetic* way of conducting practice research (Ibid. p. 2245). Wrote Xiang (Ibid. unless essential, citations in the original text are omitted for brevity), with *ecophronesis*,

> scholar-practitioners like McHarg became much capable of generating *new* knowledge that is *useful to the real*: not only did they advance scholarly rigorous—thorough and valid—knowledge that was also *immediately relevant*, *actionable*, and *potentially efficacious* to the real-world practitioners who were in specific knowledge needs under particular circumstances of ecological practice; but they also produced high caliber scholarship that is enlightening to scholars and practitioners from around the world and across generations who have interest in ecological practice research. Furthermore, because *ecophronesis* embraces inherently a transdisciplinary research capability in socio-ecological systems, *ecophronetic* scholar-practitioners like McHarg were immune from the pathogenic influence of 'ivory tower syndrome' (Toffel 2016, p. 1494). They became readily capable of bridging the arguably unbridgeable gap between scientific rigor and practical relevance, and taming the seemingly intractable problems of 'knowledge production' and 'knowledge transfer' (Sandberg and Tsoukas 2011, p. 338), all of which have been and remain to be persistent concerns in both circles of ecological practice and science in the modern-day world. As such, their *ecophronetic* way of conducting practice research manifested itself in a myriad of ecological projects and public policy instrument that has been providing lasting ecosystem services benefits to the human beings across generations.

It is noteworthy that the empowerment of *ecophronesis* equally benefits many practitioners who are engaged in pure applied ecological research that is motivated solely by the applied goals of problem-solving in practice (Xiang 2017, pp. 2242–2243). Exemplifying these *ecophronetic* practitioners are aforementioned Li Bing and his colleagues of many generations. Without seeking a scholarly understanding of the encountered phenomena through the scientific lens, they were enabled to conduct in an *ecophronetic* way preeminent research that contributed to the very success of their ecological practice of stellar quality.

Role Models and the Community of Scholar-Practitioners

One premise underlying *ecological wisdom inspired science and engineering* (EcoWISE), the overarching concept of this book series, is that science and engineering need to and should be inspired by ecological wisdom. I hope that the preceding sections on the genesis, conceptualization, and defining characteristics of ecological wisdom have corroborated the premise to be just and appropriate. With regard to the subsequent question of *how* science and engineering should be inspired by ecological wisdom to serve the community of more-than-human whole on the earth, one way forward would be for us to emulate the role models of *ecophronetic* scholar-practitioners, whom the last two sections were dedicated to.

Ecological wisdom is not an abstract concept in the scholarly papers, and it is on clear display in the well-lived and fully realized lives of many practitioners and scholar-practitioners who have done preeminent ecological practice and research, and achieved the ideal moral state of *the unity of knowledge and action*. "A good example is the best sermon," to follow the example of these outstanding human beings, *ecophronimoi*, is both fitting and indeed rewarding. As a student of McHarg's in the 1980s, for example, not only did I witness that the unity of moral knowledge and virtuous action was like second nature to him, but I can also testify that like many of his students, my academic aspiration has been ever since inspired and professional path illuminated by his role model as an *ecophronetic* scholar-practitioner. With a gentle caveat that this way of inquiry for EcoWISE aims to examine and advocate *ecophronetic* practice research as a distinctive mode of practice research drawing upon the experience and examples of *ecophronetic* scholar-practitioners, rather than promoting the individuals themselves, I trust that the EcoWISE book series will become a celebrated venue for the building of a strong community of e*cophronetic* scholar-practitioners around the world and am confident that it will serve the community well in their pursuit of exemplary ecological wisdom-inspired ecological practice research and outstanding *ecophronetic* scholarship.

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Development of Environmentally Sustainable Materials

Mona Wells

Abstract This chapter examines environmentally sustainable materials from a standpoint that might be said to be deeply ecological as it advocates for the increased use of sustainability metrics in assessing evaluations of materials' "greenness." As such, the discussion begins by examining different paradigms of environmental sustainability, and in the context of lead use and contamination, a current environmental issue. The use of sustainability metrics is discussed, segueing into identification of the two major drivers of environmental damage (fossil fuel consumption and agriculture). Subsequently, examples of interesting environmental materials are discussed: One section is devoted to materials that increase efficiency of energy use, and another section discusses the reduction of damage from agriculture via materials engineering that will enable less land use and thereby promote ecological recovery. A final section on materials development comes full circle in considering the possibility of peak metals and innovative electronic technologies that may someday be extensible to reducing the needed circuits in buildings. In closing, the fundamental tension between technology and materials' consumption is considered in the context of Jevon's paradox as a cautionary note regarding the development of sustainable materials and the need for strong sustainability and deep ecological wisdom.

Keywords Sustainable materials · Ecological wisdom · Ecological recovery
Land use · Jevon's paradox

1 What is a Sustainable Material?

Consider the case of lead. Lead is the most prevalent pollutant in the world today (McCartor and Becker 2010), and, according to the United States Environmental Protection Agency (US EPA 2000), there is "no demonstrated safe concentration of lead in blood." It has long been known that lead is particularly dangerous for

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children (US EPA 2000); however, now it is increasingly apparent that childhood lead exposure conveys lifelong effects (Brubaker et al. 2009; Cecil et al. 2008). By far, the major world producer of lead is China (ILA 2017a), where in all but 3 of 34 provincial-level administrative units, the blood lead level of children exceeds the 100 µg/L "level of concern," and, by land area, in nearly half of the country over 40% of children have blood lead levels exceeding this (Ye et al. 2007). Despite these facts, despite lead's being a non-renewable resource, despite the production and use of lead's having increased exponentially over recent decades, and despite the laws of thermodynamics (which dictate that no recycling process could ever be 100% efficient), the International Lead Association claims to support a sustainable lead industry (ILA 2017b) and lead producers call for the use of more lead–acid batteries in hybrids as "supporting sustainability" (Prweb 2017).

In his book Beyond Growth: The Economics of Sustainable Development, Daly (1996) notes that

> One way to render any concept innocuous is to expand its meaning to include everything. By 1991 the phrase 'sustainable development' had acquired such cachet that everything had to be sustainable, and the relatively clear notion of environmental sustainability of the economic subsystem was buried under 'helpful' extensions such as social sustainability, political sustainability, financial sustainability, cultural sustainability, and on and on. Any definition that excludes nothing is a worthless definition… which is why

we define sustainability as the ability to continue a defined behavior indefinitely.

In other words, the term sustainability has been largely co-opted to include things that are *not*. According to a recent North American Product Survey, over 95% of the products reviewed made claims that violated one or more of the Seven Sins of Greenwashing (defined as disinformation disseminated by an organization so as to present an environmentally responsible public image, Terrachoice 2010). Our point of departure, therefore, is to first delineate what is meant herein by sustainability, and secondly to consider ways in which claims of sustainability might constructively be assessed.

Perhaps the most well-known conception of sustainability is the so-called triple bottom line (TBL, Elkington 1998), wherein something might only be considered sustainable if involving harmony between environmental, social, and economic considerations (also known as the three pillars of sustainability). In the TBL view of sustainability (Fig. 1, left), the three pillars of support are all of equal importance, though it should be remembered that TBL is referred to as an accounting framework, which is not a priori a particularly envirocentric construct. TBL, by extension, has led to the conceptualization in Environmental Economics that different types of capital (environmental, social, economic) are substitutable; hence, social and economic factors might readily outweigh environmental concerns. This has been referred to as weak sustainability (Fig. 1, center). Countering weak sustainability, the field of Ecological Economics has given us strong sustainability (Fig. 1, right, Daly 1995; Daly and Cobb 1989). Strong sustainability is based on the laws of thermodynamics, wherein growth is constrained by the size and resources of the earth and no productive matter and energy change is possible without an irreversible entropic degradation process that generates waste, and while it is possible to reduce the amount of waste by increasing efficiency, there are nonetheless insurmountable entropic limits to efficiency gains (Daly 2007). Strong sustainability recognizes that economic capital is derived from social capital (i.e., economy is a social construct) and that in turn social and economic capital are derived from environmental capital. Both TBL and weak sustainability represent a fundamentally anthropocentric view, whereas strong sustainability recognizes that humans need the earth, and not vice versa, and strong sustainability may therefore be said to be more closely aligned with deep ecology and ecological wisdom. Whether there are any actual "Laws" of economics might be said to be debatable (Karabell 2013). The laws of thermodynamics have been extensively tested for over a century by the scientific method, and this article will adopt the perspective that sustainability is only valid in having scientific underpinnings, i.e., in referencing strong sustainability.

2 Measuring the Sustainability of Materials

In order to know if a material is environmentally sustainable or not, it is important to have some way to measure sustainability—development of sustainable materials, therefore, must occur in tandem with development of better evidence-based approaches to quantification of sustainability. Sustainability metrics and sustainability development indices (SDIs) are tools that measure the benefits achieved through the implementation of sustainability/sustainable practices. It is important to keep in mind that sustainability metrics crosscut all dimensions (e.g., economic, social, environmental, and others) and paradigms of sustainability (e.g., weak and strong), as well as different views of development (e.g., whether or not globalization and/or urbanization are desirable). Most metrics encounter difficulties with transparency in the need for weighting, which comes into play with multi-dimensional SDIs, particularly in the context of weak sustainability. The purpose of this section is not to provide a comprehensive overview of sustainability metrics and SDIs, but rather to raise awareness for readers who are interested in sustainable materials about the most well-developed metrics and indices used in determining the *environmental sustainability* of materials.

It is helpful to distinguish metrics and indicators in terms of generality and specificity. Four indicators that might be referred to as general, i.e., ecosystem—scale metrics, include the Environmental Vulnerability Index (EVI), the Environmental Performance Index (EPI), the Living Planet Index (LPI), and Ecological Footprint Accounting (EFA). The EVI (SOPAC 2005) is calculated based on 50 environmental indicators of three aspects of environmental vulnerability: risks to the environment (natural and anthropogenic), environmental resilience, and ecosystem integrity (the health or condition of the environment as a result of past impacts). The Environmental Performance Index (EPI) is a method of quantifying and numerically marking policy-based environmental performance and

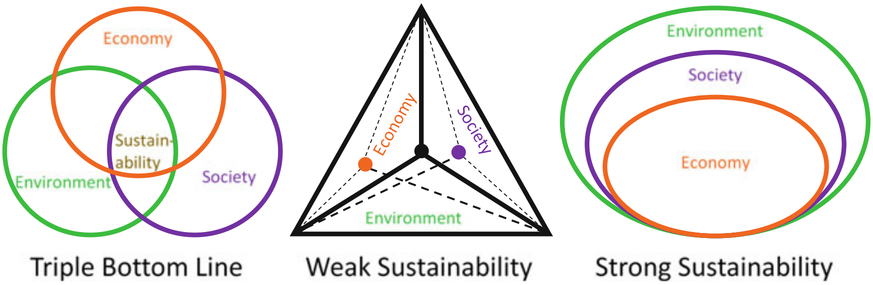

Fig. 1 Graphical depictions of conceptualizations of sustainability, adapted from Wu (2013)

is calculated based on 25 indicators of two overall environmental quantities: environmental health (human) and ecosystem vitality (Esty et al. 2008; Hsu et al. 2016). The LPI (Loh et al. 2005; McRae et al. 2017; WWF 2016) is global, calculated based on the Living Planet Database using over 14,000 population time series, and overall species trends are aggregated for the terrestrial, marine, and freshwater systems. The three system indices are averaged to produce the global LPI. EFA (GFN 2017; Rees and Wackernagel 2013) is based on the biological concept of carrying capacity and tracks the amount of land and/or water needed to produce the resources needed to support and absorb waste produced by any given population. Results are typically expressed in terms of how many planets are needed to support a given region, which is shockingly high in some developed nations. All four of these indicators are potentially useful in providing states or businesses with information to undertake self-assessment and policy refinement regarding their own environmental damage and/or vulnerability, particularly taking regional considerations into account, but from the standpoint of sustainable materials, these indicators are not practically useful to evaluate a product or process.

We distinguish indicators that we refer to as specific as being those indicators that are practically useful to evaluate a specific product or process. Examples of these include exergy analysis (EXA), embodied energy, emergy analysis (EMA), and life cycle assessment (LCA). Exergy is a thermodynamic term that reflects the maximum useful work possible during a process that brings a system into equilibrium with a heat reservoir. In practical terms, exergy may be thought of as the energy that is available for use. Exergy is eliminated for irreversible processes in proportion to the entropy of the system and its surroundings. Exergy analysis may be used to evaluate the impact of human activities on the environment (Apaiah et al. 2006; Hajjaji et al. 2012; Kanoglu et al. 2009); however, a flaw is that this analysis requires assumptions about thermodynamic reference states that are not testable assumptions.

Embodied energy includes the primary and secondary energy use for the production of materials, including process (Stein et al. 1981). Primary energy includes sources such as fossil fuel, and secondary energy is, for example, electricity.

Work of the biogeosphere that may be required (e.g., space heating for a building) in the future is not explicitly included; hence, the embodied energy is not able to offer information on a given product or process over from a life cycle perspective.

Emergy sums of all the available energy of one kind required directly and indirectly for the production of a product or service, and this does reference the biogeosphere (e.g., often expressed in terms of solar radiation). Emergy has thus been described as the total environmental support (rather than a measure of actual energy content) of a product or process (Odum 1996; Odum and Odum 1980; Scienceman 1987).

LCA is a tool to assess the environmental impacts and resources over a product or process lifetime, typically "from cradle to grave" (ISO 2006a, b). LCA identifies flows into (e.g., resources use) and emissions from (e.g., pollutants) a product or process, and then uses these flows to assess impacts across a range of potential impact categories, such as land use, ecotoxicity, etc. While the process was historically laborious and is subject to known limitations, the advent of new software and ever-increasing amounts of software-compatible data have brought this technique into the mainstream. Perhaps no example is as illustrative of the potential materiality and transparency of LCA as its role in the French Grenelle II laws (Cros et al. 2010).

A number of other indicators in addition to those described herein, particularly as pertains to building and construction materials, exist. While the use of sustainability metrics and indicators represent a quantum leap forward, most of the indicators in common use might be said to be incomplete, particularly in respect of neglecting environmental indirect costs of human activity, as discussed for instance by the Millennium Ecosystem Assessment. In the next sections of this chapter, we will examine particular areas wherein development of sustainable materials might be said to have the greatest cost–benefit potential, and the different categories of sustainable material will be evaluated according to material evaluation of sustainability where possible.

3 What to Do First?

Being able to measure sustainability may to some extent address issues of whether a product, process, or material is sustainable or not; it is not simply enough to know this. In addition to Greenwashing, the urgency of the need to transition to sustainability has arguably generated many "solutions looking for a problem." The United Nations (UN) has sensibly called for a "What do I do first?" approach, i.e., which problem is most important in order to determine how to make a meaningful contribution to sustainability? The UN Environment Programme (UNEP) International Panel for Sustainable Resource Management has assessed the best available science, and on a global level, to identify the primary drivers of environmental damage, which perforce arise from an ever-growing human population and concomitant ever-increasing level of production and consumption. The UNEP report *Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials* (UNEP 2010) reviews "all the available science and conclude that two broad areas are currently having a disproportionately high impact on people and the planet's life support systems—these are energy in the form of fossil fuels (including for agriculture and alternative energy products such as solar panels) and agriculture, especially the raising of livestock for meat and dairy products."[1] These areas of impact are not limited to but largely center upon biodiversity loss, climate change, and freshwater resources depletion. As such, the focus on sustainable materials should be informed by these two key drivers of fossil fuel use and agriculture.

4 Energy Use and Building Insulation

A group of scientists at Cambridge University recently conducted an analysis and found that "73% of global energy use could be saved by practically achievable design changes to passive systems" (Cullen et al. 2011). Of the three possible areas that they identified for energy savings, buildings accounted for over half of the energy used and the greatest potential energy savings of 80%. Insulation, for the buildings themselves, but also for appliances and services in buildings, accounted for the greatest proportion of possible energy savings. The technology to produce increasingly effective insulation has developed in a manner that might be described as meteoric in the last two to three decades, and three examples of advanced insulation materials discussed herein include aerogels, vacuum, and photonic crystals.

Aerogels are solids with a porosity of greater than 50%, a density in the range of 1–150 kg/m^3 and are typically 90–99.8% air by volume (Cuce et al. 2014; Schiavoni et al. 2016). Silica is the most common aerogel substrate; however, aerogels can also be based on alumina, lanthanide and transition metal oxides, metal chalcogenides, organic and inorganic polymers, and carbon (Sadineni et al. 2011). Production involves drying a gel at supercritical temperature, and aerogels may be produced as either granular materials or monoliths. Aerogels are best known for having low thermal conductivity, in the range of 0.012–0.020 W/mK (see Fig. 2, right), some of the lowest values known, however also have excellent fire resistance (Fig. 2, left), are (as monoliths) excellent vapor barriers, have excellent resistance to direct sunlight, have a high service temperature, excellent durability, excellent sound resistance, and may also serve as effective infiltration barriers (Cuce et al. 2014). Thus, in most ways, aerogels outperform other conventional insulation materials and most other currently existing advanced insulation materials. While aerogel insulation materials are currently available commercially, the barrier to

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[1] Note—LCA-based evidence was the predominant basis for formulation of conclusions and the highest available standards for quality of evidence were used.

uptake thus far is cost; however, use of aerogel insulation is increasing exponentially and cost may be usefully reduced as manufacturing and production improve and sales volumes increase.

Another characteristic of aerogels that holds promise for emerging applications relates to aerogel optical properties. Some silica aerogels have high transmittance of visible light, with, for instance, a 10-mm-thick panel having a transmittance of 88% overall (and transmittance largely attenuated in the ultraviolet or UV portion of the spectrum, Sadineni et al. 2011). It is expected that modifications in the composition of gels used in production of aerogels will enable tuning of optical properties in future. In addition to transmittance, greater control on the aerogel pore size might enable tuning of reflectance/scattering characteristics of aerogel insulation. Granular aerogel has been used inside the cavity of double-glazed windows and polycarbonate construction panels for windows that weigh less than 20% of the equivalent glass unit and have 200 times more impact strength (Baetens et al. 2011; Sadineni et al. 2011; Schiavoni et al. 2016). Such windows are increasingly used in both vertical and roof-lighting applications to supplement ambient lighting from windows.

Potential health hazards associated with aerogel-based insulation are largely associated with dust, much as with many other forms of insulation, and are amendable therefore to standard operational controls in handling and installation (Schiavoni et al. 2016). Solvents and energy used in production of aerogels are inherently environment-unfriendly, and probably because the commercial use of these materials is relatively new, there are few detailed sustainability metrics. Embodied energy has been investigated and one study found that, on a per weight basis, a number of conventional materials have lower embodied energy than silica aerogel (Schiavoni et al. 2016). On a per area basis, compared to EPS, XPS, glass wool, cork, foam glass, PUR and PIR, only glass wool had a lower embodied energy than silica aerogel. However, the most appropriate metric is instead the amount of material used to achieve a given level of insulation (akin to the functional unit in LCA) and on this basis aerogels require a factor of ~2–3 times less material (Schiavoni et al. 2016). Embodied energy is a relatively limited measure of sustainability, and hopefully more detailed analysis of environmental impacts will be forthcoming soon. With respect to aerogel glazing/window replacement, two LCA studies have been thus far been performed: one detailed, one streamlined, and both focusing on climate change as the primary impact category of interest (Dowson et al. 2012; Lolli and Andresen 2016). The detailed study found emissions savings of up to 9%, as compared to triple-glazing with argon gas. The streamlined study found that aerogel windows "paid" for themselves in CO_2-e emissions reduction after two years. Based on the information of environmental performance available thus far, future development of improved aerogels appears promising, but particularly in respect of the potential optical properties.

By definition, since a vacuum contains no atoms or molecules, thermal conduction and convection are not possible; ergo the thermal conductivity of a perfect and infinite vacuum is zero. This physical fact forms the basis for the development of vacuum insulation panels (VIPs), which are constructed of an evacuated, open-porous material that is enveloped into a multilayer film. The common core

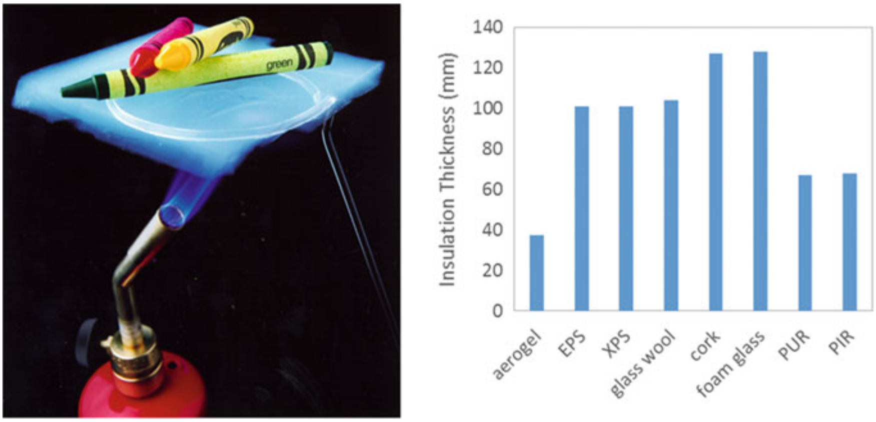

Fig. 2 Photograph of aerogel by courtesy of the US National Aeronautics and Space Administration (left) and comparison of the thickness of various materials needed to achieve a thermal insulation U-value of 0.3 W/m^{2}K (right) illustrating that the aerogel material is a far superior insulator to conventional insulation materials (data from Cuce et al. 2014). EPS, XPS, PUR, and PIR are expanded polystyrene, extruded polystyrene, polyurethane, and polyisocyanurate, respectively

material is fumed silica; however, aerogels, EPS and PUR, and fiberglass are also in use (Alotaibi and Riffat 2014). A vacuum is imposed on the voids of the core material, and thus, a barrier is required to preserve the integrity of the vacuum during handling, and VIPs are typically enclosed in one or more thicknesses of metal film. Getters or desiccants are also incorporated to absorb water vapor or other gases that might penetrate the barrier. In consequence of the need to preserve vacuum, VIP performance is dependent on the performance of each of its parts, both singly and integrated (Alotaibi and Riffat 2014; Kalnæs and Jelle 2014).

As might be expected in consequence of part of the VIP material being under vacuum, the thermal conductivity of VIPs is very low, on average some 17 times lower than that of conventional glass fiber batts (Baetens et al. 2010). The range of thermal conductivity for VIPs suitable for use in buildings has been cited to be 0.0035–0.008 W/mK, with VIPs suitable for use in appliances being even lower (Kalnæs and Jelle 2014). Thus, the thermal conductivity of VIPs is about half to a third that of aerogels, on average, and VIPs are generally recognized as having the overall best thermal performance of any single insulation material in commercial use for buildings (Alotaibi and Riffat 2014; Jelle 2011). This also conveys a simultaneous savings in space needed to accommodate insulation. On the negative side, one review describes VIPs as suffering from the four cardinal weaknesses of fragility, perforation vulnerability, increasing thermal conductivity during time and lack of building site adaption cutting (Jelle 2011). Additionally, this insulation technology is still relatively costly (Baetens et al. 2010; Jelle 2011).

VIPs have been sufficiently adopted for use in Switzerland and Germany that the Institute of Energy at the University of Applied Sciences, Basel, Switzerland, has conducted analysis of environmental performance to see whether more energy is used in production than is actually saved and what the life cycle disposition of ecological damage is (Schonhardt et al. 2003). In the Swiss study, one VIP material was compared with glass wool and EPS. Results indicate that the embodied energy in the VIP material was the greatest, with the embodied energy of EPS and glass wool being 90% and <50% of the VIP, respectively, for the same amount of insulation over a given area. In terms of ecological damage, the LCA result indicates glass wool is least environmentally damaging, followed by VIPs and EPS. Glass wool outperformed VIPs in most damage categories, including (in descending order of importance) respiration hazard, release of carcinogenic substances, climate change, and land use. Glass wool was also best for resource use, with VIPs being worst, with major VIP damage categories being (in descending order of importance) emissions to air, generation of radioactive waste, landfill waste, and emissions to water. Most of the ecological damage originates from energy use. Overall, while the attractive thermal conductivity of VIPs drives their current use, practical issues entail that development of alternatives, particularly in the area of nanomaterials, is an active area of research. The LCA results indicate that much of the environmental damage comes from energy use in production and raises the question of whether improvements in energy savings from improved building insulation should be substituted for increased energy use in production of improved building insulation.

The quest for new materials that will have the same or better thermal performance as VIPs, without the disadvantages of VIPs, continues apace. Examples of materials that have gained attention and research effort include vacuum insulation materials (VIMs), dynamic insulation materials (DIMs), and nano-insulation materials (NIMs) (Baetens et al. 2010; Jelle 2011). VIMs differ from VIPs in that the base material is homogeneous and has a closed pore structure, thus eliminating problems with punctures and being able to cut the material for use in construction. DIMs are materials that exhibit changing thermal conductivity in a dynamic and/or controllable fashion. This field might be regarded as exploratory. NIMs are based on nanomaterials, and the literature in this area is vast. One form of NIM that is of particular interest is photonic crystals. Photonic crystals consist of periodic nanostructures, the arrangement of which affects how light travels through them and enables blocking of specific kinds of radiation, including thermal or infrared radiation. Recently, a team of researchers at Stanford University found that 1 μm thick layers of such nanostructures separated by 90 μm gaps of vacuum would theoretically reduce the thermal conductance of the material to about half that of a pure vacuum across the same thickness (Lau et al. 2009). In theory, the ability to tailor the material characteristics would mean that, as well as blocking light, such material might be used to capture heat energy for solar-thermal applications. While research into this sort of material is in its infancy, at least one patent application has already been filed for the use of photonic crystals as thermal insulation (Sterzel et al. 2008).

While this area of materials science is no doubt exciting, both in terms of progress in fundamental knowledge and in the development of new and ever more exotic technologies, it is easy to become distracted from the eventual purpose.