

Green Energy and Technology

Sheng Wang
Hongxun Hui
Yi Ding
Yonghua Song



Hydrogen Integration in Energy Systems: Modeling, Optimization, and Reliability Evaluation

Ensuring a Reliable Net Zero Transition

Green Energy and Technology

Climate change, environmental impact and the limited natural resources urge scientific research and novel technical solutions. The monograph series Green Energy and Technology serves as a publishing platform for scientific and technological approaches to “green”—i.e. environmentally friendly and sustainable—technologies. While a focus lies on energy and power supply, it also covers “green” solutions in industrial engineering and engineering design. Green Energy and Technology addresses researchers, advanced students, technical consultants as well as decision makers in industries and politics. Hence, the level of presentation spans from instructional to highly technical.

Indexed in Scopus.

Indexed in Ei Compendex.

Sheng Wang · Hongxun Hui · Yi Ding ·
Yonghua Song

Hydrogen Integration in Energy Systems: Modeling, Optimization, and Reliability Evaluation

Ensuring a Reliable Net Zero Transition

Sheng Wang  School of Engineering Newcastle University Newcastle upon Tyne, UK

Yi Ding College of Electrical Engineering Zhejiang University Hangzhou, China

Hongxun Hui The State Key Laboratory of Internet of Things for Smart City (SKL-IOTSC) University of Macau Macao, China

Yonghua Song The State Key Laboratory of Internet of Things for Smart City (SKL-IOTSC) University of Macau Macao, China

ISSN 1865-3529
Green Energy and Technology
ISBN 978-3-032-07166-8
<https://doi.org/10.1007/978-3-032-07167-5>

ISSN 1865-3537 (electronic)
ISBN 978-3-032-07167-5 (eBook)

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2025

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

Preface

Global warming has been witnessed in the past few decades, caused by the emission of greenhouse gases, such as carbon dioxide, which not only affects the habitat of animals but also threatens the lives of mankind in modern societies. Around the world, resulting from the excessive consumption of fossil fuels, such as natural gas, the energy sector is the culprit behind carbon dioxide emissions and climate change. To achieve net-zero ambitions, energy systems worldwide urgently call for cleaner energy sources. Green hydrogen, produced through electrolysis facilities using surplus renewable energy generation, has emerged as a promising solution. However, because hydrogen shares distinctive properties with natural gas, many fundamental questions, including how to smoothly integrate hydrogen into the existing energy systems, how to operate such a new structured energy system, and what the systematic impact will be, remain unclear.

To bridge the research gap and ensure a net-zero energy transition, this book aims to develop new modelling, optimisation, and reliability evaluation approaches that support the transition of current energy systems to hydrogen-integrated energy systems (HI-ES). This book can potentially set the theoretical foundations for developing, more advanced control strategies and application scenarios for HI-ES, and inform policymakers through bespoke advice on hydrogen integration road maps. This book is organised as follows:

Chapter 1 introduces the motivation, basic concept, political environments, and ongoing demonstration projects of HI-ES, summarises the challenges we are facing, and presents the organisation of this book.

Chapter 2 develops the reliability modelling and evaluation frameworks of the generic integrated electricity-gas systems, which are the predecessor of HI-ES. First, reliability network equivalents are utilised to represent reliability models of gas-fired generating units, gas sources, power-to-gas facilities, and other conventional generating units. A contingency management scheme is then developed considering the coupling between electricity and gas systems based on an integrated electricity and gas optimal power flow technique. Finally, the time-sequential Monte Carlo simulation approach is used to model the chronological characteristics of the corresponding reliability network equivalents.

Chapter 3 proposes a coordinated optimisation framework for multi-energy systems and end-users to promote operational flexibility. First, we develop a multi-level self-scheduling framework for the demand side resources to comprehensively explore the flexibility potential. The constraints of gas flow dynamics are then formulated to ensure that the linepack in the energy systems can accommodate the fluctuating gas demand. The second-order cone (SOC) relaxation is adopted to convexify the nonlinearity in the motion equation of gas flow dynamics. Moreover, to tackle the overall mixed-integer SOC programming problem, we propose an enhanced Benders decomposition strategy by embedding the lift-and-project cutting plane method, and further, devise a novel solution procedure.

Chapter 4 tries to conceptualise the unique reliability trade-off effects in integrated energy systems, considering flexibility from both the demand side and the transmission system. Firstly, the flexibility of end-users and linepacks is explored based on the Energy Hub and gas flow dynamics models. Then, the reliability models of energy system components are developed using the discretised-time Markov process to characterise the temporal state evolution in the operational horizon. A look-ahead contingency management scheme is then proposed to minimise the electricity and gas load curtailments. Taking account of all the possible system states, the operational reliabilities of the energy system are evaluated using the time-sequential Monte Carlo simulation.

Chapter 5 develops the steady-state optimal energy flow model and tractable solution techniques for HI-ES based on the mathematical models developed in previous chapters. Firstly, we develop a novel optimal energy flow model of HI-ES, where the physical characteristics (e.g., specific gravity) of the gas mixtures are modelled as variables to reflect the impacts of alternative gas injections more accurately. Security indices are introduced to restrain the variation in gas composition. Then, convex optimisation techniques are tailored to transfer the original highly nonlinear and nonconvex optimisation problem into a tractable form. An advanced sequential programming procedure is proposed with self-adaptive convergence criteria to better balance the feasibility and convergence.

Chapter 6 further extends the optimal energy flow model and tractable solution techniques for HI-ES to the transient state analysis. First, a convex hull of the gas security range is derived from the Dutton method. Then, the multi-period optimal energy flow is proposed to mitigate the impacts of alternative gas injection on gas security over the entire operational period. Both the dynamics of gas composition and gas flow are modelled, which can accurately describe the travel of alternative gas concentrations in real-time. The dynamics in the gas mixture properties (e.g., specific gravity) are modelled as variables to fully reveal the impacts of time-varying gas compositions. To tackle the high non-convexities in the multi-period optimal energy flow problem, second-order-cone relaxation is well-tailored and first used in the case of varying gas compositions, making the motion equations and advective transport equations more tractable. An advanced second-order-cone sequential programming is devised to drive the relaxation tight more efficiently.

Chapter 7 proposes the long-term reliability evaluation method for HI-ES based on Chap. 5. First, new reliability indices are proposed to evaluate both gas adequacy and

gas interchangeability under uncertainties. Then, a multi-state reliability model of the pipeline is developed to characterise the corrosion evolution and hydrogen embrittlement in the long term. A contingency management scheme is devised to minimise load curtailments and gas interchangeability deviations under component failures. Moreover, several reformulation techniques are tailored to convexify the original two-stage mixed-integer nonlinear contingency management scheme optimisation problem. An analytical reliability evaluation method embedded with a system state reduction technique is designed to evaluate the long-term reliability of the HI-ES more efficiently.

Chapter 8 proposes a short-term reliability assessment approach for HI-ES based on Chap. 6. First, the multi-performance and multi-state universal generating functions are constructed to efficiently model the short-term reliability of the power-to-gas facility and the wind farm, respectively. Then, a reliability management universal generating functions operator is proposed to minimise both load shedding and gas security violations. A set of novel reliability indices is proposed to comprehensively assess the gas security violations under uncertain gas compositions. Moreover, an analytical short-term reliability assessment approach is proposed, where the state-based sequential approximation and state-based McCormick envelope techniques are tailored and embedded. By optimising the solution ordered by the system states, the nonconvexities in the reliability management optimisation problem can be handled tractably without increasing the computation burden.

Chapter 9 proposes a gas interchangeability resilience evaluation method for HIES. First, gas interchangeability resilience is defined by proposing several novel metrics. Then, A two-stage gas interchangeability management scheme is proposed to accommodate the hydrogen injections. The steady-state optimal electricity and hydrogen-gas energy flow technique is performed first to obtain the desired operating state of the H-IEGS. Then, the dynamic gas composition tracking is implemented to calculate the real-time travelling of hydrogen contents in the gas network and evaluate the time-varying gas interchangeability metrics. Moreover, to improve the computation efficiency, a self-adaptive linearization technique is proposed and embedded in the solution process of discretised partial derivative equations.

Chapter 10 presents the outlook for the future energy market framework for HIES considering heterogeneous gas compositions. First, we propose a joint market-clearing model, where the nonlinear physical properties of gas mixtures caused by varying gas compositions are characterised. The impacts of hydrogen blending on the carbon emission cost are also quantified. To retrieve the nodal energy price from this highly nonlinear and nonconvex optimisation problem, a successive second-order cone programming method is tailored to get the dual variables tractably. Considering the continuous market-clearing process, a warm-start technique is proposed to provide initial reference points for the successive second-order cone programming to improve the computation efficiency.

For reading this book, a basic knowledge of advanced mathematics (including linear algebra, calculus, probability theory, optimisation theory, etc.) and a basic knowledge of electricity/gas systems are required. This book focuses on the recently hot topics on net-zero energy systems. It may be of interest to those researchers,

engineers, and policymakers who are working on net-zero energy system design, planning, operation, economics, markets, and relevant policy making.

Newcastle upon Tyne, UK
November 2024

Sheng Wang

Acknowledgements Funding Information. The authors would like to acknowledge the financial support from the National Natural Science Foundation of China (52407075); the Science and Technology Development Fund, Macau SAR (File no. 001/2024/SKL and File no. 0117/2022/A3); the Guangdong Basic and Applied Basic Research Foundation (2023A1515110163), the State Key Laboratory of Power System Operation and Control (SKLD24KM11); the Chair Professor Research Grant of University of Macau (File no. CPG2025-00023-IOTSC), and Newcastle University Academic Track (NUAcT) Fellowship.

Copyrights. Parts of this book incorporate content from the following publications, all of which were authored/co-authored by the book contributors and have been reproduced with permission from the original publishers:

1. Wang, Sheng, Yi Ding, Chengjin Ye, Can Wan, and Yuchang Mo. “Reliability evaluation of integrated electricity—gas system utilizing network equivalent and integrated optimal power flow techniques.” *Journal of Modern Power Systems and Clean Energy* 7, no. 6 (2019): 1523–1535.
2. Wang, Sheng, Hongxun Hui, Yi Ding, and Junyi Zhai. “Decentralized demand response for energy hubs in integrated electricity and gas systems considering linepack flexibility.” *IEEE Internet of Things Journal* 11, no. 7 (2023): 11848–11861.
3. Wang, Sheng, Junyi Zhai, Hongxun Hui, Yi Ding, and Yonghua Song. “Operational reliability of integrated energy systems considering gas flow dynamics and demand-side flexibilities.” *IEEE Transactions on Industrial Informatics* 20, no. 2 (2023): 1360–1373.
4. Wang, Sheng, Junyi Zhai, and Hongxun Hui. “Optimal energy flow in integrated electricity and gas systems with injection of alternative gas.” *IEEE Transactions on Sustainable Energy* 14, no. 3 (2023): 1540–1557.
5. Wang, Sheng, Hongxun Hui, Tao Chen, and Junyi Zhai. “Multi-period operation of integrated electricity and gas systems with hydrogen blending considering gas composition dynamics.” *Applied Energy* 377 (2025): 124563.
6. Wang, Sheng, Hongxun Hui, Yi Ding, and Yonghua Song. “Long-term reliability evaluation of integrated electricity and gas systems considering distributed hydrogen injections.” *Applied Energy* 356 (2024): 122374.
7. Wang, Sheng, Hongxun Hui, and Junyi Zhai. “Short-term reliability assessment of integrated power-gas systems with hydrogen injections using universal generating function.” *IEEE Transactions on Industry Applications* 59, no. 5 (2023): 5760–5773.
8. Wang, Sheng, Hongxun Hui, and Pierluigi Siano. “Resilience of gas interchangeability in hydrogen-blended integrated electricity and gas systems: A transient approach with dynamic gas composition tracking.” *iEnergy* 2, no. 2 (2023): 143–154.
9. Wang, Sheng, Hongxun Hui, Junyi Zhai, and Pierluigi Siano. “Carbon-embedded nodal energy price in hydrogen-blended integrated electricity and gas systems

with heterogeneous gas compositions.” IEEE Transactions on Sustainable Energy (2024).

The authors gratefully acknowledge the respective publishers for granting permission to reuse these materials. These adaptations are made in accordance with the publishers’ reuse policies, and proper attribution has been maintained throughout.

Competing Interests The authors have no competing interests to declare that are relevant to the content of this manuscript.

Contents

| | | |
|----------|---|----|
| 1 | Introduction | 1 |
| 1.1 | Role of Hydrogen in Net Zero | 1 |
| 1.2 | Hydrogen Integration in Energy Systems | 4 |
| 1.3 | Political Environment | 7 |
| 1.3.1 | Europe | 7 |
| 1.3.2 | The US | 8 |
| 1.3.3 | China | 9 |
| 1.3.4 | Other Countries or Regions | 10 |
| 1.4 | Demonstration Projects | 10 |
| 1.4.1 | Europe | 10 |
| 1.4.2 | The US | 11 |
| 1.4.3 | China | 12 |
| 1.4.4 | Other Countries or Regions | 13 |
| 1.5 | Technical Challenges | 14 |
| 1.6 | Literature Reviews | 15 |
| 1.6.1 | Modelling of Traditional Energy Systems With Uniform Gas Composition | 15 |
| 1.6.2 | Modelling of HI-ES | 16 |
| 1.6.3 | Reliability Evaluation Methods | 19 |
| 1.7 | Summary | 21 |
| 1.8 | Organisation of This Book | 22 |
| | References | 23 |
| 2 | Reliability Modelling Framework of Energy Systems With Uniform Gas Composition | 31 |
| 2.1 | Introduction | 31 |
| 2.2 | Framework of IEGS | 32 |
| 2.3 | Reliability Network Equivalents | 33 |
| 2.3.1 | Reliability Network Equivalents for Gas-Fired Generating Units | 33 |

| | | |
|----------|---|-----------|
| 2.3.2 | Reliability Network Equivalents for Conventional Fossil Generating Units | 36 |
| 2.3.3 | Reliability Network Equivalents for Gas Sources | 37 |
| 2.3.4 | Reliability Network Equivalents for Power-to-Gas Facilities | 37 |
| 2.4 | Contingency Management Schema | 38 |
| 2.4.1 | Interruption Costs Considering Energy Substitution | 38 |
| 2.4.2 | IOPF-Based Contingency Management Schema for IEGS | 40 |
| 2.5 | Reliability Evaluation Procedures | 42 |
| 2.6 | Case Studies | 43 |
| 2.6.1 | Case 1: Reliability Impacts of Random Failures of Gas Sources | 43 |
| 2.6.2 | Case 2: Reliability Impacts of GFUs and PTGs | 47 |
| 2.6.3 | Case 3: Reliability Impacts of Flexible Loads | 50 |
| 2.7 | Conclusions | 51 |
| | References | 51 |
| 3 | Optimal Operation of Energy Systems With Uniform Gas Composition Using Linepacks | 53 |
| 3.1 | Introduction | 53 |
| 3.2 | Structure of IEGS and EHs | 56 |
| 3.3 | Multi-level Self-scheduling Model | 56 |
| 3.3.1 | Optimal Scheduling of EH in Day-Ahead | 59 |
| 3.3.2 | Multi-level Self-scheduling of EH in Intraday | 61 |
| 3.4 | Linepack Flexibility Model | 65 |
| 3.4.1 | Optimal Scheduling of IEGS in Day-Ahead | 65 |
| 3.4.2 | Gas Flow Dynamics for Linepack Utilisation in Intraday | 66 |
| 3.5 | Coordinated Optimal Control | 68 |
| 3.5.1 | Formulation of Coordinated Optimal Control Problem | 68 |
| 3.5.2 | Decentralized Solution Methodology | 69 |
| 3.6 | Case Studies | 72 |
| 3.6.1 | Case 1: Provision of DR in a Stressed Case | 72 |
| 3.6.2 | Case 2: Validation of Proposed Methods | 75 |
| 3.6.3 | Case 3: Comparison of Various DR Requirements | 78 |
| 3.7 | Conclusions | 79 |
| 3.8 | Appendix | 80 |
| | References | 81 |

| | |
|--|-----|
| 4 Reliability Evaluation of Integrated Energy Systems Considering Gas Flow Dynamics and Demand-Side Flexibilities | 85 |
| 4.1 Introduction | 85 |
| 4.2 Evaluation Framework | 87 |
| 4.3 Modelling of IES Flexibilities | 87 |
| 4.3.1 Flexibility of End-Users on the Demand Side | 87 |
| 4.3.2 Flexibility of Gas Flow Dynamics in Transmission System | 89 |
| 4.4 Look-Ahead Contingency Management | 91 |
| 4.4.1 Operational Reliability Model of Components | 91 |
| 4.4.2 Look-Ahead Contingency Management Scheme of Integrated Energy Systems | 93 |
| 4.5 Operational Reliability Evaluation Procedures | 95 |
| 4.5.1 Linearization of Gas Flow Dynamic Equations With a Forward-Approximation-Based Technique | 95 |
| 4.5.2 Operational Reliability Evaluation Procedures | 96 |
| 4.6 Case Studies | 97 |
| 4.6.1 Case 1: Impacts of Flexibilities from End-Users and Gas Flow Dynamics on the IES Operation | 98 |
| 4.6.2 Case 2: Evaluation of IES Operational Reliabilities | 100 |
| 4.6.3 Case 3: Long-Term Evaluation Results | 103 |
| 4.7 Conclusions | 106 |
| 4.8 Appendix | 106 |
| 4.8.1 Specific Elements in EH Model | 106 |
| 4.8.2 Calculation Procedures of State Transition Probabilities | 107 |
| 4.8.3 Derivation Process of Reference Point | 108 |
| References | 109 |
| 5 Steady-State Optimal Energy Flow in Hydrogen-Integrated Energy Systems | 113 |
| 5.1 Introduction | 113 |
| 5.2 Framework of Security Management in H-IEGS | 114 |
| 5.2.1 Wobbe Index | 114 |
| 5.2.2 Weaver Flame Speed Factor | 115 |
| 5.2.3 Combustion Potential | 115 |
| 5.3 OEF Model of H-IEGS With Alternative Gas Injections | 116 |
| 5.3.1 Steady-State Model of the Gas System | 116 |
| 5.3.2 Model of the Coupling Components | 120 |
| 5.3.3 Model of the Electricity System | 121 |
| 5.3.4 Objective Function | 122 |

| | | |
|-------|---|-----|
| 5.4 | Reformulation of OEF Model | 122 |
| 5.4.1 | MISOC Relaxation of Gas Flow Equations | 123 |
| 5.4.2 | Reformulation of Bilinear Terms Using McCormick Envelopes | 124 |
| 5.4.3 | Linearization of Security Indices | 125 |
| 5.5 | Solution Procedure Using Sequential Programming | 125 |
| 5.6 | Case Studies | 126 |
| 5.6.1 | Effectiveness of the Proposed Solution Methods | 127 |
| 5.6.2 | Optimisation Results of the OEF in H-IEGS | 129 |
| 5.6.3 | Applications of the Proposed OEF Model | 130 |
| 5.6.4 | Validation Using a Large-Scale Case | 140 |
| 5.7 | Conclusions | 143 |
| 5.8 | Appendix | 144 |
| 5.8.1 | Calculation of Compressibility Factor for Gas Mixture | 144 |
| 5.8.2 | Proof of Convergence of Sequential Programming | 144 |
| | References | 146 |
| 6 | Transient-State Optimal Energy Flow in Hydrogen-Integrated Energy Systems Considering Gas Composition Dynamics | 149 |
| 6.1 | Introduction | 149 |
| 6.2 | Convex Hull of Gas Security Range | 150 |
| 6.3 | Transient-State MPOEF Model | 153 |
| 6.3.1 | Transient-State Model of Gas System | 153 |
| 6.3.2 | Model of Coupling Components | 158 |
| 6.3.3 | Model of the Electricity System | 159 |
| 6.4 | Solution Method | 159 |
| 6.4.1 | SOC Reformulation of MPOEF Problem | 159 |
| 6.4.2 | Sequential SOC Programming Procedures | 161 |
| 6.5 | Case Studies | 162 |
| 6.5.1 | Validation of Proposed MPOEF | 163 |
| 6.5.2 | Travelling of Alternative Gas | 165 |
| 6.5.3 | Multi-period Operation Results | 166 |
| 6.6 | Conclusions | 169 |
| | References | 169 |
| 7 | Long-Term Reliability of Hydrogen-Integrated Energy Systems Considering Hydrogen Embrittlement | 171 |
| 7.1 | Introduction | 171 |
| 7.2 | Long-Term Reliability Indices for H-IEGS | 173 |
| 7.2.1 | Reliability Indices for Gas Adequacy | 173 |
| 7.2.2 | Reliability Indices for Gas Interchangeability | 174 |
| 7.3 | Reliability Models of H-IEGS Components | 176 |

| | | |
|-------|---|-----|
| 7.3.1 | Multi-state Reliability Model of Pipeline Considering Corrosion Effect | 176 |
| 7.3.2 | Multi-state Reliability Models of Other Components | 178 |
| 7.4 | Contingency Management Scheme of H-IEGS | 178 |
| 7.4.1 | Change of Gas Network Topology Considering Different Pipeline Failure Modes | 179 |
| 7.4.2 | Gas Network Model With Alternative Gas Injections and Pipeline Failures | 180 |
| 7.4.3 | Contingency Management Scheme of IEGS Considering Gas System Securities | 182 |
| 7.5 | Long-Term Reliability Evaluation Procedures | 184 |
| 7.5.1 | Solution Methods for Contingency Management Scheme | 184 |
| 7.5.2 | Analytical Long-Term Reliability Evaluation Procedures With System State Reduction Techniques | 186 |
| 7.6 | Case Studies | 187 |
| 7.6.1 | Case 1: Validation of Proposed CMS in the Representative System States | 188 |
| 7.6.2 | Case 2: Long-Term Reliability Indices of IEGS | 191 |
| 7.7 | Conclusions | 195 |
| 7.8 | Appendix | 195 |
| 7.8.1 | Calculation of Burst Pressure and Rupture Pressure | 195 |
| 7.8.2 | Gas Flow Direction Identification Problem | 196 |
| | References | 197 |
| 8 | Short-Term Reliability of Hydrogen-Integrated Energy Systems Using Universal Generating Function | 199 |
| 8.1 | Introduction | 199 |
| 8.2 | Short-Term Reliability Models of Components | 200 |
| 8.2.1 | Multi-performance Short-Term Reliability Model of PTG | 200 |
| 8.2.2 | Multi-state Short-Term Reliability Model of Wind Farm | 204 |
| 8.3 | Short-Term Reliability Management for H-IEGS | 205 |
| 8.4 | Short-Term Reliability Indices | 207 |
| 8.5 | Short-Term Reliability Evaluation Method | 210 |
| 8.5.1 | Solution Method for Reliability Management Problem | 210 |
| 8.5.2 | Short-Term Reliability Evaluation Procedures | 211 |
| 8.6 | Case Studies | 213 |
| 8.6.1 | Validation of Proposed Reliability Management Scheme in Representative System States | 213 |
| 8.6.2 | Operational Reliability Indices | 217 |

| | | |
|-----------|--|------------|
| 8.7 | Conclusions | 218 |
| 8.8 | Appendix | 219 |
| 8.8.1 | Feasible Region of PTG in Different States | 219 |
| 8.8.2 | Mathematical Formulation for Reliability Management Problem | 221 |
| 8.8.3 | Gas Security Indices | 224 |
| | References | 225 |
| 9 | Resilience Definition and Evaluation of Gas Interchangeability in Hydrogen-Integrated Energy Systems | 227 |
| 9.1 | Introduction | 227 |
| 9.2 | Gas Interchangeability Resilience | 228 |
| 9.2.1 | Gas Interchangeability | 228 |
| 9.2.2 | Resilience of Gas Interchangeability | 230 |
| 9.3 | Two-Stage Gas Interchangeability Management Scheme | 232 |
| 9.3.1 | First Stage: Steady-State Optimal Electricity and Hydrogen-Gas Flow Problem | 233 |
| 9.3.2 | Second Stage: Dynamic Gas Composition Tracking | 236 |
| 9.4 | Solution Method | 238 |
| 9.4.1 | Adaptive Linearizations Method | 239 |
| 9.4.2 | Solution Procedure | 240 |
| 9.5 | Case Studies | 240 |
| 9.5.1 | Validation of Proposed Method | 240 |
| 9.5.2 | Gas Interchangeability Resilience of Different Gas Buses | 242 |
| 9.5.3 | Gas Interchangeability Resilience During Daily Operation | 245 |
| 9.5.4 | Validation of Proposed Metrics | 245 |
| 9.6 | Conclusions | 249 |
| 9.7 | Appendix | 249 |
| | References | 249 |
| 10 | Nodal Energy Price and Market Clearing in Carbon Emission-Embedded Hydrogen-Integrated Energy Systems | 251 |
| 10.1 | Introduction | 251 |
| 10.2 | Illustration of Nodal Energy Price in H-IEGS | 252 |
| 10.3 | Joint Market Clearing Model of H-IEGS | 254 |
| 10.3.1 | Gas System Constraints | 255 |
| 10.3.2 | Electricity System Constraints | 259 |
| 10.3.3 | Coupling Constraints | 259 |
| 10.4 | Solution Method | 260 |
| 10.4.1 | Solution Method for Nodal Energy Price | 260 |
| 10.4.2 | Warm-Start for Continuous Market Clearing | 262 |

| | |
|---|------|
| Contents | xvii |
| 10.5 Case Studies | 264 |
| 10.5.1 Validation of Proposed Methods | 264 |
| 10.5.2 Continuous Operation and Impact Factor Analysis of Nodal Energy Price | 267 |
| 10.5.3 Validation Using a Large Case | 271 |
| 10.6 Conclusions | 272 |
| References | 272 |