
Contents

Preface	xv
Inam UL HAQ, Sanna Mehraj KAK, Anand Kumar GUPTA and Muhammad Sher RAMZAN	
Chapter 1. Introduction to Sustainable Energy Systems	1
Inam UL HAQ	
1.1. Introduction.	1
1.2. Components of sustainable energy systems	4
1.2.1. Renewable energy sources	4
1.2.2. Energy storage	5
1.2.3. Smart grids.	6
1.2.4. Energy efficiency	6
1.3. Sustainability issues in energy.	7
1.3.1. Unpredictability of renewables.	7
1.3.2. Investment and infrastructure.	7
1.3.3. Policy and regulation.	8
1.3.4. Data and forecasting	8
1.4. AI in sustainable energy systems	8
1.4.1. AI techniques	10
1.5. Case studies and applications	11
1.5.1. Smart grid optimization	12
1.5.2. Renewable integration	12
1.5.3. Energy efficiency management.	12
1.5.4. Decision support systems	13
1.6. Future directions.	13
1.6.1. Explainable AI (XAI)	13
1.6.2. Digital energy systems twins	14

1.6.3. Circular economy integration	14
1.6.4. AI for energy equity	14
1.7. Conclusion	14
1.8. References	15

Chapter 2. Overview of AI, ML and DL Applications in Energy and Sustainability 17

Priya PANDEY, Ashish PANDEY and Hema MAHAWAR

2.1. Introduction.	17
2.1.1. Brief overview of AI, ML and DL technologies.	19
2.1.2. AI and its role in energy sustainability	20
2.1.3. ML and the fundamentals for proactive and adaptive networks	20
2.1.4. DL and its advanced energy efficiency with complex data modeling	21
2.1.5. Integrating AI, ML and DL for sustainable development	21
2.1.6. Motivation for AI, ML and DL adoption in energy and sustainability domains	22
2.1.7. Scope and objectives	23
2.2. Literature review.	25
2.3. Methodology	27
2.4. Challenges	30
2.5. Conclusion and future scope.	32
2.6. References	33

Chapter 3. Overview of AI, ML and DL Applications in Energy and Sustainability 37

Mrinal PANDEY and Monika GOYAL

3.1. Introduction.	37
3.2. Literature survey.	39
3.3. Brief description of AI, ML and DL	40
3.3.1. Relationship between AI, ML and DL	40
3.3.2. Steps in AI application development	42
3.4. Applications of AI in energy sectors and sustainability	42
3.4.1. Applications of ML (supervised learning) in the energy sector	44
3.4.2. Applications of ML (unsupervised learning) in the energy sector	44
3.4.3. Applications of DL in the energy sector	44

3.5. Case study	45
3.5.1. Methodology	45
3.5.2. Comparison of GRU with ensemble models	47
3.6. Conclusion	49
3.7. References	49

Chapter 4. Conceptual and Methodological Insights into AI, ML and DL for Energy and Environmental Challenges 51

Inderdeep KAUR

4.1. Introduction.	52
4.1.1. Background and motivation.	52
4.1.2. Energy and environmental challenges in the modern era.	53
4.1.3. Role of AI, ML and DL in sustainable development	54
4.1.4. Objectives and scope of the chapter	56
4.2. Conceptual foundations of AI, ML and DL	57
4.2.1. Evolution of AI	57
4.2.2. ML paradigms: supervised, unsupervised and reinforcement learning.	59
4.2.3. DL architectures: CNNs, RNNs, LSTMs and transformers	61
4.2.4. Comparison of traditional models versus DL approaches	62
4.3. Methodologies for environmental data acquisition.	64
4.3.1. Data sources: IoT, satellite imagery, UAVs and sensor networks.	64
4.3.2. Big data and cloud platforms for environmental analysis	65
4.3.3. Data preprocessing and feature engineering	66
4.3.4. Data quality, uncertainty and validation techniques.	67
4.4. AI-based predictive modeling for environmental challenges.	68
4.4.1. Climate change and temperature forecasting models	69
4.4.2. AI-based extreme event prediction (floods, heatwaves and cyclones)	70
4.4.3. Air quality and pollution level estimation	71
4.4.4. Water resource management and quality prediction	72
4.5. AI-driven energy system optimization	73
4.5.1. Renewable energy generation forecasting (solar and wind)	73
4.5.2. Energy demand and storage prediction models	74
4.5.3. Smart grid management and load optimization	75
4.5.4. AI-based energy trading and demand response systems	75
4.6. Smart agriculture and precision forestry.	76
4.6.1. Real-time anomaly detection in environmental data	77

4.7. Challenges and ethical considerations	78
4.7.1. Data availability and quality problems	78
4.7.2. Explainable AI and model transparency	79
4.7.3. Bias, fairness and environmental impact	80
4.8. Future directions and emerging trends	81
4.8.1. Autonomous environmental monitoring systems	81
4.8.2. Green AI and energy-efficient algorithms	82
4.8.3. AI for climate resilience and policy making	82
4.9. Conclusion	83
4.10. References.	84
Chapter 5. AI in Renewable Energy Technologies	89
Jagdeep KAUR, Vidhi GUPTA and Aditi RAJ	
5.1. Introduction to sustainable energy systems	89
5.1.1. Global energy crisis, climate change and sustainability principles	91
5.1.2. AI for environmental and energy challenges.	92
5.1.3. Overview of AI, ML and DL applications in energy and sustainability.	93
5.1.4. Conclusion.	94
5.2. Introduction to AI in renewable energy technologies	94
5.2.1. AI for forecasting solar energy and its optimization	95
5.3. Smart grids, IoT and AI for energy management.	99
5.3.1. Blockchain and AI for renewable energy trading	102
5.3.2. Big data analytics and predictive models in energy systems.	103
5.3.3. Integration challenges and future prospects	105
5.3.4. Conclusion.	106
5.4. Global policies and AI-enabled energy strategies	106
5.4.1. Economic models and financing sustainable energy	107
5.4.2. Case studies: developed nations and developing nations.	109
5.4.3. Community and microgrid-based AI applications.	110
5.4.4. Future trends in AI for renewable energy.	113
5.5. Future directions, pathways to net-zero: challenges, risks and future of AI in sustainable energy.	114
5.5.1. The global net-zero agenda	115
5.5.2. Role of AI in achieving net-zero	115
5.5.3. Issues and potential limitations.	116
5.5.4. Smarter energy: how the future could look.	117
5.6. Conclusion	118
5.7. References	119

Chapter 6. Big Data Analytics and Predictive Models in Energy Systems	121
Biswajit DAS, Himanshu PABBI, Shweta SINGH, Monika MEHRA and Sanny KUMAR	
6.1. Introduction.	121
6.2. Big data analytics in energy systems basics.	126
6.2.1. Big data.	127
6.3. Predictive modeling: concepts and techniques	131
6.3.1. Role of predictive analytics in energy systems	131
6.3.2. Types of predictive models	132
6.3.3. Model development process	134
6.3.4. Evaluation metrics	134
6.3.5. Challenges in predictive modeling.	135
6.3.6. Dataset description and experimental setup	135
6.4. Applications of big data analytics in energy systems	140
6.4.1. Demand forecasting	140
6.4.2. Renewable energy forecasting	141
6.4.3. Load management and demand response	141
6.4.4. Predictive maintenance and asset management	142
6.4.5. Smart grid optimization	142
6.4.6. Energy market analytics	143
6.5. Integration of IoT, Edge and cloud technologies.	144
6.5.1. Role of IoT in data collection.	144
6.5.2. Edge analytics for real-time processing.	145
6.5.3. Cloud computing for scalable storage and processing	145
6.5.4. Digital twins and simulation	146
6.5.5. Cybersecurity considerations	146
6.6. Case studies and real-world implementations.	147
6.6.1. Smart grid implementations.	147
6.6.2. Renewable energy forecasting projects	148
6.6.3. Predictive maintenance in power plants.	148
6.6.4. Demand response systems.	149
6.6.5. Energy market predictive analytics	149
6.7. Challenges, limitations and future directions	150
6.7.1. Data-related challenges	150
6.7.2. Technical challenges	151
6.7.3. Regulatory and policy issues	151
6.7.4. Future research directions	152
6.8. Conclusion	154
6.9. References	156

Chapter 7. Smart Grids, IoT and AI: Transforming Energy Management for a Sustainable Future	161
Khalid Hafiz MIR and Anzah BASHIR	
7.1. Introduction.	162
7.2. Ethical considerations.	164
7.2.1. Autonomy and informed consent.	165
7.2.2. Liable and responsible	166
7.2.3. Bias, fairness and equity.	168
7.2.4. Privacy and data security	170
7.3. Regulatory frameworks.	170
7.3.1. Current landscape.	170
7.3.2. Adaptive regulation.	171
7.3.3. Standardization and certification	172
7.4. Metrics for ethical and regulatory compliance	172
7.4.1. Risk assessment metrics	172
7.4.2. Explainability index	172
7.5. Future directions.	173
7.6. Conclusion	173
7.7. References	174
Chapter 8. Digital Twins and AI for Predictive Maintenance of Renewable Energy Assets	177
Abdul Malik ANSARI	
8.1. Introduction.	177
8.2. DTs in renewable energy	179
8.2.1. Digital twin	179
8.2.2. Architecture of a renewable energy DT.	179
8.2.3. AI for predictive maintenance	181
8.2.4. Adoption trends	182
8.3. System architecture of DT–AI integration.	183
8.3.1. Data acquisition layer	183
8.3.2. Communication layer	184
8.3.3. Data storage and processing layer	184
8.3.4. AI/ML modeling layer	184
8.3.5. DT simulation layer	185
8.3.6. Decision and maintenance layer	185
8.4. Integration of DTs and AI	185
8.4.1. The rationale for integration	185

8.4.2. Framework of integration	186
8.4.3. Applications of DT–AI integration in renewable energy.	188
8.5. Comparative analysis of maintenance strategies	192
8.6. Conclusion	194
8.7. References	194

Chapter 9. Digitally Enhanced Fire Alarm System Using Sensor Driven Arduino Implementation for Smart Energy Management 197

Ranjit Kumar BINDAL and Akhil NIGAM

9.1. Introduction.	198
9.2. Literature review.	198
9.3. Problem formulation	201
9.4. Constraints	202
9.4.1. Detection accuracy	202
9.4.2. Hardware compatibility	202
9.4.3. Data logging functionality.	202
9.4.4. Power consumption.	203
9.4.5. Response time.	203
9.5. Advantages of Arduino Uno over other types of Arduino modules	207
9.5.1. Lower cost	207
9.5.2. Energy efficient	207
9.5.3. Open-source interfacing	207
9.5.4. Providing awareness of more innovative approaches.	208
9.5.5. Hardware complexity	208
9.5.6. Compatibility with programming	208
9.5.7. Limited executing power	208
9.5.8. Small storage	208
9.5.9. Automated system	209
9.5.10. Robotics operation	209
9.5.11. Industry applications	209
9.5.12. Renewable energy sources.	209
9.5.13. Integration with IoT.	210
9.5.14. Healthcare and medical operation	210
9.6. Concluding remarks.	210
9.7. References	211

Chapter 10. AI and Blockchain for Renewable Energy Trading	215
Hitendra SINGH, Pradeep Kumar SHARMA, Deepti GUPTA, Fardeen Ahmad KHAN, Bandana KUMARI, Shivani SHARMA, Prashant KUMAR and Sanny KUMAR	
10.1. Introduction	215
10.1.1. The climate crisis and emissions reduction imperative	216
10.1.2. Global energy transition progress and momentum.	217
10.2. AI in renewable energy	218
10.2.1. Predicting energy production and consumption	218
10.2.2. Smart grid optimization	219
10.2.3. Predictive renewable infrastructure maintenance	219
10.2.4. Consumer-focused applications (EVs and smart homes).	219
10.2.5. Future prospects and challenges	220
10.3. Renewable energy with blockchain	220
10.3.1. P2P energy trading	221
10.3.2. Renewable energy certificates (RECs) and carbon credits	223
10.3.3. Decentralized microgrids	224
10.3.4. Supply chain visibility and equipment monitoring	225
10.4. AI–blockchain synergy	226
10.4.1. Intelligent decentralized energy systems	227
10.4.2. Stable grids and secure transactions	228
10.4.3. Prosumers and community energy markets.	228
10.5. Challenges and limitations in blockchain and AI-based renewable energy trading	230
10.5.1. Technical barriers: scalability and integration	230
10.5.2. Economic and financial limitations	231
10.5.3. Data privacy and security issues	231
10.5.4. Regulatory and policy issues	232
10.5.5. Conclusion	232
10.6. Future prospects	233
10.6.1. Decentralized autonomous energy markets powered by AI	233
10.6.2. IoT, 5G and smart cities integration – 5G smart cities	234
10.6.3. Paths to net-zero and carbon neutrality	235
10.7. Summary	236
10.8. References.	237

Chapter 11. Smart Energy Grids: Architecture, Security and Emerging Technologies	241
Dhruv GOEL, Pratham KUMAR, Mamta NARWARIA and Md Jauhar IMAM	
11.1. Introduction	241
11.1. Literature review/background	242
11.2.1. Evolution of smart grids	242
11.2.2. IoT in energy systems	243
11.2.3. Related work	243
11.2.4. Key standards and protocols	244
11.3. IoT-enabled smart energy grid framework (methodology)	245
11.3.1. Overview	245
11.3.2. System architecture	245
11.3.3. Sensing and data acquisition technologies	246
11.3.4. Communication technologies	246
11.3.5. Cloud and edge computing integration	246
11.3.6. Security framework	247
11.4. Results and discussion	248
11.4.1. Performance evaluation of IoT in smart grids	248
11.4.2. Real-time data analytics	248
11.4.3. Demand-side management	249
11.5. Security vulnerabilities and threat models	249
11.5.1. Threat landscape	249
11.5.2. Attack models	250
11.5.3. Security mitigation frameworks	251
11.5.4. U.S. Department of Energy Smart Grid Investment Grant (SGIG)	251
11.6. Challenges and future scope	252
11.6.1. Significant challenges	252
11.6.2. Role of advanced technologies	252
11.6.3. Future scope	253
11.7. Conclusion	254
11.8. References	255
 List of Authors	 257
 Index	 261

