

Edited by
Lawrence E. Jones, PhD



RENEWABLE ENERGY INTEGRATION

Practical Management of Variability, Uncertainty, and
Flexibility in Power Grids

SECOND EDITION



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"Like many other industries, the energy sector is undergoing a transformation. As a number of countries strive to reduce the environmental footprint of their energy production, new technologies are opening up unforeseen possibilities and challenging the status quo. There is no doubt that renewable energy, including hydropower, is part of the solution. This work brings together a wide range of information and visions to better understand the importance of developing and integrating various sources of clean energy in order to ensure the long-term viability of our industry and to help society move towards sustainability. In short, this forward-looking work will educate and equip readers for the future."

-Éric Martel, President and Chief Executive Officer, Hydro-Québec

"We are living through a second Renaissance. And as this, the 2nd edition of Renewable Energy Integration, makes clear, nowhere are the possibilities and stakes of this Renaissance moment clearer than in our energy infrastructure. Now is a moment, like 500 years ago, when humanity sets out on brave new voyages of discovery—voyages whose outcome is uncertain. This book takes what we've found so far from these voyages and expertly compiles the definitive map of the renewable energy landscape as we now know it: from Africa, to India, to Denmark and California; from pumped hydro to compressed air storage; from market management systems to smart grid operations; from residential batteries to global power distribution. It's a must-read for every captain, every pilot of our energy renaissance."

- Dr. Chris Kutarna, Author, Age of Discovery: Navigating the Risks and Rewards of Our New Renaissance

The second edition of ***Renewable Energy Integration: Practical Management of Variability, Uncertainty, and Flexibility in Power Grids*** offers a distilled examination of the intricacies of integrating renewables into power grids and electricity markets. It offers informed perspectives from internationally renowned experts on related challenges and solutions based on demonstrated best practices developed by operators around the world. The book's focus on practical implementation of strategies provides real-world context for the theoretical underpinnings and the development of supporting policy frameworks. The second edition includes new and revised chapters that consider a myriad of integration issues ensuring that grid operators with low or high penetration of renewable generation can leverage the best practices achieved by their peers.

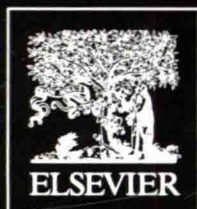
Key Features

- Lays out the key issues around the integration of renewables into power grids and markets, from the intricacies of operational and planning considerations to supporting regulatory and policy frameworks
- Provides updated global case studies that highlight the challenges of renewables integration and present field-tested solutions and new Forewords from Europe, United Arab Emirates, and United States
- Illustrates technologies to support the management of variability, uncertainty, and flexibility in power grids

About the Editor

Dr. Lawrence E. Jones, a recognized thought leader and practitioner, has over twenty-five years of experience in the energy industry. His expertise includes renewable energy integration, the application of smarter technologies in engineering design, and operations of energy systems and other critical infrastructures. He also focuses on system resilience, disruptive and innovative business and regulatory models, and strategies for addressing challenges to harnessing opportunities at the food-energy-water nexus. Dr. Jones received the Renewable Energy World's 2012 Award for Leadership in Technology and the Utility Variable-Generation Integration Group 2012 Achievement Award. He is Vice President at the Edison Electric Institute and Honorary Industry Fellow at Monash University in Melbourne, Australia.

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Jones

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Renewable Energy Integration

Praise for the Second Edition of Renewable Energy Integration

Like many other industries, the energy sector is undergoing a transformation. As a number of countries strive to reduce the environmental footprint of their energy production, new technologies are opening up unforeseen possibilities and challenging the status quo. There is no doubt that renewable energy, including hydropower, is part of the solution. This work brings together a wide range of information and visions to better understand the importance of developing and integrating various sources of clean energy to ensure the long-term viability of our industry and to help society move toward sustainability. In short, this forward-looking work will educate and equip readers for the future.

Éric Martel, President and Chief Executive Officer, Hydro-Québec

We are living through a second Renaissance. And as this, the second edition of Renewable Energy Integration, makes clear, nowhere are the possibilities and stakes of this Renaissance moment clearer than in our energy infrastructure. Now is a moment, like 500 years ago, when humanity sets out on brave new voyages of discovery—voyages whose outcome is uncertain. This book takes what we have found so far from these voyages and expertly compiles the definitive map of the renewable energy landscape as we now know it: from Africa, to India, to Denmark and California; from pumped hydro to compressed air storage; from market management systems to smart grid operations; from residential batteries to global power distribution. It is a must-read for every captain, every pilot of our energy renaissance.

Dr. Chris Kutarna, Author, Age of Discovery: Navigating the Risks and Rewards of Our New Renaissance

The universal agreement on a set of sustainable development goals reached in 2015 puts at its heart the need for sustainable energy for all including a commitment to achieve universal access to affordable, reliable, modern energy. At the heart of closing the energy access gap, providing energy services for the 1 billion people who lack access to electricity today, is off-grid renewable energy. By supporting energy systems that allow for a thriving off-grid energy market to operate alongside grids, countries can exploit new renewable energy technologies at low prices and new business models to reach those that have always been considered the last mile, first. Integration offers a cheaper, quicker way to end energy poverty.

Rachel Kyte, Chief Executive Officer, SE4ALL and Special Representative of the UN Secretary General

Today, one-third of U.S. power generation comes from zero-emissions sources—nuclear energy and renewables, such as hydropower, wind, and solar. As this trajectory continues, the topics covered in the second edition of Renewable Energy Integration are center stage. This book provides practical examples of the electric power industry's evolutionary transformation, as electric companies work to deliver the energy future that customers want and expect in ways that continue to enhance reliability and affordability. The insights in this book provide greater understanding of the challenges and opportunities facing the electric power industry as it continues to integrate renewables—in both developed and developing countries.

Thomas R. Kuhn, President, Edison Electric Institute

Renewable energy is changing the electricity market and electric power systems at a phenomenal rate. This has profound consequences not only on grid operation but also on economy, market, and customer behavior and awareness. This is an outstanding book that offers a global view of renewable energy. In 33 chapters, internationally leading professionals describe experiences and consequences related to physics, systems modeling, grid and island operations, and integration, as well as market, policy, and regulation issues. This is a must-read book for all power system professionals, planners, managers, engineers, or researchers who want to understand the impact of renewable energy.

Gustaf Olsson, Professor in Industrial Automation, Lund University, Sweden

This is a sweeping, essential reference work by a highly distinguished group of experts examining every important facet of renewable energy integration.

Peter Fox-Penner, Professor and Director, Boston University Institute for Sustainable Energy

I am very pleased to be asked to comment on this second edition as I was asked for the first edition. This topic of efficient integration of renewable energy is one of the most important in terms of securing a rapid transition to less carbon-intensive energy systems. It is also one of those key issues governments around the world are devoting a lot of attention to; and rightly so as this will increasingly prove crucial to securing a lower-carbon footprint of the power and sectors. The challenges and opportunities are well brought out by the rich analyses offered in this edition, whether devoted to particular topics or more country-specific studies. Flexibility, market design, technological solutions, dynamic components of a modern energy system—whatever your focus area, this volume provides insights for you. I recommend you dive in.

Christian Pilgaard Zinglersen, Head of the Clean Energy Ministerial Secretariat at the International Energy Agency

The last decade has seen exponential growth of renewable energy resources for the power grid. This text provides a timely and comprehensive perspective on not only engineering concerns but also policy issues and market incentives to allow the large-scale integration of renewables. The second edition provides a valuable update to the first edition as the primary integration issues are rapidly evolving under higher penetration levels and as practical experience has been gained around the world.

Kevin Tomsovic, Professor and Director of CURENT an NSF/DOE Engineering Research Center, University of Tennessee

Well done! Dr. Lawrence Jones has the merit of addressing both the technical and economic aspects of the practical aspects of integrating renewables, which the excitement and euphoria generated by the development of renewable energies do not allow to evoke substantially. The new issues, such as storage that this edition analyzes, give us the opportunity to harness the huge endowment of renewable resources in Africa. Read this book with circumspection to benefit most from it.

Eng. Abel Didier Tella, Director General, Association of Power Utilities of Africa

As we continue to live in interesting times, our sector bears unique challenges to energy security, resource management, and energy access. The global journey and in-depth array of insights from the thought leaders included in this edition are extremely helpful. It highlights the impact of federal and state policies critical to integrating variable energy resources. There is a need for flexibility on the grid for reliability and enhanced situational awareness. These renewable sources all have to

operate in a competitive power market. I believe this book illustrates well that “the addition of incremental renewable sources has economic benefit” and will add to the resiliency of the grid.

**Hon. Vicky A. Bailey, Former Assistant Secretary, International Affairs and Domestic Policy, Department of Energy,
and Former Commissioner, Federal Energy Regulatory Commission**

What started as a wave of additions of central station renewables (primarily wind and solar) onto the bulk power system has in recent years morphed into the addition of a whole family of distributed energy resources (DERs). Some are variable (e.g., rooftop solar) and some can mitigate variability and make the grid more resilient (e.g., storage, microgrids and combined heat and power). Even the long-standing effort to promote energy efficiency now can have a locational and temporal value. All of these resources must be integrated, managed, and valued. Dr. Jones, in his second edition of Renewable Energy Integration, has again assembled a unique team of experts to address the technical, regulatory, and business model challenges posed by the technology revolutions happening in the energy sector. The book also takes a global perspective, with case studies illustrating how different countries and regions are tackling these issues. Very informative!

Philip Mihlmester, Executive Vice President-Global Energy, ICF

Lawrence Jones has done it again! The first edition of this book was already a success in terms of pulling together a diverse array of experts who provided broad insights on many aspects of renewable integration. This second edition goes a couple of steps further, confirming (if needed) Lawrence's incredible ability to network people around a common cause. The world is definitely heading toward higher, if not 100%, penetration of renewables. This development is accelerated by the fast-track deployment of new cost-effective technologies and the growing appetite of consumers and businesses for renewable power for a sustainable future. But this is just the beginning. The changes afoot in the industry over the next 10–15 years will provide an incredible opportunity for mankind. I am thoroughly convinced that, collectively, our global community will fully participate in and support the greening of the economy and of the energy sector, notwithstanding a few bumps along the way. Enjoy reading!

Pierre Bernard, Founder and Managing Partner, Bernard Energy Advocacy, and Chairman Friends of the Supergrid

Dr. Lawrence Jones and the exceptional team of expert contributors have made an outstanding effort to write this timely “must-read book,” which will serve as a great reference source for future innovations, state-of-the-art technology adoption, and integration of renewable energy in power grids for a sustainable future.

**Dr. Anil K. Garg, President, World Renewable Energy Technology Congress, and CEO of Energy and Environment
Foundation Delhi, India**

Embracing renewable resources has emerged as an important grid strategy, aside from decarbonization. Wind and solar resources have become the least-cost supply options for many electric utilities. Undoubtedly, more utilities will encounter renewable integration technical challenges in the future. A big mahalo to Lawrence Jones for advancing our understanding how to better integrate higher penetrations of intermittent renewable resources, as Hawaii advances toward our 100% renewable energy goal.

Michael Champley, Former Commissioner, Hawaii Public Utilities Commission

This book hits the mark on some of the significant factors for the proper integration of renewable and distributed technologies to the power grid. It is a great read and enhances the first edition with important additions on energy storage, a potentially transformative technology. Dr. Lawrence Jones continues to make major contributions to elevate the discussion surrounding renewable technologies and the evolving power grid by assembling the views of strategic thought leaders on an essential topic. Well done!

David Owens, Retired Executive Vice President, Edison Electric Institute

This second edition of Renewable Energy Integration comes in the nick of time, as global energy systems are transformed before the eyes of policy makers and industry professionals. For Australians witnessing world leading rates of rooftop solar penetration and South Australia's variable renewable energy levels exceeding 40% of supply, the scope of the book is appropriately ambitious and practical. It identifies emerging issues and leading practice in forecasting and visualization; system flexibility; grid codes; the blurring interface of transmission and distribution system operations; and the orchestration of distributed energy resources including storage. This invaluable guide illustrates that enabling low-cost, low-carbon energy sources at scale was just the first challenge—the real feat will be in integrating renewable resources within a remade energy ecosystem.

John Bradley, Chief Executive Officer, Energy Networks Australia

This second edition of Renewable Energy Integration provides timely, critical insights to the rapidly evolving landscape of power systems that incorporate increasing amounts of renewable energy technologies. In just a few short years since the first edition, renewables have become least-cost resources in many parts of the world, and integration knowledge has advanced considerably. This important book is a “must-have” for academics, practitioners, and decision makers.

**Dr. Doug Arent, Executive Director, Joint Institute for Strategic Energy Analysis,
National Renewable Energy Laboratory**

The knowledge and experience on how to manage massive deployment of cost-efficient renewable power in electricity grids are not available everywhere. The value of books describing how to do this has immense value in parts of the world where experience does not exist. This book deserves to be widely read as it is conveying experience and analysis in a clear and useful way. It may speed up utilization of low-cost energy and thereby provide for economic development in regions where old habits and perceptions may delay progress.

Tomas Kåberger, Executive Board Chairman, Renewable Energy Institute

The last half century of the renewable energy story has been largely defined by the drive to improve the cost-effectiveness of renewable generation resources. As the cost competitiveness question has now been sufficiently answered, the next looming challenge (and opportunity) is the depth of renewable integration across existing and new energy networks, globally. Dr. Jones's book should serve as an indispensable and approachable resource for those in the public and private sectors, seeking to deal with a complex set of policy, technical, and operational challenges, on the next phase in the journey toward a greater renewable energy future.

Jarett Carson, Managing Director, EnerTech Capital

In the UK we have seen a rapid increase in renewable generation connected to our distribution networks in recent years. This has presented not only challenges for network companies but also opportunities to work more innovatively and use new technologies to deliver benefits to all customers. The challenges of renewable integration are common across the world as we move to a more sustainable energy future, and this volume provides valuable insights from a wide range of experts making an important contribution to this transition.

David Smith, Chief Executive, Energy Networks Association

Praise for the First Edition of Renewable Energy Integration

In order to double the share of renewable energy in the global energy mix – one of the three goals of the UN Sustainable Energy for All initiative - there will need to be tools and methods for integrating high levels of variable renewable electricity into power systems and markets worldwide. This book makes an important contribution to the regulatory, operations, economic and technical aspects of that challenge. By bringing together cutting edge approaches, Dr. Jones has done much of the hard work for us. It is an extraordinary snapshot of the state-of-the-art, and I am very glad to recommend it to decision-makers in both industrialized and emerging economies alike.

**Dr. Kandeh Yumkella, Under Secretary of the United Nations, Special Representative to the United Nations Secretary General, and CEO for UN Sustainable Energy for All (SE4All) Initiative
General of the United Nations, Special Representative of the United Nations Secretary Sustainable Energy for All (SE4All)**

With the demand for water, food and energy growing beyond all measure and with the supply of these inextricably linked 'resource spheres' under increasing threat, we are facing what many experts predict will be a 'perfect storm'. The threat to human life, as well as to whole sectors of the economy, is very real. Renewable energy can be a vital part of the solution and if this comprehensive and authoritative set of essays can help to accelerate both the generation and integration of renewable energy supplies then it will have served an invaluable purpose.

Paul Polman, Chief Executive Officer of Unilever, and Chairman, World Business Council for Sustainable Development

A typically outstanding effort by Dr. Jones and his assembled expert authors. A timely, "must read" for managing the energy trifecta of addressing climate concerns and energy poverty while maintaining economic viability and promoting more secure, reliable and sustainable fuel choices. The chapters deal head on with the key issues of the day (VER, storage, distributed energy, etc.) and suggest that while we should enjoy the success of the unconventional revolution, we need to use the breathing space this moment provides to seriously move on to more sustainable energy forms.

**Frank Verrastro, Senior Vice President and James Schlesinger Chair for Energy & Geopolitics,
Center for Strategic and International Studies**

Bravo! This book is an important resource. As renewable energy plays an increasingly important role in electric grids in the years ahead, this rich volume will help policymakers, utility executives, technology providers and many more.

David Sandalow, Inaugural Fellow, Center on Global Energy Policy, Columbia University

The efficient integration of renewable energy is one of the most important challenges posed by the move towards sustainable energy systems. Renewable energy challenges the norms and traditions accumulated over the last century, and it requires new dynamic approaches that match the needs

and requirements of a modern, sustainable power system. Many of these issues are considered in this publication, which gives new insights into how power systems can move forward and provide society with clean, reliable and affordable electricity.

**Christian Pilgaard Zinglensen, Deputy Permanent Secretary,
Danish Ministry of Climate, Energy and Building**

The use of renewable energy in modern power systems has accelerated rapidly in recent years – beyond what some skeptics thought possible. There could not be a more timely topic than the practical integration of these resources into large-scale grids. This collection of expert guidance is not only valuable now, but surely will need a fresh edition on an annual basis for the foreseeable future as technology continues to evolve.

**Reid Detchon, Vice President, United Nations Foundation, and Executive Director,
Energy Futures Coalition**

Dr. Lawrence Jones has assembled an exceptional team of experts to provide deep insights into the challenges of fully leveraging renewable generation across the globe. This book will serve as a great reference source for interested readers from all levels of knowledge regardless of their area of interest. From policy to engineering to operations, it has insights for all. Innovation in the electric energy sector offers great promise for clean, reliable, resilient and affordable power across the globe, however this same innovation is increasing the complexity of an already complex system. This book gives the reader an introduction into this promise as well as into the complexity that it will bring.

Becky Harrison, Chief Executive Officer, GridWise Alliance

Transitioning our power system to clean, renewable energy is one of the most important challenges of our lifetime. In many ways the task is familiar, as since the days of Edison and Westinghouse grid operators have accommodated fluctuating electricity demand and abrupt power plant failures to keep electricity supply and demand in balance. From remote Pacific islands to mainland Europe, Jones insightfully spans the globe to distill the success stories of grid operators who now reliably obtain more than a quarter of their electricity from wind and solar energy. The path forward for integrating even higher levels of renewable energy is clear, and we have the technology to do it today.

Rob Gramlich, Senior Vice President, American Wind Energy Association

Electrical systems around the world are undergoing radical change due to the rapid growth of solar and wind energy. We must modernize the grid to make it compatible with these critically important energy sources. This collection provides real-world examples of how the power sector, and society's leaders generally, can achieve this goal, which is key to energy security, environmental protection, and economic progress.

Andrew L. Shapiro, Founder & Partner, BROADSCALE Group

As the world searches for pathways towards a sustainable and inclusive energy future, one of the fundamental opportunities lies in ensuring that renewable energy technologies meet their vast potential. To that end, it has become evident that we need to urgently address the tools, regulations, and operational and institutional issues that will serve to elegantly integrate renewable energy

generation into the wider power system. Through rigorous analysis and sensitively designed contributions, Dr. Jones has brought us a book on just the right topic at just the right time. It clearly and coherently presents the state-of-the-art on this complex set of issues, and provides us with the confidence that these challenges can be addressed.

Dr. Morgan Bazilian, Adjunct Professor, Sustainable Engineering Lab, Columbia University

To simultaneously address climate change and meet the needs of the global poor for clean energy, renewable energy on a very large scale will have to play a central role. This book provides a detailed response to the central challenge in making this dream a reality: how to integrate clean but intermittent energy sources within utility systems that require a high degree of central planning and coordination.

Alan Miller, Principal Climate Change Specialist, International Finance Corporation (retired)

Solar and wind power is growing around the globe. Merits are obvious; fuel free electricity production is advantageous in terms of climate footprint and absence of other pollutants. However, integration of these variable power sources is challenging. This book is a comprehensive collection of contributions ranging from very technical challenges to market models and policies for this new era of electricity. Read and you will broaden and deepen your expertise in how to best integrate renewables in our power systems.

Dr. Magnus Olofsson, President, Elforsk—Swedish Electrical Utilities' Research & Development Company

Great book! Lawrence Jones has managed to capture the most important renewable energy topics in a single volume, and he has done so through the contributions of working experts in each topic. If you are interested in renewable energy integration, this book captures the current state-of-the-art for the entire field.

Mark Ahlstrom, CEO WindLogics

Renewable generation is becoming ever more prolific. The timing of this book is perfect. It combines practical examples with theory and will guide decision makers dealing with today's issues as well as those seeking ways to deal with tomorrow's challenges. The lessons learned will help avoid pitfalls and provide insight and inspiration. The topics covered are relevant to both developed and developing countries, those countries starting from a low renewables base as well as those with high proportions of renewables.

Eric Pyle, Chief Executive New Zealand Wind Energy Association

The timing of the publication is just perfect. Renewable energy has gone mainstream globally i.e. 45 GW of new wind installations in 2013. The content and focus of this remarkable book is both unique and demanding. It's all about integration: of markets, physical infrastructure, policies. This integrated approach is as often lacking in current debates as it is needed for progress. And the design both of the modern electricity markets and a modern grid are crucial for a transition to safer, cleaner energy world of the future. No transition without transmission, and no communication without electrification. Reading this book you might learn how integration can accelerate the transition.

Dr. Klaus Rave, Chairman Global Wind Energy Council

With wind and solar energy expanding at an ever-quicken pace, the time is right for a thorough and cross-disciplinary assessment of the integration challenge. This book hits the mark, with the industry's leading experts addressing a wide assortment of topics that are central to managing higher shares of variable generation.

Dr. Ryan H. Wiser, Staff Scientist, Lawrence Berkeley National Laboratory

Renewable Energy Integration is a critically needed and wonderfully comprehensive book that highlights the next frontier; not how much renewable energy potential exists, but how to most effectively and seamlessly merge this new power system with the old one.

Daniel Kammen, Class of 1935 Distinguished Professor of Energy, University of California, Berkeley

Understanding the intricacies discussed in Renewable Energy Integration is a predicate for achieving universal access to affordable, sustainable, reliable energy across a diverse portfolio of fuel sources. Towards this end, we must be able to maintain the balance and resilience of the power grid using technology, regulatory, and market forces. Dr. Lawrence Jones' outstanding compendium, based on an in-depth array of insights from an unique cast of renowned thought leaders, demonstrates that he clearly understands how critical this subject is for quality of life, continued economic growth and prosperity around the globe.

Hon. Vicky A. Bailey, former Assistant Secretary, International Affairs and Domestic Policy, Department of Energy and Former Commissioner, Federal Energy Regulatory Commission

There are many that have made a convincing case that we could move to 80% renewable electricity generation by 2030. As we unlock the greatest wealth creation opportunity since the mobile phone revolution, I am sure this resource from Dr. Jones and his assembled dreamteam will find its way onto the desks of every major grid operator and electricity policymaker in the World.

Jigar Shah, Founder SunEdison and Author of Creating Climate Wealth

The future of the energy landscape cannot be envisioned without taking into account renewable energy. It is a secret for no one however that the integration of renewable energy into the grid is an important challenge that will need to be overcome if we want to ensure its deployment to full capacity. Dr. Lawrence Jones brings together critical contributions from experts across the globe to address precisely these issues in a must-read, unique publication. It is an invaluable resource for anyone in the industry who wants a comprehensive overview of one of today and tomorrow's hottest topics.

Pierre Bernard, Founder and Managing Partner, Bernard Energy Advocacy