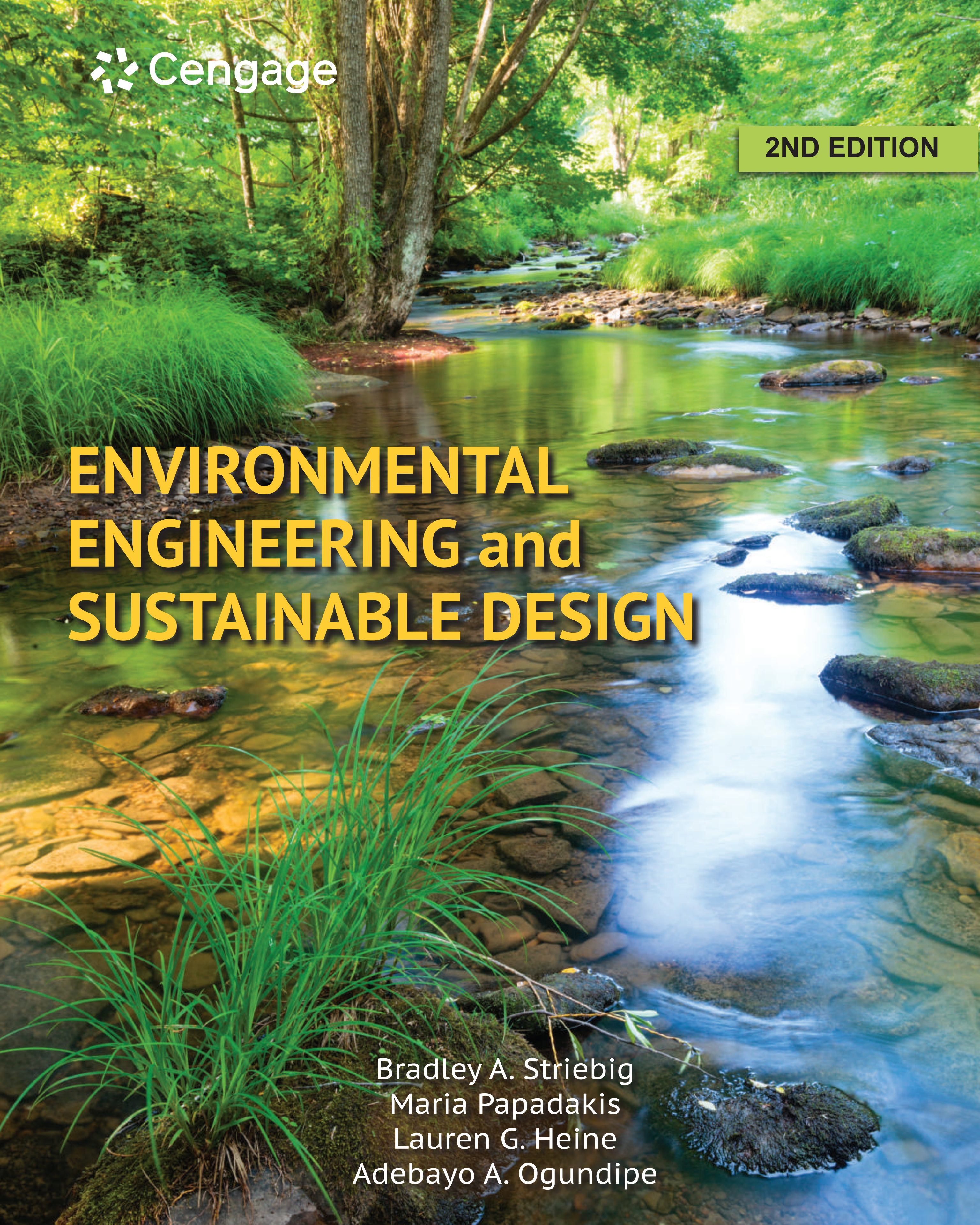

Cengage

2ND EDITION

ENVIRONMENTAL ENGINEERING and SUSTAINABLE DESIGN

Bradley A. Striebig
Maria Papadakis
Lauren G. Heine
Adebayo A. Ogundipe

- Atomic number
- Electron configuration
- Symbol
- Melting point [ºC]
- Boiling point [ºC]
- Atomic mass (mean relative)
- Oxidation states
- Name
- Density [g/cm^3], for gases [g/l] (0º C, 1013 mbar)
- Electronegativity
- Radioactive (*)

Example: 43 (98.91) / [Kr] $4d^{5}5s^{2}$ / 7 / Tc / Technetium / 2140 11.5 / 5030 * 1.9

Period	1 1A	2 2A	3 3A	4 4A	5 5A	6 6A	7 7A	8 8	9 8	10 8	11 1B	12 2B	13 3B	14 4B	15 5B	16 6B	17 7B	18 0
1	1 1.01 $1s$ 1, −1 **H** Hydrogen −259 0.09 −253 2.1																	2 4.00 $1s^{2}$ **He** Helium — 0.18 −269 —
2	3 6.94 [He] $2s$ 1 **Li** Lithium 181 0.53 1330 1.0	4 9.01 [He] $2s^{2}$ 2 **Be** Beryllium 1277 1.85 2970 1.5											5 10.81 [He] $2s^{2}2p$ 3 **B** Boron (2030) 2.35 2550 2.0	6 12.01 [He] $2s^{2}2p^{2}$ 4, 2, −4 **C** Carbon (3550) 2.2 4830 2.5	7 14.01 [He] $2s^{2}2p^{3}$ 5, 4, 3, 2, −3 **N** Nitrogen −210 1.25 −196 3.0	8 16.00 [He] $2s^{2}2p^{4}$ −2, −1 **O** Oxygen −219 1.43 −183 3.5	9 19.00 [He] $2s^{2}2p^{5}$ −1 **F** Fluorine −220 1.7 −188 4.0	10 20.18 [He] $2s^{2}2p^{6}$ **Ne** Neon −249 0.9 −246 —
3	11 22.99 [Ne] $3s$ 1 **Na** Sodium 98 0.97 892 0.9	12 24.31 [Ne] $3s^{2}$ 2 **Mg** Magnesium 650 1.74 1107 1.2											13 26.98 [Ne] $3s^{2}3p$ 3 **Al** Aluminum 660 2.70 2450 1.5	14 28.09 [Ne] $3s^{2}3p^{2}$ 4, −4 **Si** Silicon 1410 2.33 2680 1.8	15 30.97 [Ne] $3s^{2}3p^{3}$ 5, 3, −3 **P** Phosphorus 44 1.82 280 2.1	16 32.06 [Ne] $3s^{2}3p^{4}$ 6, 4, 2, −2 **S** Sulfur 119 2.07 445 2.5	17 35.45 [Ne] $3s^{2}3p^{5}$ 7, 5, 3, 1, −1 **Cl** Chlorine −101 3.2 −35 3.0	18 39.95 [Ne] $3s^{2}3p^{6}$ **Ar** Argon −189 1.78 −183 —
4	19 39.10 [Ar] $4s$ 1 **K** Potassium 64 0.86 760 0.8	20 40.08 [Ar] $4s^{2}$ 2 **Ca** Calcium 838 1.55 1440 1.0	21 44.96 [Ar] $3d\,4s^{2}$ 3 **Sc** Scandium 1539 3.0 2730 1.3	22 47.88 [Ar] $3d^{2}4s^{2}$ 4, 3 **Ti** Titanium 1668 4.54 3260 1.5	23 50.94 [Ar] $3d^{3}4s^{2}$ 5, 4, 3, 2, 0 **V** Vanadium 1900 6.1 3450 1.5	24 52.00 [Ar] $3d^{5}4s$ 6, 3, 2, 0 **Cr** Chromium 1875 7.19 2200 1.6	25 54.94 [Ar] $3d^{5}4s^{2}$ 7, 6, 4, 3, 2, 0, −1 **Mn** Manganese 1245 7.43 2097 1.5	26 55.85 [Ar] $3d^{6}4s^{2}$ 6, 3, 2, 0, −2 **Fe** Iron 1536 7.86 3000 1.8	27 58.93 [Ar] $3d^{7}4s^{2}$ 3, 2, 0, −1 **Co** Cobalt 1495 8.9 2900 1.9	28 58.70 [Ar] $3d^{8}4s^{2}$ 3, 2, 0 **Ni** Nickel 1453 8.9 2730 1.9	29 63.55 [Ar] $3d^{10}4s$ 2, 1 **Cu** Copper 1453 8.9 2730 1.9	30 65.38 [Ar] $3d^{10}4s^{2}$ 2 **Zn** Zinc 420 7.13 906 1.6	31 69.72 [Ar] $3d^{10}4s^{2}4p$ 3 **Ga** Gallium 30 5.91 2237 1.6	32 72.59 [Ar] $3d^{10}4s^{2}4p^{2}$ 4 **Ge** Germanium 937 5.32 2830 1.8	33 74.91 [Ar] $3d^{10}4s^{2}4p^{3}$ 5, 3, −3 **As** Arsenic Subl. 5.72 — 2.0	34 74.91 [Ar] $3d^{10}4s^{2}4p^{4}$ 6, 4, 2 **Se** Selenium 217 4.79 685 2.4	35 79.90 [Ar] $3d^{10}4s^{2}4p^{5}$ 7, 5, 3, 1, −1 **Br** Bromine −7 3.12 58 2.8	36 83.80 [Ar] $3d^{10}4s^{2}4p^{6}$ **Kr** Krypton −157 3.7 −152 —
5	37 85.47 [Kr] $5s$ 1 **Rb** Rubidium 39 1.53 688 0.8	38 87.62 [Kr] $5s^{2}$ 2 **Sr** Strontium 768 2.6 1380 1.0	39 88.91 [Kr] $4d\,5s^{2}$ 3 **Y** Yttrium 1509 4.47 2927 1.2	40 91.22 [Kr] $4d^{2}5s^{2}$ 4 **Zr** Zirconium 1852 6.49 3580 1.4	41 92.91 [Kr] $4d^{4}5s$ 5, 3 **Nb** Niobium 2468 8.57 4927 1.6	42 95.94 [Kr] $4d^{5}5s$ 6, 5, 4, 3, 2, 0 **Mo** Molybdenum 2610 10.2 5560 1.8	43 (98.91) [Kr] $4d^{5}5s^{2}$ 7 **Tc** Technetium 2140 11.5 5030 * 1.9	44 101.07 [Kr] $4d^{7}5s$ 8, 6, 4, 3, 2, 0, −2 **Ru** Ruthenium 2500 12.4 3900 2.2	45 102.91 [Kr] $4d^{8}5s$ 5, 4, 3, 1, 2, 0 **Rh** Rhodium 1966 12.4 3730 2.2	46 106.42 [Kr] $4d^{10}$ 4, 2, 0 **Pd** Palladium 1552 12.0 3140 2.2	47 107.87 [Kr] $4d^{10}5s$ 2, 1 **Ag** Silver 961 10.5 2210 1.9	48 112.41 [Kr] $4d^{10}5s^{2}$ 2 **Cd** Cadmium 321 8.65 765 1.7	49 114.82 [Kr] $4d^{10}5s^{2}5p$ 3 **In** Indium 156 7.31 2080 1.7	50 118.69 [Kr] $4d^{10}5s^{2}5p^{2}$ 4, 2 **Sn** Tin 232 7.30 2270 1.8	51 121.75 [Kr] $4d^{10}5s^{2}5p^{3}$ 5, 3, −3 **Sb** Antimony 631 6.69 1380 1.9	52 127.60 [Kr] $3d^{10}5s^{2}5p^{4}$ 6, 4, −2 **Te** Tellurium 450 6.24 990 2.1	53 126.90 [Kr] $4d^{10}5s^{2}5p^{5}$ 7, 5, 1, −1 **I** Iodine 114 4.94 183 2.5	54 131.29 [Kr] $4d^{10}5s^{2}5p^{6}$ **Xe** Xenon −112 5.89 −108 —
6	55 132.91 [Xe] $6s$ 1 **Cs** Cesium 29 1.90 690 0.7	56 137.33 [Xe] $6s^{2}$ 2 **Ba** Barium 714 3.76 1640 0.9	71 174.97 [Xe] $4f^{14}5d\,6s^{2}$ 3 **Lu** Lutetium 1652 9.84 3327 1.2	72 178.49 [Xe] $4f^{14}5d^{2}6s^{2}$ 4 **Hf** Hafnium 2222 13.31 5400 1.3	73 180.95 [Xe] $4f^{14}5d^{3}6s^{2}$ 5 **Ta** Tantalum 2996 16.5 5425 1.5	74 183.85 [Xe] $4f^{14}5d^{4}6s^{2}$ 6, 5, 4, 3, 2, 0 **W** Tungsten 3410 19.3 5930 1.7	75 186.21 [Xe] $4f^{14}5d^{5}6s^{2}$ 7, 6, 4, 2, −1 **Re** Rhenium 3180 21.0 5900 1.9	76 190.20 [Xe] $4f^{14}5d^{6}6s^{2}$ 8, 6, 4, 3, 2, 0, −2 **Os** Osmium 3050 22.6 5500 2.2	77 192.22 [Xe] $4f^{14}5d^{7}6s^{2}$ 6, 4, 3, 2, 1, 0, −1 **Ir** Iridium 2454 22.7 4500 2.2	78 195.08 [Xe] $4f^{14}5d^{9}6s^{2}$ 4, 2, 0 **Pt** Platinum 1769 21.4 3830 2.2	79 196.97 [Xe] $4f^{14}5d^{10}6s$ 3, 1 **Au** Gold 1063 19.3 2970 2.4	80 200.59 [Xe] $4f^{14}5d^{10}6s^{2}$ 2, 1 **Hg** Mercury −38 13.6 357 1.9	81 204.38 [Xe] $4f^{14}5d^{10}6s^{2}6p$ 3, 1 **Tl** Thallium 303 11.85 1457 1.8	82 207.20 [Xe] $4f^{14}5d^{10}6s^{2}6p^{2}$ 4, 2 **Pb** Lead 327 11.4 1725 1.9	83 208.98 [Xe] $4f^{14}5d^{10}6s^{2}6p^{3}$ 5, 3 **Bi** Bismuth 271 9.8 1560 1.9	84 (209) [Xe] $4f^{14}5d^{10}6s^{2}6p^{4}$ 6, 4, 2 **Po** Polonium 254 9.3 962 2.0	85 (210) [Xe] $4f^{14}5d^{10}6s^{2}6p^{5}$ 7, 5, 3, 1, −1 **At** Astatine (302) — 337 2.2	86 (222) [Xe] $4f^{14}5d^{10}6s^{2}6p^{6}$ **Rn** Radon (−71) 9.73 −62 —
7	87 (223.0) [Rn] $7s$ 1 **Fr** Francium (27) — 677 * 0.7	88 226.03 [Rn] $7s^{2}$ 1 **Ra** Radium 700 5.0 1140 * 0.9	103 (262.1) [Rn] $5f^{14}6d\,7s^{2}$ 3 **Lr** Lawrencium — — — * —	104 (261.1) [Rn] $5f^{14}6d^{2}7s^{2}$ **Rf** Rutherfordium — — — * —	105 (262.1) [Rn] $5f^{14}6d^{3}7s^{2}$ **Db** Dubnium — — — * —	106 (263.1) [Rn] $5f^{14}6d^{4}7s^{2}$ **Sg** Seaborgium — — — * —	107 (264.1) [Rn] $5f^{14}6d^{5}7s^{2}$ **Bh** Bohrium — — — * —	108 (265.1) [Rn] $5f^{14}6d^{6}7s^{2}$ **Hs** Hassium — — — * —	109 (268) [Rn] $5f^{14}6d^{7}7s^{2}$ **Mt** Meitnerium — — — * —	110 (269) [Rn] $5f^{14}6d^{8}7s^{2}$ **Uun** — — — * —	111 (272) [Rn] $5f^{14}6d^{10}7s^{2}$ **Uuu** — — — * —	112 (277) **Uub** — — — * —		114 (289) **Uuq** — — — * —		116 (289) **Uuh** — — — * —		118 (293) **Uuo** — — — * —

6 Lanthanoids	57 138.91 [Xe] $5d\,6s^{2}$ 3 **La** Lanthanum 920 6.17 3470 1.1	58 140.12 [Xe] $4f\,5d\,6s^{2}$ 4, 3 **Ce** Cerium 795 6.67 3468 1.1	59 140.91 [Xe] $4f^{3}6s^{2}$ 4, 3 **Pr** Praseodymium 935 6.77 3127 1.1	60 144.24 [Xe] $4f^{4}6s^{2}$ 3 **Nd** Neodymium 1024 7.00 3027 1.2	61 (145) [Xe] $4f^{5}6s^{2}$ 3 **Pm** Prometheum (1027) 7.22 2460 * —	62 150.36 [Xe] $4f^{6}6s^{2}$ 3, 2 **Sm** Samarium 1072 7.54 1790 1.2	63 151.96 [Xe] $4f^{7}6s^{2}$ 3, 2 **Eu** Europium 828 5.26 1439 —	64 157.25 [Xe] $4f^{7}5d\,6s^{2}$ 3 **Gd** Gadolinium 1312 7.89 3000 1.1	65 158.93 [Xe] $4f^{9}6s^{2}$ 4, 3 **Tb** Terbium 1356 8.27 2800 1.2	66 162.50 [Xe] $4f^{10}6s^{2}$ 3 **Dy** Dysprosium 1407 8.54 2600 —	67 164.93 [Xe] $4f^{11}6s^{2}$ 3 **Ho** Holmium 1461 8.80 2600 1.2	68 167.26 [Xe] $4f^{12}6s^{2}$ 3 **Er** Erbium 1497 9.05 2900 1.2	69 168.93 [Xe] $4f^{13}6s^{2}$ 3, 2 **Tm** Thulium 1545 9.33 1727 1.2	70 173.04 [Xe] $4f^{14}6s^{2}$ 3, 2 **Yb** Ytterbium 824 6.98 1196 1.1
7 Actinoids	89 (227) [Rn] $6d\,7s^{2}$ 3 **Ac** Actinium 1050 10.1 — * 1.1	90 232.04 [Rn] $6d^{2}7s^{2}$ 4 **Th** Thorium 1750 11.7 3850 * 1.3	91 231.04 [Rn] $5f^{2}6d\,7s^{2}$ 5, 4 **Pa** Protactinium (1230) 15.4 — * 1.4	92 238.03 [Rn] $5f^{3}6d\,7s^{2}$ 6, 5, 4, 3 **U** Uranium 1132 19.07 3818 * 1.4	93 (237.05) [Rn] $5f^{4}6d\,7s^{2}$ 6, 5, 4, 3 **Np** Neptunium 637 19.5 3900 * 1.3	94 (244) [Rn] $5f^{6}7s^{2}$ 6, 5, 4, 3 **Pu** Plutonium 640 19.81 3235 * 1.3	95 (243) [Rn] $5f^{7}7s^{2}$ 6, 5, 4, 3 **Am** Americium 994 13.7 — * 1.3	96 (247) [Rn] $5f^{7}6d\,7s^{2}$ 4, 3 **Cm** Curium (1340) 13.51 3100 * —	97 (247) [Rn] $5f^{9}7s^{2}$ 4, 3 **Bk** Berkelium — — — * —	98 (251) [Rn] $5f^{10}7s^{2}$ 4, 3 **Cf** Californium — — — * —	99 (254) [Rn] $5f^{11}7s^{2}$ 3 **Es** Einsteinium — — — * —	100 (257) [Rn] $5f^{12}7s^{2}$ 3 **Fm** Fermium — — — * —	101 (258) [Rn] $5f^{13}7s^{2}$ 3 **Md** Mendelevium — — — * —	102 (259) [Rn] $5f^{14}7s^{2}$ 3, 2 **No** Nobelium — — — * —

Environmental Engineering and Sustainable Design

SECOND EDITION

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***Environmental Engineering and Sustainable Design,* Second Edition**

Bradley A. Striebig, Maria Papadakis, Lauren G. Heine, and Adebayo A. Ogundipe

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For Echo and Zachary

—Bradley A. Striebig

In memory of Pete Papadakis

—Maria Papadakis

In memory of P. Aarne Vesilind

—Lauren G. Heine

To all my Teachers

—Adebayo A. Ogundipe

Contents

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CHAPTER 8 Wastewater Treatment 514

Preface

Environmental Engineering and Sustainable Design, Second Edition is an invaluable resource for today's engineering and applied environmental science students. As engineering curriculum becomes more crowded, challenges arise in addressing the new paradigm of engineering in a resource-limited environment and adapting design to a new climactic condition. The authors have developed a comprehensive text that provides foundational knowledge and traditional engineering skills while also integrating our present understanding of resource consumption and climate issues into this new edition. This curriculum is focused upon applying engineering principles to real-world design and problem analysis. It includes specific step-by-step examples and case studies for solving complex conceptual and design problems related to sustainable design and engineering. This textbook also applies the principles of sustainable design to issues in both developed and developing countries. Instructors will benefit from having this updated best seller to bring sustainability science, environmental impact analysis, and models of sustainability to the undergraduate and graduate level.

Sustainability is important in manufacturing, construction, planning, and design. Allenby et al. state that: "Sustainable engineering is a conceptual and practical challenge to all engineering disciplines." The teaching of sustainability has sometimes been pigeonholed into graduate level courses in Industrial Ecology or Green Engineering. Environmental engineering and chemical engineering textbooks may cover some basic concepts of sustainability, but the extent and breadth of knowledge is insufficient to meet the multifaceted demand required to engineer sustainable processes and products.

Dr. John Crittenden, 2002, suggests that sustainable solutions include the following important elements/steps: (a) translating and understanding societal needs into engineering solutions such as infrastructures, products, practices, and processes; (b) explaining to society the long-term consequences of these engineering solutions; and (c) educating the next generation of scientists and engineers to acquire both the depth and breadth of skills necessary to address the important physical and behavioral science elements of environmental problems and to develop and use integrative analysis methods to identify and design sustainable products and systems.

New to the Second Edition

The Second Edition has been expanded to appeal to traditional foundational environmental engineering courses.

The content has been organized into three key sections:

- Part I: Environmental and Sustainability Science Principles
- Part II: Engineering Environmental and Sustainable Processes
- Part III: Designing Resilient and Sustainable Systems

Significant content from this textbook is adapted from *Introduction to Environmental Engineering,* Third Edition by P. Aarne Vesilind, Susan M. Morgan, and Lauren G. Heine. This content expands the use of the textbook to traditionally taught environmental engineering courses. This text is also used in courses focused on sustainable design and engineering, and this update provides content that is suitable to teaching a course on climate adaptation and resilience, as illustrated in Table P.1.

Topics new or significantly expanded in this edition include:

- Chapter 4: Material Flow and Processes in Engineering
- Chapter 5: Natural Resources, Materials, and Sustainability
- Chapter 6: Hazardous Substances and Risk Assessment
- Chapter 8: Wastewater Treatment
- Chapter 11: Energy Conservation, Development, and Decarbonization
- Chapter 12: Designing for Sustainability
- Chapter 15: Assessing Alternatives

New homework problems have been added and integrated into this textbook. Each chapter includes both qualitative and quantitative problems that cover a range of difficulty and complexity. Additional Active Learning Exercises have been added, with a focus on peer-to-peer learning activities to stimulate discussion, including the incorporation of climate and energy simulations for group role playing activities.

Organization and Potential Syllabus Topics

Sustainability is most often covered in existing environmental engineering courses; however, these courses are typically limited to civil and environmental engineering majors. Introductory environmental engineering courses often have objectives focused more upon historical perspectives in remediation and large-scale treatment systems than upon forward-looking sustainability concepts. Students will benefit from having methods for quantifying sustainability through environmental impacts, case studies, Life Cycle Analysis (LCA) models, and best practices. Case studies and active learning exercises make the learning experience real-world and hands-on. This title is the first to bring sustainability science, environmental impact analysis, and models of sustainability to the undergraduate level. Prerequisites for such a course are the foundational courses in calculus, chemistry, and physics.

Environmental Engineering and Sustainable Design, Second Edition is clearly arranged in three parts. *Part I: Environmental and Sustainability Science Principles* includes foundational content in the physical and social sciences that describe sustainability. *Part II: Engineering Environmental and Sustainable Processes* describes processes that relate to understanding and creating more sustainable systems for water development, air quality, climate adaptation, and energy development. *Part III: Designing Resilient and Sustainable Systems* addresses new tools and models that can be used in the design of products and infrastructure to create systems adapted to living in a resource-limited world that requires more sustainable approaches to the lifestyle of the developed world's nations. Suggested topics for courses are shown in Table P.1.

TABLE P.1 Suggested topics for courses in environmental engineering, sustainable design and engineering, and climate adaptation and resilience. New or reorganized chapters are bolded

CHAPTER	ENVIRONMENTAL ENGINEERING	SUSTAINABLE DESIGN AND ENGINEERING	CLIMATE ADAPTATION AND RESILIENCE
PART I: ENVIRONMENTAL AND SUSTAINABILITY SCIENCE PRINCIPLES			
Ch. 1 Sustainability, Engineering, and Design	X	X	X
Ch. 2 Analyzing Sustainability Using Engineering Science	X		X
Ch. 3 Biogeochemical Cycles	X		X
Ch. 4 Material Flow and Processes in Engineering	X		
Ch. 5 Natural Resources, Materials, and Sustainability	X	X	X
Ch. 6 Hazardous Substances and Risk Assessment	X		
PART II: ENGINEERING ENVIRONMENTAL AND SUSTAINABLE PROCESSES			
Ch. 7 Water Quality Impacts	X		
Ch. 8 Wastewater Treatment	X		
Ch. 9 Impacts on Air Quality	X		
Ch. 10 The Carbon Cycle and Energy Balances	X	X	X
Ch. 11 Energy Conservation, Development, and Decarbonization		X	X
PART III: DESIGNING RESILIENT AND SUSTAINABLE SYSTEMS			
Ch. 12 Designing for Sustainability		X	X
Ch. 13 Industrial Ecology		X	
Ch. 14 Life Cycle Analysis		X	
Ch. 15 Assessing Alternatives		X	X
Ch. 16 Sustainability and the Built Environment		X	X
Ch. 17 Challenges and Opportunities for Sustainability in Practice		X	X

Supplements

Additional instructor resources for this product are available online. Instructor assets include a Solution Answer Guide, Image Library, and PowerPoint® slides. Sign up or sign in at www.cengage.com to search for and access this product and its online resources.

Acknowledgments

The authors are grateful to their colleagues and students for their contributions to the development of this textbook. Although there are too many contributors to name, a few deserve special mention. Professor P. Aarne Vesilind was an inspiration for much of the content of this textbook. Professor Vesilind's devotion to the ethical uses of engineering skills to improve the human condition were foundational for many of his students, colleagues, and peers, and his lifelong works and words are influential in this edition of *Environmental Engineering and Sustainable Design.*

Dr. Striebig would like to thank two mentors, Dr. Raymond Regan and Dr. Robert J. Heinsohn, for encouragement throughout his career and with the development of this curriculum and textbook. He would like to acknowledge the support of his parents Janet and Ronald for making education a priority. Dr. Striebig is also indebted to his children, Echo and Zachary, who are a constant inspiration for the hope and potential of future generations.

Dr. Papadakis owes her love of technology to her father, Pete Papadakis, a career-long experimental stress and design engineer. Tom Walls, Robert Zetzl, Gladys Good, and Donald Clodfelter had a bigger impact than they could possibly know, and innately understood the needs of K-12 girls in STEM decades before this issue came to national prominence. She would like to thank her husband Fred Copithorn for his steady presence and love of the Earth, and her mother Iris Joseph continues to be a profound role model.

Dr. Heine was a graduate student of P. Aarne Vesilind and is profoundly grateful for his mentorship and love of teaching. Lauren is grateful to her parents Arthur and Sherry Glass for their support and for showing her how environmental engineering is integral to our daily lives. She would like to thank her husband Carl, and Hani and Cooper for their love and support; as well as dear friend and chemist Laura Gray for helping to ensure that the problems and active learning exercises are engaging and challenging. She would also like to thank Chem*FORWARD* friend and co-founder, Stacy Glass, for her vision and for valuing educational endeavors.

Dr. Ogundipe will be forever indebted to Dr. Washington Braida; a terrific teacher and friend who inspired him and pointed him in the right direction. He would also like to thank Tola, Safiyyah, Haneef, and Sumayyah for being the reason.

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Professor Striebig earned his Ph.D. from Pennsylvania State University. He has served as editor on major journals in his subject area. He has led major, funded, award-winning research activities focused on working with developing communities and natural treatment systems. He has written over 100 publications, including several book chapters, numerous peer-reviewed journal articles, and many peer-reviewed conference presentations and proceedings.

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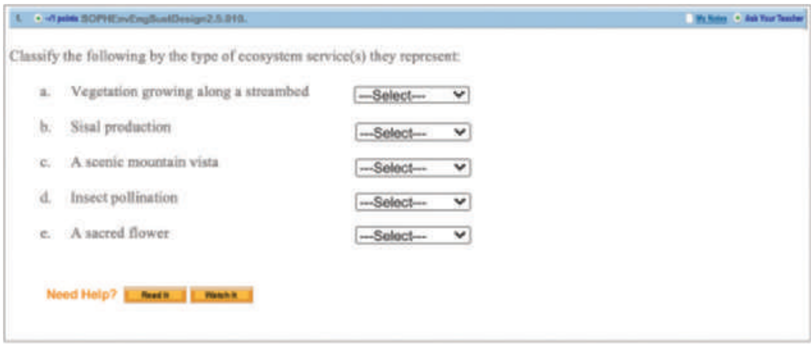

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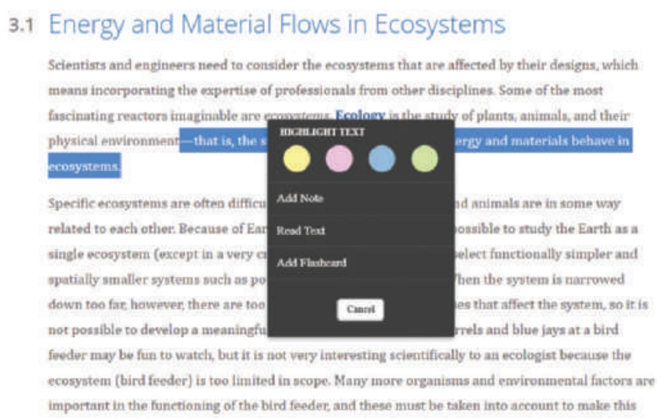

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PART 1

Environmental and Sustainability Science Principles

CONTENTS

CHAPTER 1

Sustainability, Engineering, and Design

FIGURE 1.1 A high-resolution photo of our planet showing various ecosystems and weather patterns. Many believe the first images of Earth taken from space had a profound effect on how people in general perceived the interconnectedness between people, the planet, and future prosperity.

Source: NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group. Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

It is known that there are an infinite number of worlds, simply because there is an infinite amount of space for them to be in. However, not every one of them is inhabited. Any finite number divided by infinity is as near nothing as makes no odds, so the average population of all the planets in the Universe can be said to be zero. From this it follows that the population of the whole Universe is also zero, and that any people you may meet from time to time are merely products of a deranged imagination.

—Douglas Adams, from *The Restaurant at the End of the Universe* (1980, p. 142)

GOALS

The educational goals of this chapter are to define sustainability and understand how social norms influence discussions about sustainability. We also examine how population changes and resource consumption have created the need for engineers, economists, scientists, and policymakers to consider sustainability in the design of products, infrastructure, and systems. The key concepts that are used to quantitatively consider sustainable design include the human development index, population growth models, and the ecological footprints analysis. This chapter also provides a greater context for the social and economic factors that shape successful design. In this chapter, we explore the ethical basis of human-centered design as a way of meeting the essential needs of people, which is an explicit element of sustainable development. In addition, we explain the dynamics of the adoption and diffusion of innovations, which is a critical prerequisite to the widespread social impact of more sustainable practices, products, and processes. Finally, we address the economic concepts that help us understand why achieving greater environmental sustainability can be a challenge and the role of governmental policymaking in surmounting those obstacles.

OBJECTIVES

At the conclusion of this chapter, you should be able to:

1.1 Calculate and relate the Human Development Index to indices for lifespan, education, and income.

1.2 Discuss ethical frameworks and engineering ethics in relation to sustainability.

1.3 Explain the different ethical principles that inform sustainable development, and discuss how these affect engineering design.

1.4 Give examples of successful and unsuccessful technologies appropriate for meeting the essential needs of people, and explain the reasons for their success or failure.

1.5 Define and discuss different definitions of sustainability, sustainable design, and sustainable development.

1.6 Evaluate global trends in population and describe how those trends challenge engineers to develop sustainable products, infrastructure, and systems.

1.7 Define and evaluate the carrying capacity of systems of various scales.

1.8 Define and discuss quantitatively the indicators of sustainable design, including the ecological footprint and the impact, population, affluence, and technology (IPAT) equation.

1.9 For a given innovation, summarize and analyze the social, cultural, technical, and economic factors that affect its potential impacts.

Introduction

Genetically modern humans appeared on Earth about 200,000 years ago, and biologically and behaviorally modern humans appeared about 70,000 years ago. The number of people and their effects on the planet were negligible for most of the history of the planet (Figure 1.2).

The number of humans on the planet remained very small until a few hundred years ago when advances in farming, energy, and mechanization took place, allowing the human population to increase exponentially (see Figure 1.3). Rapid changes in technology allowed humans to live longer; the decreasing death rates contributed to the high rate of human population growth over the past thousand years. Some time shortly after the year 1800, the world population reached 1 billion people for the first time (UN, 1999).

Demographers, people who study trends in population, say we are likely heading toward a world population of 9.5 to 12.5 billion over the next century (UN, 2019). While the human population on the planet is growing, natural resources that we have relied on for food, energy, and water are shrinking owing to the increasing human consumption of those resources. The human species has had a profound environmental impact on the planet, threatening the Earth's biodiversity, climate, energy resources, and water supply.

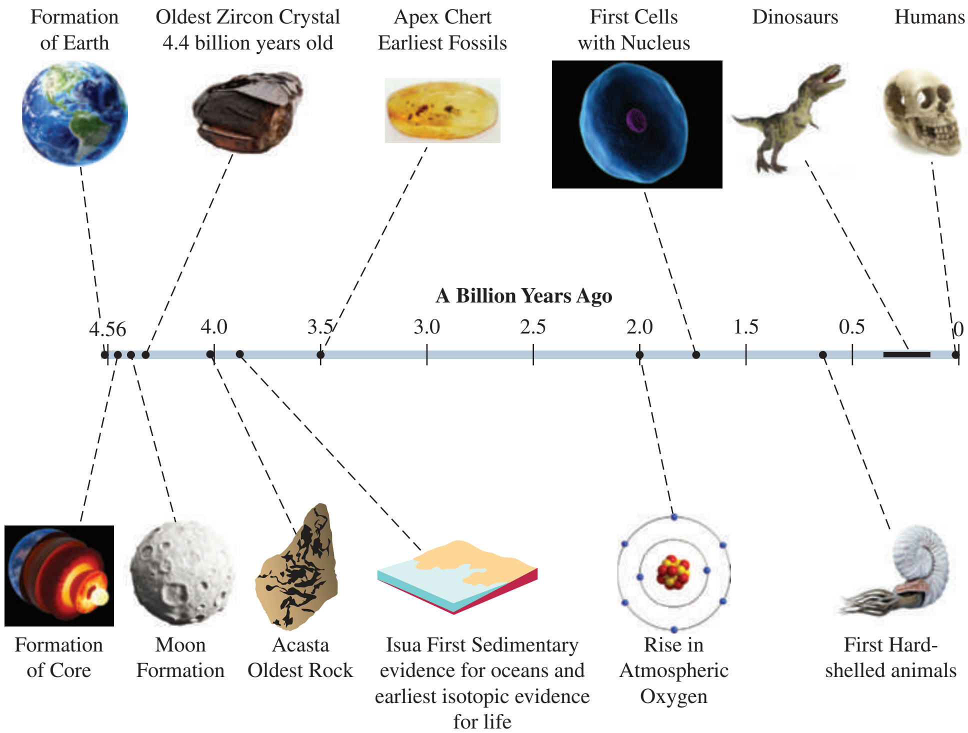

FIGURE 1.2 A timeline of planetary history showing the relatively short time humans have existed on Earth compared to the entirety of the history of Earth.

Source: Based on www.geology.wisc.edu/zircon/Earliest%20Piece/Images/28.jpg; leonello calvetti/Shutterstock.com; Johan Swanepoel/Shutterstock.com; Ortodox/Shutterstock.com; Imfoto/Shutterstock.com; falk/Shutterstock.com; oorka/Shutterstock.com; Sebastian Kaulitzki/Shutterstock.com; Number001/Shutterstock.com; DM7/Shutterstock.com; Empiric7/Shutterstock.com; SciePro/Shutterstock.com.

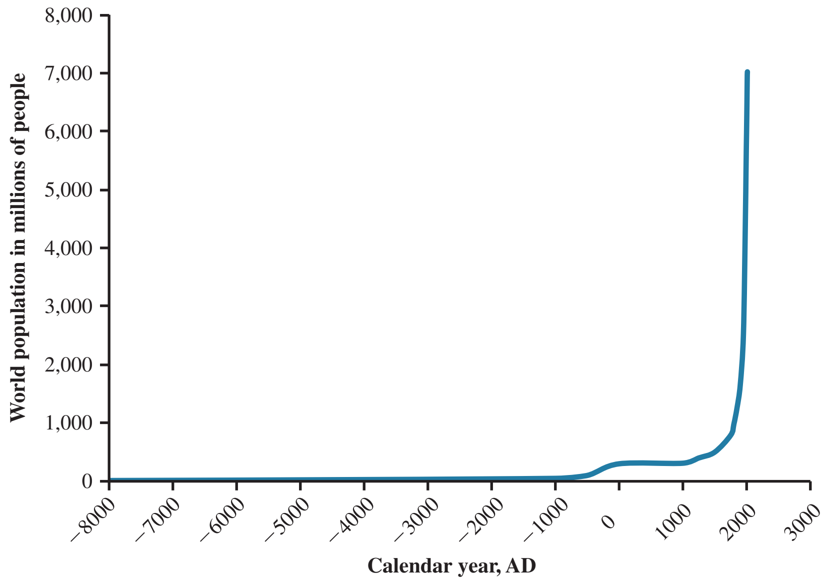

FIGURE 1.3 Historic estimates of human population from pre-history until 2011.

Source: Based on Kremer, M. (1993). "Population Growth and Technological Change: One Million B.C. to 1990." *The Quarterly Journal of Economics* 108(3): 681–716. AD 0–1990: United Nations Population Division Report, *The World at Six Billion. AD 1995–2012*: U.S. Census Bureau Data: *The World Population Clock*.

In the industrialized world, many people move faster, eat more, know more, and live in larger homes than even royalty could have dreamed of only a few centuries ago. Yet despite the great advances in science, technology, government, economics, education, and medicine over the past hundred years, these resources are not distributed equally on the planet. Economic, scientific, and technological advances have increased the lifespan and improved access to many marvelous things in the industrialized world, but this overall increase in the standard of living has failed to raise many people out of poverty. The standard of living relates income, comfort, and material goods to the socioeconomic classification of people. Scientists and engineers have played a key role in increasing both the average human life span and standard of living through applications of energy development and distribution, water treatment, sanitation, and other technological advances. As we will see later in this chapter, those who have not benefited from modern science, technology, and industrialization may not be able to meet their basic needs for food, clothing, shelter, water, and sanitation.

ACTIVE LEARNING EXERCISE 1.1 **Preconceptions about Sustainability**

Define "sustainability" in your own words to the best of your ability. Sketch a visualization of your definition using a cartoon or mind map. Show the linkages to things you perceive are related to sustainability on your sketch. Share your sketch with peers, and listen to how your peers think your sketch illustrates concepts of sustainability.

1.1 Human Development Index

The United Nations Development Programme (UNDP) devised a ***Human Development Index (HDI)*** that is based on three dimensions: life expectancy, education, and income. These dimensions are combined into a single comparable value, as illustrated in Figure 1.4 (UN, 2011a). The HDI is calculated using the data reported each year by the United Nations and the following equations (1.1) to (1.6.)

Life expectancy (LE) at birth uses the 2018 Life Expectancy Index:

$$\text{Life Expectancy Index (LEI)} = (\text{LE} - 20)/(85 - 20) \tag{1.1}$$

The Education Index (EI) is based on the Mean Years of Schooling Index (MYSI) and Expected Years of Schooling Index (EYSI), where

$$\text{MYSI} = \text{mean years of schooling}/15 \tag{1.2}$$

$$\text{EYSI} = \text{expected years of schooling}/18 \tag{1.3}$$

$$\text{EI} = (\text{MYSI} + \text{EYSI})/2 \tag{1.4}$$

The Income Index (II) is based on the gross national income (GNI_{pc}) at purchasing power parity (PPP) per capita, which is an estimate and standardization of each individual's income in a country:

$$\text{II} = \{\ln(\text{GNI}_{pc}) - \ln(100)\}/\{\ln(75{,}000) - \ln(100)\} \tag{1.5}$$

The Human Development Index is determined from the geometric mean of the Life Expectancy Index, the Education Index, and the Income Index:

$$\text{HDI} = (\text{LEI} \times \text{EI} \times \text{II})^{1/3} \tag{1.6}$$

Based on this index, the United Nations categorizes countries as Very High Human Development ($\text{HDI} \geq 0.800$), High Human Development ($0.800 > \text{HDI} \geq 0.700$), Medium Human Development ($0.700 > \text{HDI} \geq 0.550$), and Low Human Development ($\text{HDI} < 0.550$).

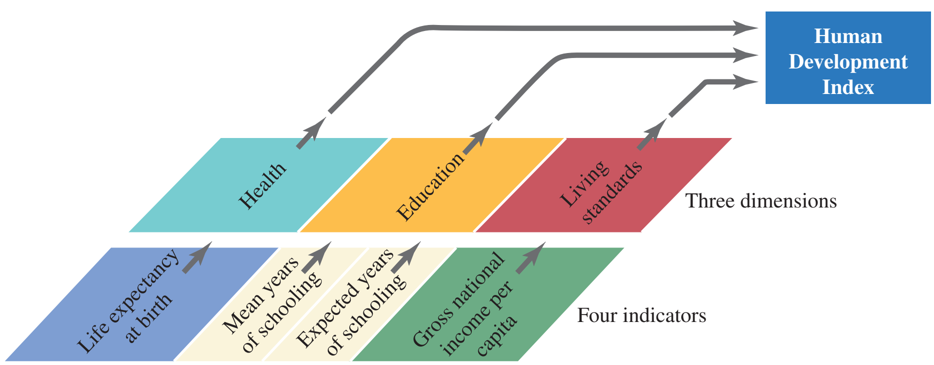

FIGURE 1.4 Components of the Human Development Index.

Source: Based on *Human Development Report 2011*. Sustainability and Equity: A Better Future for All. United Nations Development Programme.

EXAMPLE 1.1 Calculating the Human Development Index

Calculate the Human Development Index for the selected countries from 2018 data.

TABLE 1.1 Component values of the Human Development Index for selected countries

COUNTRY	LIFE EXPECTANCY AT BIRTH (YEARS)	EXPECTED YEARS OF SCHOOLING (YEARS)	MEAN YEARS OF SCHOOLING (YEARS)	GROSS NATIONAL INCOME (GNI) PER CAPITA (2011 PPI $)
Benin	60.2	12.6	3.6	2,061
Costa Rica	80.0	15.4	8.8	14,636
India	68.8	12.3	6.4	6,353
Jordan	74.5	13.1	10.4	8,288
Norway	82.3	17.9	12.6	68,012
United States	79.5	16.5	13.4	54,941

Source: Based on the *Human Development Report 2019*. Beyond income, beyond averages, beyond today: Inequalities in human development in the 21st century. New York. ISBN: 978-92-1-126439-5.

For Benin, the Life Expectancy Index can be calculated using Equation (1.1) from the life expectancy at birth:

$$(LEI) = (LE - 20)/(85 - 20)$$

$$= (60.2 - 20)/65$$

$$= 0.618$$

In order to calculate the Education Index, we first need to calculate the Mean Years of Schooling Index (MYSI) and the Expected Years of Schooling Index (EYSI) from Equations (1.2) and (1.3), respectively:

$$MYSI = \text{mean years of schooling}/15$$

$$= 3.6/15 = 0.240$$

$$EYSI = \text{expected years of schooling}/18$$

$$= 12.6/18 = 0.700$$

Substituting into the equation for the education index yields

$$EI = (MYSI + EYSI)/2$$

$$= (0.240 + 0.70)/2 = 0.470$$

We can calculate the Income Index (II) from the gross national income (GNI_{pc}) at purchasing power parity per capita using Equation (1.5):

$$II = \{\ln(GNI_{pc}) - \ln(100)\}/\{\ln(75{,}000) - \ln(100)\}$$

$$= \{\ln(2{,}061) - \ln(100)\}/\{\ln(75{,}000) - \ln(100)\} = 0.457$$