RENEWABLE ENERGY INTEGRATION

PRACTICAL MANAGEMENT OF VARIABILITY, UNCERTAINTY, AND FLEXIBILITY IN POWER GRIDS

Editor
Lawrence E. Jones, Ph.D.
Praise for 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 unconventionals 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 Zinglersen, 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-quicker 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
This book is dedicated to my parents, Emmanuel E. W. Jones, Jr. and Comfort H. Jones, who taught me many valuable lessons in life, two of which guided me especially on this journey: to always value and respect humanity and nature; and to work with people from different backgrounds toward a higher purpose.

This book honors the operators of power grids around the world. They are the unsung heroes and heroines who work around the clock, ensuring that we have electricity to light up our nights and fuel our lives.
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Acknowledgments

One of the most valuable experiences of serving as a book editor is having the chance to collaborate and cocreate with many wonderful people around the world.

The idea of this book was born from a conversation I had in 2011 with Tiffany Gasbarrini, then a Senior Acquisitions Editor at Elsevier. For over a year, she persistently asked if I would serve as editor for a book on renewable integration for which I repeatedly demurred. But after months of careful consideration and discussion with my family, Tiffany’s persistence thankfully paid off. Hence, you hold this book in your hands.

Special thanks to the team at Elsevier; in particular Laura Colantoni, Joe Hayton, Poulouse Joseph, Rajakumar Murthy, Sruthi Satheesh and Kattie Washington, for their commitment and dedication to seeing the idea come to fruition.

This book is underpinned by the knowledge, insights and experiences of leading experts and practitioners who graciously devoted their time and talent to writing the chapters. Thanks to: V.K. Agrawal, Stefano Alessandrinri, Anders N. Andersen, Göran Andersson, Reza Arghandeh, Tatiana M. L. Assis, Chaitanya A. Baone, Carl Barker, Diane Broad, Maxime Baudette, Audun Botterud, Richard Candy, Spyros Chatzivasileiadis, Puneet Chitkara, Erik Connors, Anish De, Luca Delle Monache, Christopher L. DeMarco, Ken Dragoon, John Dumas, Erik Ela, Mica Endsley, Pavel V. Etingov, Steven Fine, Jarett Goldsmith, Santiago Grijalva, Udi Helman, Anders Plejdrup Houmøller, Mark Howells, Brendan Kirby, Kiran Kumaraswamy, Helena Lindquist, Clyde Loutan, Jian Ma, Phillip Mack, David Maggio, Yuri V. Makarov, Dimitris Mentis, Michael Milligan, David Mohler, Matthias Müller-Mienack, Tim Mundon, Ijeoma Onyeji, Andrew L. Ott, Mark Rothleder, Peter Schell, Fereidoon P. Sioshansi, Sushil K. Soonee, Daniel Snyder, Glauco N. Taranto, T. Bruce Tsuchida, Andreas Ulbig, Luigi Vanfretti, Alexandra von Meier, Xing Wang, Manuel Welsch, and Austin D. White.

Thanks are also due to two forward-thinking leaders, George Arnold and Daniel Dobbeni, for their eloquent forewords, which highlight the drivers and opportunities for integrating renewable energy from their unique vantage points in the U.S. and Europe, respectively.

Making predictions is never easy. However, when it comes to integrating renewables, I can, with a high degree of confidence, place my bets on projections made by J. Charles Smith. As the Executive Director of the Utility Variable Generation Integration Group, and an eminent thought leader in the field, Charlie’s impressive prescience made him the unquestionable choice to write the epilogue for this book. I am grateful to him.

I was fortunate to have extraordinary teachers and role models who inspired me and shared their wisdom and expertise, which prepared me for this task. In this context, there are four individuals I would like to express my thanks to: Barbro Hellermark, my Swedish teacher at the University of Stockholm, whose brilliant pedagogical skills helped me to quickly become fluent in the language, and also gave me the foundation to function in today’s multilingual world; Professor Göran Andersson, my PhD supervisor at the Royal Institute of Technology in Sweden, who, as head of the Power Systems Group, demonstrated the importance of being able to work on a team with individuals from different cultures; Professor Emeritus Gustaf Olsson at Lund University for our stimulating in-depth discussions, which led to interesting ‘A-ha!’ moments, helping me appreciate the complexity and enormity of the water-energy nexus problem, as well as the need for holistic approaches to tackle mega challenges like climate change; and finally, to Margaretha Andolf, the former head of Language and Didactics at
the Royal Institute of Technology, for assigning me a class project that taught me a lot about intercultural communications, and eventually led me to write the book, *Visiting Students in Stockholm, Encountering and Adjusting to Swedish Culture*.

I would like to acknowledge and offer thanks to the following individuals, who provided early praise for this book: Mark Ahlstrom, Vicky Bailey, Morgan Bazilian, Pierre Bernard, Reid Detchon, Rob Gramlich, Becky Harrison, Daniel Kammen, Alan Miller, Magnus Olofsson, Paul Polman, Eric Pyle, Klaus Rave, David Sandalow, Andrew L. Shapiro, Jigar Shah, Frank Verrastro, Ryan H. Wiser, Kandeh Yumkella, and Christian Pilgaard Zinglersen.

I am also thankful to the intellectual sparring partners with whom I have worked, brainstormed, coauthored, and debated over the years, always with the mutual goal of advancing solutions for integrating renewables. They include: Thomas Ackermann, Charlton Clark, David Elzinga, Russell Philbrick, Olof Samuelsson, Jon O’Sullivan, Eric Goutard, Ali Sadjadpour, and Robert Zavadil.

I am always mindful of the village that it took to get me to where I am, so it is in the spirit of gratefulness that I acknowledge the support over the years of my family and friends around the world.

I owe an infinite debt of gratitude to my mother, Comfort Hadoo Jones, and my departed father, Emmanuel E. W. Jones, Jr. They made countless sacrifices to ensure my siblings and I received a well-rounded education. I will be forever grateful to them for instilling in us the importance of faith, courage, and determination. They taught us to always strive for excellence in everything we do, and to remember that “No Man Is an Island” - we will always need one another in our interconnected and interdependent world.

To serve as editor for a book with so many contributors requires that one patiently listens to a myriad of disparate views, before synthesizing and integrating them into a scholarly roadmap that tells a cohesive story. In this regard, I am extraordinarily grateful to my uncle, Charles Gyude Bryant, II, who not only taught me about the importance of listening, but exemplified this estimable skill when he successfully led the transition of Liberia from war, to peace and democracy. Sadly, he died a few months before this book was completed. I will always strive to be as good a listener as he was.

I am thankful for the relationships with my siblings, Jerome, Vivien, and Jestina. Vivien had the foresight to persuade me to take a leap of faith, and make the transition from Sweden to the USA, in order to broaden my horizon. Without that decision, the opportunity to work on this book would probably not have come about.

Writing a book always takes the biggest toll on the immediate family. Therefore, my immeasurable gratitude goes to my wife, Facia, and our daughter, Nohealani. They are my endless source of love, joy, inspiration, enthusiasm, and optimism. Although this endeavor meant less time for us to spend together over the many weekends this effort demanded, they never complained. Instead, Facia was steadfast in encouraging me to remain focused on completing this journey. Nohealani’s innocent inquisitiveness helped sharpen my explanations of wind and solar energy.

I hope that this book will catalyze greater investments in, and integration of, renewable energy resources. Thus, in the near future, Nohealani and her contemporaries will continue to reap from, enjoy, and maintain a more sustainable planet universally gifted to all of us by divine providence.

Lawrence E. Jones
*Washington DC, May, 2014*
Foreword from Europe

From the early days of Thomas Edison till the middle of last decade, the growth of the power industry was based on four main pillars. In first place, in order to meet the instantaneous power consumption, generation plants were instructed to deliver electricity starting from the lowest marginal cost (nuclear) up to the most expensive (fuel). This so-called merit order model combined with local energy resources and predictable demand curves determined the portfolio of generation technologies. Secondly, economies of scale were readily available with increasingly larger centrally dispatched power plants. Thirdly, grids connecting demand areas with different demand curves improved reliability and lowered peak demand, reducing overall cost. Finally, when combined these features allowed for lower tariffs, encouraging an ever-growing demand. They also contributed to appearance of increasingly larger vertically integrated utilities. These national champions and their predecessors successfully developed one of the most important industries in mankind; an industry that is on the very basis of today’s economies, health, and welfare.

In those years, the future of a power systems could be planned with the near certainty that it would materialize in due time. Return on investment was (nearly) guaranteed as customers had often only one national supplier that, in return for this privilege, would ensure long-term security of supply and day-to-day reliability. Rising issues were permits and rights of ways, while the inroad of new technologies, such as combined heat and power generation and combined cycle gas plants, was perceived not as a threat but as an opportunity.

The European power industry is upside down after 17 years, witnessed by the decreasing share value of what remains from the national champions!

At a joint press conference in Brussels, October 11, the CEOs of 10 leading European companies, representing half of Europe’s power capacity, painted a bleak future and raised concerns about security of supply, as they close loss-making (fossil) plants.

What happened?

As with each black swan event, several elements concurred to disrupt the four pillars.

In the first place, the generation mix changed fast and drastically. Attractive support mechanisms for combined heat and power generation and renewable energy sources led new investors, such as private capital, municipalities, energy intensive industries, small and medium enterprises, as well as millions of residential customers, to enter the power industry. Two support mechanisms are the foundations of this revolution. One gives priority access to the grid for CO₂-friendly generation while the second offers a fixed and attractive return on investment, which often shields the owner from potential disruption of the wholesale market during 20 years.

Europe’s ambitious target of 20% renewable energy sources in 2020 (or 33% of renewable generation for electricity) prompted several member states to propose highly attractive support mechanisms. Denmark, Germany, Spain, Italy, Ireland, and Belgium for example have seen their share of renewable energy sources, manly wind and solar, increase drastically in less than 5 years.

While previous (and current) support mechanisms for nuclear and fossil fuel generation are funded by the Europe Union and the concerned states, the cost of the support for renewable energy sources appears as a surcharge added on top of the transmission and/or distribution tariffs. This cost is much more visible and measurable.

An unprecedented wave of investments induced major side effects.
In the first place, the contemplated growth in wind and solar power generation attracted worldwide manufacturers, leading for example to price plummeting for photovoltaic panels. Soon, these technologies will become competitive without support mechanisms; challenging the second pillar. The operational impact of large shares of variable generation grew quickly, whether in terms of large power flows impacting neighboring countries or reduced number of operating hours for fossil plants (less than 10% of the time during sunny and/or windy months in some countries).

Secondly, exploitation of shale gas in the United States and a very low CO₂ price led to a trend reversal in less than 3 years. Coal plants became the cheapest to operate at the expense of more efficient and modern gas plants while fast ramping gas plants are disappearing at the very moment that system operators hardly need them.

Thirdly, the tremendous growth of renewable energy sources with nearly zero-marginal cost pulled down the wholesale price from around 80 €/MWh in 2008 to 45 €/MWh in 2013. Together with the decreasing number of generation hours, fossil plants are facing a bleak future; challenging the merit order model and first pillar.

Finally, the financial and economic crisis in Europe with its toll on employment amplified the impact of the fast rising cost of support mechanisms for renewable energy sources. Large industries started to complain heavily about worldwide competitiveness, attracting media and political attention. And although, residential customers are not (yet) reacting to this situation, some policy markers are now moving from “saving the planet first” toward “saving us first and then eventually the planet”.

Renewable energy sources are more and more depicted as guilty for higher electricity bills, future blackouts, decreasing reliability, insufficient security of supply, inefficient electricity markets, etc.

Could these assertions be true? Should all support to CO₂-friendly generation be stopped?

As usual, the picture is neither white nor black and the initiative of the editor, Lawrence Jones, comes at the right moment. There is actually an urgent need to clarify the real challenges induced by larger shares of (variable) renewable energy sources and to put forward practical and efficient solutions.

The various authors provide state-of-the-art contributions from a research and development perspective as well as case studies. The major role of grids and interconnections between power systems is highlighted as well as the need to invest in advanced forecasting of wind and solar generation, especially for the design of energy management system. Several contributions also demonstrate that smart tools are readily available to maximize the efficient use of the existing assets, such as dynamic line rating, phasor measurements, data mining, demand response and flexibility. As former CEO of the Elia Group, a fully unbundled transmission system operator listed on the stock exchange with branches in Belgium and Germany, I have witnessed the added value brought by dynamic line rating as a cost efficient and reliable solution to increase transmission capacity. Another example is phasor measurements that were recognized by the members of the GO15, (i.e. the association of the world’s 16 largest power system operators with a total of 3.5 billion customers), as a major tool to ensure reliability in a cost-effective way. The need for flexible generation and demand, an issue faced by all power systems with an increasing share of wind and solar energy, is a common theme of several contributions. Improved visualization in control centers, intentional islanding of distribution network operation, energy storage, demand response, high-performance computing, integration of renewable energy sources in ancillary services are all examples of the creativity unleashed by the energy system mutation toward a carbon-free power generation. From the many challenges humanity will face in the future, there is one this generation has to tackle now! Path the way
toward an affordable, climate friendly, and secure supply of electricity for all inhabitants of this planet, whether my two grandsons Ethan and James or any present and future children’s and I am grateful to Lawrence Jones and all authors for having taken the initiative to share such wealth of information at this critical moment.

Daniel Dobbeni
Belgium
In his second Inaugural Address in January 2013, President Obama stated, “We will respond to the threat of climate change, knowing that the failure to do so would betray our children and future generations.”

Reducing carbon pollution is a key element of the United States climate action plan. Today’s electric grid represents the largest single source—accounting for over one-third of carbon emissions into the atmosphere. It is imperative that we reduce the carbon footprint of the power grid. At the federal level, the Environmental Protection Administration has proposed carbon pollution standards for new power plants, and 35 states have introduced renewable portfolio standards. Penetration of renewable energy sources is increasing rapidly. Since 2009, the United States more than doubled the generation of electricity from wind and solar energy, and renewable energy sources accounted for about half of the new generating capacity installed in 2012.

The power grid has benefited from many technological innovations over the past century. However in some respects, the basic architecture of the grid is little changed. The traditional operating paradigm assumes controllable generation and variable demand. Today’s grid is designed to ensure near-instantaneous balance between generation and consumption by controlling generation to match stochastically variable demand. The widespread use of renewable generation necessitates the reverse paradigm: variable generation and controllable demand. In other words, renewable generation is stochastically variable but not controllable (we cannot control when the sun shines or when the wind blows), and thus demand must become much more controllable in order to maintain balance. Energy storage technologies, not widely used today, will be needed to provide additional flexibility by buffering short-term mismatches between generation and demand. Reversing the grid’s operating paradigm and incorporating new technologies such as energy storage requires fundamental reengineering of the grid as it exists today.

Reengineering the grid to accommodate widespread use of renewable energy generation presents many difficult challenges, in both technical and policy dimensions. For example, dynamic models of variable energy resources, storage, and demand must be integrated into large-scale system-level models to measure and control the operation of the grid. Improved methods of forecasting variable generation are needed. Strategies for dealing with variability in generation through a combination of demand response, storage, and diversity must be developed. Case studies and empirical data are essential to ensure that models and strategies for managing the grid are valid and are practical to deploy at scale. Appropriate policies and regulation to facilitate economic deployment of new technologies while maintaining system reliability must be understood. The experience of the telecom industry in undergoing technology, policy, and regulatory change also suggests that the reengineering of the grid may lead to new game-changing business models for the industry. In noting the technological achievements of the last hundred years, the National Academy of Engineering cited the electric grid as the greatest engineering achievement of the twentieth century. If we are successful in meeting the challenges posed by renewable energy integration, future generations may well think of the future grid powered by renewable energy as one of the great engineering achievements of the twenty-first century.

Lawrence Jones has produced an impressive collection of works with the help of distinguished experts around the world who address the many aspects of renewable energy integration. This book...
makes a significant contribution by presenting a rich set of case studies that present empirical results from real-world application and advance our understanding of state-of-the-art approaches to practical management of electric grids powered by renewable energy.

Dr. George Arnold
Washington DC
Introduction

Our changing global climate, access to clean energy and water, food security, and population growth are all among the web of complex interdependent challenges facing the world. The first, global climate change is perhaps the most pressing threat to humanity and the future of the planet. Recent reports such as the Climate Change 2014: Impacts, Adaptation and Vulnerability from the Intergovernmental Panel on Climate Change (IPCC), and the 2014 US National Climate Assessment document that climate change is real, and that the related impacts are already beginning to affect different parts of the world. Everyone can relate to the apparent physical and financial impacts of this anthropogenic phenomenon. These impacts will be exacerbated in the coming decades, unless aggressive measures are taken to mitigate negative consequences and adapt our responses to the new environment.

One response to climate change is for the world to transition to a low-carbon energy future through increased use of renewable energy sources. Across the world, governments are scaling up their efforts to spur more investments in wind, solar, and other forms of low-carbon energy. As a result, electricity generated from wind and solar energy is growing rapidly worldwide. There is strong correlation between successful integration of renewable energy and the employment of policies and regulatory mechanisms that catalyze private sector investment. Businesses, therefore, also need to adapt radically practical strategies, as outlined in the book, The Big Pivot, by Andrew Winston. However, as the penetration of renewables increases, one quandary that continues to receive much attention focuses on how to gracefully integrate these nonconventional, variable forms of energy into existing grids and eventually emerging grids, as well as into electricity markets.

My interest in renewable energy began as a child growing up in the West African nation of Liberia, located about 6° north of equator. I was fascinated by the sun and the power of its radiation. In 1998, this interest shifted more toward wind energy while I was working on my doctoral thesis a PhD at the Royal Institute of Technology (KTH) in Stockholm Sweden. In 2000, I cofounded the International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms at KTH. During the past decade, I have collaborated with many leading experts around the world on the subject of renewable integration. In 2010/11 I was fortunate to serve as the principal investigator of the 2010/11 Global Survey on Renewable Energy Integration in Power Grids, funded by the U.S. Department of Energy (DOE). Surveys were conducted on 33 grid operators of electric power systems in 18 countries about their operating policies, best practices, examples of excellence, lessons learned, and decision support tools. The power grids encompassed by the study are located in varying geographies with diverse climate weather patterns and many of the utilities surveyed operate under dissimilar regulatory frameworks, whether within regulated or deregulated electricity markets. The survey findings are published in the report, Strategies and Decision Support Systems for Integrating Variable Energy Resources in Control Centers for Reliable Grid Operations.

The idea behind this book began in 2011 during a brief conversation I had with Tiffany Gasbarrini, who at the time was a Senior Acquisitions Editor at Elsevier. Tiffany had listened to me present findings from the aforementioned report at the annual conference of the American Wind Energy Association (AWEA). When she expressed her interest in publishing the report as a book, I replied that was not possible due to the terms of the contract with the DOE. Given the huge interest in renewable integration worldwide, she asked if I would consider writing a completely new book on the subject. Initially I declined. However, she was persistent and made multiple requests for over a year. Finally,
after getting the green light from my family (although they knew this would consume time during the weekends), I agreed to serve as editor. Thus began the fulfilling journey of preparing what has now emerged as a groundbreaking book. One of the most valuable experiences shaping this endeavor has been collaborating and cocreating with 59 renowned experts from around the world.

During the past decade, results from numerous studies have shown that integrating renewable energy is a multidisciplinary undertaking. Therefore, it was clear from the outset that for this volume to help advance the goal of supplying more of the world’s electric energy from renewable sources, it would have to cover a broad spectrum of topics, featuring carefully selected material based on the myriad experiences of contributing authors working around the world with diverse power systems.

There is no one-size-fits-all solution for integrating renewable energy that applies to all power systems. This book constitutes a singular attempt to provide a distilled examination of the intricacies of integrating renewables into power grids and electricity markets. It offers informed perspectives from an internationally renowned cadre of researchers and practitioners on the challenges and solutions derived from demonstrated best practices as developed by operators of power systems and electricity markets across the globe. The book’s focus on practical implementation of strategies provides real-world context for theoretical underpinnings and enables the development of supporting policy frameworks. It considers a multitude of wind, solar, wave, and tidal integration issues, thus ensuring that grid operators with low or high penetration of renewable generation can leverage the victories achieved by their peers.

As suggested by the book’s subtitle, the three underlying attributes that characterize the integration of renewables in power grids and markets are variability, uncertainty, and flexibility. Similarly, this book’s journey involved coping with all three. There was variability in the style of writing, the systems presented in the case studies, and how authors perceived different, but often interrelated topics. Uncertainty was inherent in the process, given that until the authors submitted the first draft of the chapters, I could not entirely know what to expect. Analogously to integrating renewable generation, as the editor, initially all I could do was to try to forecast or predict the content I was going to receive, based on my historical knowledge of the authors’ works and expertise. In the end, my best efforts to integrate and interweave all 35 chapters into a synchronous and seamless flow of ideas that conveys key coherent themes and approaches bore fruit only by allowing some flexibility to the contributors. Elsevier also gave me a great deal of flexibility.

OVERVIEW OF CHAPTERS

The book you are holding (and will hopefully read) is the result of successfully integrating what initially seemed to be a disjointed collection of chapters into a pioneering volume consisting of 10 interrelated parts, comprising 35 cohesive and carefully written chapters which circumscribe the practical management of variability, uncertainty, and flexibility.

Part 1, Policy and Regulation consists of three chapters that examine the policy and regulatory issues, and the future outlook of renewables in the Europe Union, the United States of America, and Africa. Chapters 1, 2, and 3: The Journey of Reinventing the European Electricity Landscape—Challenges and Pioneers by Helena Lindquist; Policies for Accommodating Higher Penetration of Variable Energy Resources—U.S. Outlook and Perspectives by Steven Fine and Kiran Kumaraswamy; and Harnessing and Integrating Africa’s Renewable Energy Resources by Ijeoma Onyeji. review the
evolution of renewables in the different regions. The authors provide suggestions about what it will take to accommodate even higher penetration of renewables.

Deriving from parts of the European Union and the United States where the percentage of renewable generation capacity is now in double digits, the first two chapters offer good insights about the specific policies and regulatory incentives which catalyzed private sector investments, but also alleviated operational electricity barriers to integrating new variable generation in those jurisdictions.

Africa, with its vast and largely untapped endowment of renewables, is beginning to see greater interest in using solar, geothermal, wind and other forms of renewables to address the vexing problem of lack of access to electricity. Onyegi provides a thorough discussion of the continent’s renewable landscape, the potential challenges, and the opportunities of tapping clean energy resources. Whether grid-connected or off-grid systems, appropriate long-term policies along with adequate investment in infrastructure and human capacity are crucial to harnessing the renewable energy in African countries.

Chapters in Part 2, Modeling of Variable Energy Resources, address the important first step to integrating renewable generation in power systems. Modeling renewable energy must address emerging behavior at new spatial and temporal scales. Modeling must also consider factors associated with resource availability, economic viability, and other grid-related issues.

In Chapter 4, Challenges and Opportunities of Multidimensional, Multiscale Modeling and Algorithms for Integrating Variable Energy Resources in Power Networks, Santiago Grijalva reviews the relevant spatial, temporal, and scenario dimensions. He discusses the state of the art in three key areas of multiscale, multidimensional analysis: (1) modeling and analysis, (2) optimization and control, and (3) data management and visualization. An integrated multidimensional, multiscale framework for design, deployment, operation, and management of networks with high levels of renewable energy is proposed.

The case study in Chapter 5, Scandinavian Experience of Integrating Wind Generation in Electricity Markets, by Anders Plejdrup Houmøller describes the experiences of integrating renewables in the Nordic region. The four countries—Denmark, Finland, Norway, and Sweden—have four separate but fully integrated power systems and a single wholesale electricity market. The chapter focuses mainly on Denmark, which gets a substantial amount of its energy from wind power. Wind energy growth in Denmark is expected to grow unabated over the next decade as the country seeks to achieve the goal of 100% carbon-free energy by the year 2050.

In Chapter 6, Case Study—Renewable Integration: Flexibility Requirement, Potential Over-generation, and Frequency Response Challenges, Mark Rothleder and Clyde Loutan provide an overview of analyses the California Independent System Operator (ISO) conducted to better understand the challenges related to renewable integration. The foundation for performing such a study relies on successfully modeling the renewable resources. The study includes recommendations that the generation fleet needs to have a flexible component. Load shifting and storage technologies are necessary to mitigate potential overgeneration conditions, and inertial response is a characteristic that asynchronous resources should provide to maintain grid reliability.

The chapters in Part 3, Variable Energy Resources in Power System and Market Operations, examine system and market impacts of variable generation. Operation of power systems and electricity markets requires that the aggregate generation and load must be balanced instantaneously and continuously for the electric power system to perform reliably. Integration of more and more variable energy resources (VER) introduces new challenges to power system and market operations.
In Chapter 7, Analyzing the Impact of Variable Energy Resources on Power System Reserves, Brendan Kirby, Erik Ela, and Michael Milligan discuss the different reserve types and requirements in general, and address how to determine impacts. Furthermore, the task of determining the additional reserves required is explained in-depth. The authors make clear that the task is complicated by the nonlinear nature of reserves, as well as by the lack of data and experience.

In Chapter 8, Advances in Market Management Solutions for Variable Energy Resources Integration, Xing Wang provides an overview of wholesale electricity markets and market management systems. Enhancements are being made in both market design and market analytical tools in terms of managing operational uncertainties introduced by VER integration. The chapter focuses on two such areas of market enhancement. First, it explores the feasibility of a ramp market in real time, balancing operation to create the right market incentives for resources to provide enough ramping energy to compensate for VER volatility. Second, it examines how to manage short-term VER uncertainty by applying robust optimization to look ahead unit commitment.

In Chapter 9, Reserve Management for Integrating Variable Generation in Electricity Markets, John Dumas and David Maggio present a case study from the Electric Reliability Council of Texas (ERCOT). As an independent system operator, ERCOT is tasked with ensuring the balance of electrical supply and demand. Over the last several years, this function has been complicated by the additional uncertainty and volatility introduced by increased installment of renewable energy resources, particularly wind generation. The chapter discusses many of the steps that ERCOT and its market participants have made to address and minimize these issues. Particular focus is put on the evolution of wind power at ERCOT, including the use of a probabilistic wind power output ramp event forecast tool, and enhancements made to their methodology for determining the minimum level of ancillary services required to maintain system reliability.

In Chapter 10, Grid and Market Integration of Wind Generation in Tamil Nadu, India, Anish De and Puneet Chikara discuss results from a case study of wind farms in Tamil Nadu conducted to identify the micro-practices in variable renewable energy (VRE) management in the state. Renewable energy in India has grown at a fast pace over the past few years. Compared to other Indian states, Tamil Nadu has considerable experience in operating a power system with VRE resources. The study analyses the intrastate impacts of wind integration, and examines commercial mechanisms, such as Feed-in-Tariff, as well as other regulatory and policy measures meant to encourage renewable integration.

Part 4, Forecasting Renewables, deals with the fundamental task of managing uncertainty via accurate prediction of output from intermittent sources of power. Forecasting of renewable energy has increasingly taken on the sine qua non role in the operations of power systems with more wind, solar, and other forms of variable generation. The chapters in this section discuss the state of the art and state of the science of forecasting, and how the forecast information can be integrated in utility control centers.

In Chapter 11, Forecasting Renewables Energy for Grid Operations, Audun Botterud discusses the potential applications of renewable energy forecasts for system operators, renewable power producers, and other participants in the electricity market, followed by a brief overview of forecasting methods for wind and solar energy. The author argues that good estimates of forecast uncertainty are also of major importance to better handle renewable energy in grid operations. The conclusion highlights that improved forecasting systems and corresponding decision support tools are key solutions to enable a clean, reliable, and cost efficient future electricity grid driven by renewable resources.
In Chapter 12, Probabilistic Wind and Solar Power Predictions, Luca Delle Monache and Stefano Alesandrini review several state-of-the-science techniques supporting probabilistic power predictions for wind and solar generation, and demonstrate how to verify and evaluate such predictions. Deterministic prediction has provided useful information for decision making in the conventional operational paradigm. However, under the new grid regime of increased operational uncertainty, deterministic approaches have fundamentally limited value. For one, the prediction represents only a single plausible future state from the continuum of possible states that result from imperfect initial conditions and model deficiencies. Accurate knowledge of that continuum is considerably more useful to decision making.

In Chapter 13, Incorporating Forecast Uncertainty in Utility Control Centers, Yuri Makarov, P. V. Etingov, and J. Ma examine different sources of uncertainty and variability, demystify the overall system uncertainty model, and propose a possible plan to transition from deterministic to probabilistic methods in planning and operations. Uncertainties in forecasting the output of intermittent generation and system loads are not adequately reflected in existing industry-grade tools used for transmission system management, generation commitment, dispatch, and market operation. An example of uncertainty-based tools for grid operations is presented.

Part 5, Connecting Renewable Energy to Power Grids, takes on the salient issue of physically connecting renewable generation plants to power grids.

In Chapter 14, Global Power Grids for Harnessing World Renewable Energy, Spyros Chatzivasileiadis, Damien Ernst and Goran Andersson introduce the concept of a Global Grid that all regional power systems feed into one electricity transmission system spanning the entire globe. The Global Grid will facilitate the transmission of “green” electricity to load centers, serving as a backbone. This chapter elaborates on four stages that could gradually lead to the development of a globally interconnected power network. Quantitative analyses are carried out for all stages, demonstrating that a Global Grid is both technically feasible and economically competitive. Real price data from Europe and the USA are used to identify the potential of intercontinental electricity trade, showing that substantial profits can be generated through such interconnections.

Chapter 15, Practical Management of Variable and Distributed Resources in Power Grids, by Carl Barker discusses the use of High Voltage Direct Current (HVDC) technology to transmit electricity. Barker reviews the latest HVDC technology, the known as Voltage Source Converter (VSC). Introduced in 2000, VSC technology further increases the flexibility of DC transmission; hence the realistic prospect of DC transmission networks on- and offshore. These DC transmission networks may replace AC transmission applications in the future or may act as a backbone reinforcing the existing AC grid. This new infrastructure may be critical for the power systems of tomorrow to adapt to the increased use of renewable sources, e.g., the Global Grid discussed in Chapter 14.

In Chapter 16, the case study Integration of Renewable Energy—Indian Experience is presented by Sushil Kumar Soonee and Vinod Kumar Agrawal. Integration of renewable energy sources is a priority area in India at all levels, from policy to regulation, implementation, and grid integration. The chapter explores Indian policies, as well as regulatory initiatives, transmission planning and power system operator’s perspectives on integration of renewable energy in the country. The experience of the Renewable Energy Certificate (REC) mechanism introduced in India is discussed.

Part 6, System Flexibility, addresses several pertinent issues related to the ability of a power grid to accommodate the variability and uncertainty in the load and generation, while simultaneously maintaining specified acceptable levels of performance across different timescales. Increasing
penetration of variable generation leads to more variability in the net load and thus the need for solutions that provide additional flexibility in the grid grows. Grid operators need the proper mix of flexible resources, ranging from the supply-side, delivery-side, and the demand-side. While the need for greater flexibility is well established, how to model and determine the amount of system flexibility that is needed for certain levels of variable generation capacity is the subject of extensive research and debate.

In Chapter 17, Long-Term Energy Systems Planning: Accounting for Short-Term Variability and Flexibility, Manuel Welsch, Dimitris Mentis, and Mark Howells describe the provision of flexibility in power systems through supply- and demand-side operating reserves and storage options. They review several modeling approaches and present the limitations of long-term models regarding their temporal resolution and the metrics applied to ensure the power system’s reliability. The authors also consider selected modeling approaches which address the gap between the short timescales required to assess operational issues and the long-time planning horizons of the investment decisions calculated by these models.

In Chapter 18, Role of Power System Flexibility, Andreas Ulbig and Goran Andersson analyze the role of operational flexibility in power systems and its value for integration of high-penetration shares of renewable energy source in power grids. The chapter introduces a new method for assessing the technically available operational flexibility along with illustrative examples. An important research topic is how to quantify flexibility in a given power system. The authors discuss necessary metrics for defining power system operational flexibility, namely the power ramp rate, power and energy capability of generators, loads, and storage devices.

In Chapter 19, The Danish Case: Taking Advantage of Flexible Power in an Energy System with High Wind Penetration, Anders N. Andersen and Sune Strom describe how wind generators and decentralized combined heat and power (CHP) plants can contribute to efficient balancing of power systems. While other grids around the world have different mixes of load, generators, and interconnection to neighboring systems, this Danish case study challenges the conventional thinking about the how variable generation impacts grid operations. Under the right conditions, wind generation can contribute to operational flexibility of power systems.

The chapters in Part 7, Demand Response and Distributed Energy Resources, explore the application of demand response (DR) and distributed energy resources (DER) to help accommodate higher penetration of renewable energy in power grids.

In Chapter 20, DR for Integrating Variable Renewable Energy: A Northwest Perspective, Diane Broad and Ken Dragoon provide a study on the use of demand response in the US Pacific Northwest region. This region, which has large amounts of hydropower, is experiencing the same rapid growth in variable renewable generation that is occurring in many other parts of the world. However, the limits to flexibility are now being reached and the region has embarked upon a number of demand response pilot projects demonstrating the ability of loads to both rise and fall to help accommodate new renewable resources. Despite the pilot projects’ success in showing how demand can help integrate renewable energy at low cost, the development of markets and policies is likely needed to achieve widespread commercial application.

In Chapter 21, Case Study: Demand Response and Alternative Technologies in Electricity Markets, Andrew Ott discusses how the PJM Interconnection’s (PJM) wholesale electricity market has evolved to promote open competition between existing generation resources, new generation resources, demand response, and alternative technologies to supply services to support reliable power grid
operations. PJM has adapted market rules and procedures to accommodate smaller alternative resources, while maintaining and enhancing stringent reliability standards for grid operation. While the supply resource mix has tended to be less operationally flexible, the development of smart grid technologies, breakthroughs in storage technologies, microgrid applications, distributed supply resources, and smart metering infrastructure have the potential to make power transmission, distribution, and consumption more flexible than it has been in the past. Competitive market signals in forward capacity markets and grid services markets have resulted in substantial investment in demand response and alternative technologies to provide reliability services to the grid operator. This chapter discusses these trends and the market mechanisms by which both system and market operators can manage and leverage these changes to maintain the reliability of the bulk electric power system.

In Chapter 22, The Implications of Distributed Energy Resources on Traditional Utility Business Model, Fereidoon P. Sioshansi explores the impact of the recent rise in distributed self-generation through solar rooftop photovoltaics, CHP, fuel cells, and a combination thereof. He also examines the impacts of increased investment in energy efficiency and requirements such as Zero Net Energy (ZNE) on the business models of utilities.

In Chapter 23, Energy Storage and the Need for Flexibility on the Grid, David Mohler and Daniel Sowder present a case study on how energy storage is used to facilitate integration of renewable energy in the distribution grid. Energy storage is considered by many to the distributed resource that could transform the entire power industry as related technologies become more cost competitive. Stated differently, energy storage enables supply and demand to be balanced even when the generation and consumption of energy do not occur at the same time. The authors examine the ability to flexibly move energy across time as a tool that can be applied in many different applications on the electric grid. Several illustrative examples are also provided.

The two chapters in Part 8, Variable Energy Resources in Island Power Systems, explore some of the problems and solutions around integrating variable renewable energy on island power systems. Because of their isolated geographic locations, most island power systems have highly developed renewable energy resources. However, as these systems are typically not interconnected to other systems, they present a unique set of challenges when dealing with the intermittent nature of renewable resources.

In Chapter 24, Renewables Integration on Islands, Toshiki Bruce Tsuchida provides a summary of the paths and issues encountered by forward-leaning islands that have been planning and implementing ways to integrate renewables at penetration levels in excess of 30%, a level higher than any interconnected system in the world. Challenges ranging from long-term planning to short-term operations require island system operators to meld existing technologies and further explore innovative technology options. The challenges these island systems face when addressing renewable integration amalgamate a variety of issues considered as separate topics in interconnected grids, ranging from smart grid and distributed generation, to climate policy, system resilience, and storage technologies. For the first time in history, island systems are the test bed of innovative technologies that can potentially lead the future of large interconnected systems.

In Chapter 25, Glaucio Nery Taranto and Tatiana M. L. Assis present a case study from Brazil on Intentional Islanding of Distribution Network Operation with Mini Hydrogeneration. The abundant presence of large river basins made Brazil a worldwide powerhouse of hydroelectricity. According to official numbers, the installed capacity of hydrogeneration in the country surpasses 70%, which, in a favorable precipitation year, can account for over 90% of the country’s annual electric energy needs.
The highly industrialized southern part of the country, although largely hydro-based, currently faces an exhaustion of its hydro capacity, and is exploring alternative renewable sources by exploiting small hydro plants. Due to hilly terrain in large parts of the country, and to government incentives, more mini hydro plants generating a few megawatts each are being used to supply small towns in rural areas, which are essentially island power systems. This chapter focuses on a case study of a real mini hydropower plant connected to a 25 kV rural distribution feeder located within Brazil’s south eastern state of Rio de Janeiro.

Part 9, Solar, Tidal, and Wave Energy Integration, explores the integration of emerging low-carbon technologies. While wind and solar PV account for most of the variable renewable energy produced today, technology advances are increasing the future outlook for electricity generation from large-scale grid-connected solar plants, wave and tidal energy, as well as mass deployment of solar PV in large power systems.

In Chapter 26, Economic and Reliability Benefits of Large-Scale Solar Plants, Udi Helman examines the economic valuation methods used by utilities and regional energy planners to determine the net costs of adding renewable energy sources. The net cost equation is the renewable plant’s contracted cost or estimated levelized cost of energy plus its transmission and integration costs, minus its energy, ancillary service, and capacity benefits. Helman reviews key findings in large and growing research literature analyzing components of this net cost equation for solar resources, both on an individual project level and as components of expanding renewable portfolios. He also discusses the operational limits and the use of storage to cope with the growing presence of solar plants.

Chapter 27, State of the Art and Future Outlook for Integrating Wave and Tidal Energy by Timothy R. Mundon and Jarett Goldsmith discuss key aspects of wave energy and tidal energy as separate areas and describe the key features of each resource, including the basic principles involved in generating electric power. It highlights the variability of the resources and explains how we may use modern tools to predict power and energy output in order to successfully integrate these resources in power grids.

In Chapter 28, German Renewable Energy Sources Pathway in the New Century, Matthias Müller-Mienack presents a case study about Germany which focuses on challenges with integrating renewable and the solutions being explored by Transmission System Operators (TSOs) in the country. The particular problems with the occurrence of 50.2 Hz frequency and potential risks this poses to grid operation and the design standards for new PV devices are discussed.

Finally, the chapters in Part 10, Enabling and Disruptive Technologies for Renewable Integration, present new approaches and illustrative examples for applying advances in control systems, measurement and sensing devices, visualization tools, methodologies for decision support systems, data mining and analytical tools, and high-performance computing to integrate variable renewable energy resources.

In Chapter 29, Control of Power Systems with High Penetration Variable Generation, Christopher L. DeMarco and Chaitanya A. Baone consider new challenges that wind and photovoltaic pose to the existing philosophies of primary and secondary control practices in power systems operations. The authors consider the impact of potentially very different control characteristics of the new power-delivery technologies of renewables. If increased penetration of renewable generation brings a new class of control actuators to the power grid, in a complementary fashion, increasing penetration of phasor measurement units (PMUs) brings a new class of sensor technologies. The chapter approaches renewables’ control design differently, seeking to answer two salient questions: (1) what are the
objectives associated with primary control that are necessary to maintain stable, secure operation of the power grid with more renewables and (2) what control actions can renewables and storage provide to help meet these objectives, while remaining within their operating limits?

In Chapter 30, Enhancing Situation Awareness in Power Systems under Uncertainty, Mica R. Endsley and Erik S. Connors address the increasingly important need for high levels of situation awareness (SA) to ensure the reliable and sustained operation of today’s highly interconnected electric power systems. As the industry advances toward a more renewables and energy-friendly smart grid, compensating for the complications and challenges that variable generation imposes on operator’s SA within transmission and distribution control centers becomes increasingly important. This chapter discusses how to overcome uncertainty and variability with renewable resources through the use of SA-Oriented Design to ensure that system operators are presented with the right information in an effective and integrated manner, so that they can develop the proper mental models to fully understand the state of a complex and dynamically changing system, project future changes, and respond in a timely manner.

In Chapter 31, Managing Operational Uncertainty through Improved Visualization Tools in Control Centers with Reference to Renewable Energy Providers, Richard Candy presents a case study from South Africa. The installation of renewable generation in power systems is tantamount to throwing large stones into a quiet pond. The consequences are similar in that both cause waves and surges that disrupt the harmony of the system. In order to account for the disruption and unpredictability of renewable energy providers, additional tools are needed to both visualize and manage the uncertainty and to soften the impact on the control staff. Classical SCADA and alarm systems simply do not have the ability to deal with the situation. Classical SCADA and alarm systems simply do not have the ability to deal with the situation. The chapter describes a completely different approach to designing and implementing visualization tools in control centers, one in which the environmental factors that drive the uncertainty in renewable energy and the SCADA monitoring systems are combined, on a common platform, to provide the control staff with predictability and full situational awareness of these disruptors.

In Chapter 32, Dynamic Line Rating (DLR): A Safe, Quick, and Economic Way to Transition Power Networks toward Renewable Energy, Peter Schell describes dynamic line rating (DLR) and the role it can play in making renewable energy integration quicker, cheaper, and safer. He explains how DLR fits within the bigger picture of future grid planning and operation with high penetration of renewable energy resources. The current-carrying capacity of an overhead line depends on the ambient conditions. The more the line is cooled, the more current can be carried without exceeding safe operational limits. In today’s power systems, with their increasing variability and need for flexibility, this weather-dependent variable, i.e. dynamic capacity, can be put to good use. But DLR is not as simple as it seems. The chapter concludes with an overview of the key challenges and possible solutions for DLR implementation.

In Chapter 33, Monitoring and Control of Renewable Energy Sources Using Synchronized Phasor Measurements, Luigi Vanfretti, Maxime Baudette, and Austin White provide an overview of how synchrophasor technology can be applied for developing real-time PMU applications, which help in monitoring and control of unwanted dynamics that are a product of renewable energy sources interacting with the power grid. Different paradigms for PMU-based monitoring and control systems are described and software environments for developing PMU applications are discussed. An example is presented to illustrate the development of real-time monitoring tools for the detection of subsynchronous wind farm oscillations, and the testing and validation of experiments performed using
historical data and laboratory experiments. The chapter concludes with an outline for the development of new PMU applications that aid in the monitoring and control of renewable energy sources and their interaction with the grid.

In Chapter 34, Every Moment Counts: Synchrophasors for Distribution Networks with Variable Resources, Alexandra von Meier and Reza Arghandeh address how the direct measurement of voltage phase angle might enable new strategies for managing distribution networks with diverse, active components such as wind and solar plants. Historically, power distribution systems did not require elaborate monitoring schemes. With radial topology and one-way power flow, it was only necessary to evaluate the envelope of design conditions. But the growth of distributed energy resources such as renewable generation, electric vehicles, and demand response programs introduces more short-term and unpredicted fluctuations and disturbances, and the increased likelihood of two-way flow of power. This suggests a need for more refined measurement, given both the challenge of managing increased variability and uncertainty, and the opportunity of recruiting diverse resources for services in a more flexible grid. Specifically, von Meir and Arghandeh discuss high-precision synchrophasors, or microphasor measurement units (μPMUs), that are tailored to the particular requirements of power distribution in order to support a range of diagnostic and control applications, from solving known problems to unveiling as yet unexplored possibilities.

Finally in Chapter 35, Big Data, Data Mining, and Predictive Analytics and High-Performance Computing, Philippe Mack explores how we can extract value from, and make use of, the huge volume of data generated in power systems operations in order to better integrate large amounts of intermittent renewable energy resources. After a brief history of the evolution of what is now known as “Big Data,” Mack provides an overview of sources of data in grid operations. He then discusses various data mining techniques, as well as tools for predictive analytics and high-performance computing. Examples of applications of predictive analytics to power systems and renewable integration are presented.

The book concludes with the Epilogue in which J. Charles Smith provides a future outlook on integration of variable resources in power grids and electricity markets. Although no one likes to make predictions, Smith makes bold, yet reasonable, projections of the near future based on society’s increasing demand for a decarbonized energy future. In addition, technology advances and continued reduction in costs make wind, solar, and emerging low-carbon energy technologies well positioned to supply a larger portion of the insatiable energy demand in the world. Smith stresses the fact that we need not wait until all challenges to integrating renewables are addressed. Instead, we must continue to make progress down the road to meet all of the challenges of the future by using what we already know. Smith concludes with the words of the singer/songwriter Bob Dylan, “The answer, my friend, is blowin’ in the wind,” but then he adds that as we look over our shoulder, we should be aware that here comes the sun!

WHO SHOULD READ THIS BOOK

The intended audience for this book includes transmission and distribution grid operators and planners; electrical, mechanical, power, control, sustainability, and systems engineers; energy economists; government regulators and utility business leaders; researchers; students; and investors in, and developers of, renewable energy technologies and projects.
HOW TO READ THIS BOOK

This book covers a broad set of both theoretical and practical aspects of renewable integration. It is intended to be more of a reference volume than a standard textbook. Therefore, depending on the specific area of interest, the reader is encouraged to skip to the relevant chapter. Each chapter contains references to additional related literature that will provide more detailed information for interested readers.

Questions and feedback about the book can be sent to editor@renewenintegrate.com.
Chapter 18 – Role of Power System Flexibility
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1. Introduction

In recent years power system dispatch optimization and real-time operation are becoming more and more driven by several major trends which include notably:

1) The wide-spread deployment of variable Renewable Energy Sources (RES), i.e. wind turbines and PV units, in many countries worldwide has led to significant relative and absolute shares of power generation that is significantly fluctuating and not perfectly predictable nor fully controllable. Well-known operational issues caused by variable RES power in-feed are non-deterministic power imbalances and power flow changes on all grid levels.

2) The growing power market activity on the increasingly integrated national and transnational power markets has led to operational concerns of its own, i.e. deterministic frequency deviations caused by transient power imbalances due to more frequent changes in the now market-driven operating set-point schedules of power plants as well as more volatile (cross-border) power flow patterns.

3) The emergence of a smart grid notion or vision as a driver for change in power system operation: Using the reference frame of control theory, the term smart grid can be understood as the sum of all efforts that improve observability and controllability over individual power system processes, i.e. power in-feed to the grid and power out-feed from the grid as well as power flows on the demand/supply side, happening on all grid levels.

Altogether, these developments constitute a major paradigm shift in the management of power generation and load demand portfolios. Operating power systems optimally in this more complex environment requires a more detailed assessment of the available operational flexibility at every point in time.

Operation flexibility in power system operation and dispatch planning is of importance and has a significant commercial value. Ancillary service markets enable system operators the cost-effective
procurement of needed control reserve products. In the case of frequency control schemes which are in
essence a set of differently structured flexibility services provided to system operators for achieving
active power regulation on different time-scales [1], the overall remuneration for providing control
power and energy on ancillary service markets is usually significantly higher than for bulk energy
from spot markets [2]. The value of operational flexibility can also be shown indirectly by looking at
the in flexibility costs incurred by conventional generation units in the form of ramping costs as well as
plant start/stop costs.

In some power markets, the real or merely perceived inflexibility of generator units to reduce their
power output from planned set-points appears in the form of negative bids in the supply-side curve of
the merit order [3]. The negative bids may then either reflect the inflexibility costs that would be
incurred in case a plant’s power output is lowered, e.g. lower efficiency as well as wear and tear, or
simply the more general goal to keep a certain generation unit online, for example must-run generation
units that provide ancillary services or RES units that have in-feed priority.

Several sources of power system flexibility exist as is illustrated in Fig. 1. Operational flexibility can
be obtained on the generation-side in the form of dynamically fast responding conventional power
plants, e.g. gas or oil-fueled turbines or rather flexible modern coal-fired power plants and on the
demand-side by means of adapting the load demand curve to partially absorb fluctuating RES power
in-feed. In addition to this, RES power in-feed can also be curtailed or, in more general terms,
modulated below its given time-variant maximum output level. Furthermore, stationary storage
capacities, e.g. hydro storage, Compressed Air Energy Storage (CAES), stationary battery or fly-wheel
systems, and time-variant storage capacities, e.g. Plug-In Hybrid Electric Vehicle (PHEV) and Electric
Vehicle (EV) fleets, are well suited for providing operational flexibility.

Additional flexibility can be obtained from other grid zones via the electricity grid’s tie-lines in case
that the available operational flexibility in one’s own grid zone is not sufficient or more expensive
than elsewhere. Matter of fact, power import and export, nowadays facilitated by more and more
integrated transnational power markets, is used in daily power system operation to a certain degree as
a ‘slack bus’ for fulfilling the active power balance and mitigating power flow problems of individual
grid zones by tapping into the flexibility potential of other zones.
For power system operation, importing needed power in certain situations and exporting undesirable power in-feed in other situations to neighboring grid zones is for the time being probably the most convenient and cheapest measure for increasing operational flexibility. However, power import/export can only be performed within the limits given by the agreed line transfer capacities between the grid zones. In the European context this corresponds to the so-called net transfer capacity (NTC) values [4], which are a rather conservative measure of available grid transfer capacity.

**Figure 1** Sources of Power System Flexibility.

2. **Metrics for Operational Flexibility**

The term operational flexibility in power systems, or simply flexibility is often not properly defined and may refer to very different things, ranging from the quick response times of certain generation units, e.g. gas turbines, to the degree of efficiency and robustness of a given power market setup.

In the following the focus is on the basic technical capability of individual power system units to modulate power and energy in-feed into the grid, respectively power out-feed out of the grid.

For analysis and assessment purposes, this technical capability needs to be characterized and categorized by appropriate flexibility metrics. A valuable method for assessing the needed operational flexibility of power systems, for example for accommodating high shares of wind power in-feed, has been proposed by Y. Makarov et al. [5]. There, the following metrics have been characterized:

- **Power capacity** $\pi$ (MW) for up/down power regulation
- **Power ramp rate** $\rho$ (MW/min.)
- **Storage energy** $\epsilon$ (MWh)
- **Ramp duration** $\delta$ (min.)
Their respective role in modulating the operation point of a power plant and with it the relative power flow into the grid (>0) and out of the grid (<0) with respect to the nominally planned operation point is shown in Fig. 2. Here, the deliberate deviation between the nominal power plant output trajectory and the actual power output trajectory is bounded by the maximum flexibility capability, i.e. the three metrics $\rho$, $\pi$ and $\epsilon$, of the power plant in question. In the following, we will stick to the same notation as was originally proposed by Makarov et al. in [5] for the sake of simplicity and clarity.

![Figure 2](Image)

**Figure 2** Flexibility Metrics in Power Systems Operation – Ramp-Rate $\rho$, Power $\pi$ and Energy $\epsilon$. The colored areas indicate the technically feasible region for the trajectory of the operation point for going above the nominal plant output (blue region) or below the nominal plant output (orange region).

Having a closer look on the proposed flexibility metrics, the following two things can be observed:

- The ramp duration $\delta$ is actually dependent on the power ramp rate $\rho$ and power capacity $\pi$ (and vice versa) as $\delta = \pi/\rho$. Three of the four above metrics are entirely sufficient for describing operational flexibility. We will thus only consider the power-related metrics $\rho$, $\pi$ and $\epsilon$.

- An intriguing feature is that the metric terms $\rho$, $\pi$ and $\epsilon$ are closely linked via integration and differentiation operations in the time domain as shown by Eq. (1). The interaction of the individual metrics clearly exhibit so-called double integrator dynamics: energy is the integral of power, which in turn is the integral of power ramping. These three flexibility metrics constitute a *flexibility trinity* in power systems, as they cannot be thought of independently in power system operation due to the inter-temporal linking.
Using these three flexibility metrics instead of, say, only one, i.e. power ramping capability $\rho$, allows a more accurate representation of power system flexibility over a time interval. The power ramping for absorbing a given disturbance event, measured in MW/min, in a power system may be abundant at a certain time instant. But for a persistent disturbance over time, the maximum regulation power that can be provided by a generator is limited as is the maximum regulation energy that can be provided in the case of storage units, which are inherently energy-constrained. Since the share of storage units in power systems as well as their importance for the grid integration of RES in-feed is rising, the inter-temporal links between providing ramping capability and eventually reaching power/energy limits cannot be neglected when assessing the overall available operational flexibility of a power system.

Having defined these flexibility metrics as well as the causal inter-linking between them, as illustrated in Fig. 3, allows the assessment of the available operational flexibility of an individual power system unit and for whole power systems. Note that the operational constraints, i.e. min/max ramping, power and energy constraints, of individual power system units have to be considered when assessing their available operational flexibility.

![Diagram](image)

**Figure 3** Inter-temporal linking of flexibility metrics including internal storage losses (dissipation).
3. Modeling Power System Flexibility via the Power Nodes Modeling Framework

The analysis and assessment of operational flexibility necessitates a modeling framework that allows to explicitly include information on the degree of freedom for shifting operation set-points so as to modulate the power in-feed and out-feed patterns of individual power system units. This includes information on whether or not a unit has a storage and is thus energy-constrained, whether or not a unit provides fluctuating power in-feed, and what type of controllability and observability, including predictability, i.e. full, partial or none, does a system operator have over fluctuating generation and demand processes. All these properties combined define the operational flexibility of individual units.

For our modeling and assessment purposes we make use of the Power Nodes modeling framework, a unified framework for the detailed functional modeling of power system units such as

- diverse storage units, e.g. batteries, pumped hydro, ..., 
- diverse generation units, e.g. fully dispatchable conventional generators, variably in-feeding power units, and
- diverse load units, e.g. conventional (non-controllable), interruptible or thermal loads (controllable within their constraint sets), ..., 

including their operational constraints as well as relevant information of their underlying power supply and demand processes. Operational constraints such as min/max ramp rates, min/max power set-points and energy storage operation ranges, information of the underlying power system processes, i.e. fully controllable, curtailable/sheddable or non-controllable, as well as information on observability and predictability of underlying power system processes, i.e. state measures and/or state-estimation and prediction of fully or only partially observable/predictable system and control input states, can also be included.

We illustrate the workings of the Power Node notation by looking at the Power Node model representation of an energy storage unit (Fig. 4). The provided and demanded energies are lumped into an external process termed $\xi$, with $\xi < 0$ denoting energy use and $\xi > 0$ energy supply. The term $u_{\text{gen}}$ describes a conversion corresponding to a power generation with an efficiency $\eta_{\text{gen}}$, while $u_{\text{load}}$ describes a conversion corresponding to consumption with an efficiency $\eta_{\text{load}}$. The introduction of
generic energy storages in the Power Nodes framework adds a modeling layer to the classical power system modeling. Its energy storage level, the State-of-Charge (SOC), is normalized to \(0 \leq x \leq 1\) with an energy storage capacity \(C \geq 0\). We can see that the illustrated storage unit serves as a buffer between the external process \(\xi\) and the two grid-related power exchanges \(u_{\text{gen}} \geq 0\) and \(u_{\text{load}} \geq 0\). Internal energy losses associated with energy storage, e.g. physical, state-dependent dissipation losses, are modeled by the power dissipation term \(\nu \geq 0\), while enforced energy losses, e.g. curtailment / shedding of a power supply or demand process, are denoted by the waste power term \(\omega\), where \(\omega > 0\) denotes a loss of provided energy and \(\omega < 0\) an unserved load demand process. The dynamics of an arbitrary power node \(i\), which can be nonlinear, are given as

\[
C_i \dot{x}_i = \eta_{\text{load},i} u_{\text{load},i} - \eta_{\text{gen},i} u_{\text{gen},i} + \xi_i - w_i - v_i,
\]

\[
\text{s.t. } \begin{align*}
\text{(a)} & \quad 0 \leq x_i \leq 1, \\
\text{(b)} & \quad 0 \leq u_{\text{gen},i}^\text{min} \leq u_{\text{gen},i} \leq u_{\text{gen},i}^\text{max}, \\
\text{(c)} & \quad 0 \leq u_{\text{load},i}^\text{min} \leq u_{\text{load},i} \leq u_{\text{load},i}^\text{max}, \\
\text{(d)} & \quad \dot{u}_{\text{gen},i}^\text{min} \leq \dot{u}_{\text{gen},i} \leq \dot{u}_{\text{gen},i}^\text{max}, \\
\text{(e)} & \quad \dot{u}_{\text{load},i}^\text{min} \leq \dot{u}_{\text{load},i} \leq \dot{u}_{\text{load},i}^\text{max}, \\
\text{(f)} & \quad 0 \leq \xi_i \cdot w_i, \\
\text{(g)} & \quad 0 \leq |w_i| \leq |\xi_i|, \\
\text{(h)} & \quad 0 \leq v_i.
\end{align*}
\]

Depending on the specific process represented by a Power Node, each term in the Power Node equation may be controllable or not, observable or not, and driven by an external process or not. Internal dependencies, such as a state-dependent loss term \(\nu_i(x_i)\), are possible. Charge and discharge efficiencies may be non-constant and possibly also state-dependent: \(\eta_{\text{load},i} = \eta_{\text{load},i}(x_i)\), \(\eta_{\text{gen},i} = \eta_{\text{gen},i}(x_i)\). Non-linear conversion efficiencies can be arbitrarily well approximated by a set of piece-wise affine (PWA) linear equations. The constraints (a) – (h) denote a generic set of requirements on the variables. They are to express that (a) the state of charge is normalized, (b) – (e) the grid power in-feeds and out-feeds as well as their time derivatives (ramp-rates) are non-negative and constrained, (f) the supply or demand and the curtailment need to have the same sign, (g) the supply / demand curtailment cannot exceed the supply / demand itself, and (h) the storage losses are non-negative.
The explicit mathematical form of a power node equation depends on the particular modeling case. The notation provides technology-independent categories that can be linked to evaluation functions for energy and power balances. Power nodes can also represent processes independent of energy storage, such as fluctuating RES generation. A process without energy storage implies an algebraic coupling between the instantaneous quantities $\xi_i$, $w_i$, $u_{\text{gen},i}$, and $u_{\text{load},i}$. Storage-dependent losses do not exist in this case ($v_i = 0$). Equation (2) thus degenerates to the algebraic constraint

$$\xi_i - w_i = \eta_{\text{gen},i}^{-1} u_{\text{gen},i} - \eta_{\text{load},i} u_{\text{load},i}$$

(3)

More detailed information on the Power Node modeling framework can be obtained from [6–9].

Figure 4 Power Node model of an energy storage unit with power in-feed ($u_{\text{gen}}$) and out-feed ($u_{\text{load}}$).

4. Assessment and Visualization of Operational Flexibility

The functional representation of complex power system interactions using the Power Nodes notation allows a straight-forward assessment of the three metrics of operational flexibility, i.e. power ramping capability $\rho$, power capability $\pi$ and energy storage capability $\varepsilon$. Taking as an example the operational flexibility of a generation unit $i$ that also has an inherent storage function and the possibility for curtailment, e.g. a hydro storage lake, given by following Power Node modeling equation

$$C_i \dot{x}_i = -\eta_{\text{gen},i}^{-1} u_{\text{gen},i} + \xi_i - w_i - v_i$$

(4)
for providing power regulation is accomplished by calculating the set of all feasible power regulation points \{π^+(k)\} of this unit \(i\) at time-step \(k\), where up/down power regulation is denoted by '+'/'-' respectively, based on equation

\[
\{π^±(k)\} = \{u^\text{feasible}_{\text{gen},i}(k)\} - u^0_{\text{gen},i}(k) \\
= \{u_{\text{gen}} \cdot (ξ - w - v_x - Cx)\}_{k,i} - u^0_{\text{gen},i}(k) \\
s.t. \ 0 \leq u^\text{min}_{\text{gen},i}(k) \leq \{u^\text{feasible}_{\text{gen},i}(k)\} \leq u^\text{max}_{\text{gen},i}(k) 
\]

Here, \(u^0_{\text{gen},i}(k)\) denotes the nominal set-point of the generation unit and the term \(u^\text{feasible}_{\text{gen},i}(k)\) represents any operation point from the set of all feasible operating points \{\·\}. Both terms can be chosen to be time-variant, i.e. changing from one time-step \(k\) to the next. The set of all feasible operation points thus depends upon the internal status of the generation unit, as defined by the terms \(ξ_i(k), w_i(k), v_i(x_i(k))\) and \(C_i(x_i(k))\), and is bounded by the unit’s power ramping and power rating constraints (Eq. 2 b-d).

The maximum for up/down power regulation for this generation unit type is given analytically as

\[
π^±_{\text{max},i}(k) = \min [u_{\text{gen}} \cdot (ξ^\text{max} - w^\text{min} - v_x - Cx), u^\text{max}_{\text{gen},i}]_{k,i} - u^0_{\text{gen},i}(k) \\
π^±_{\text{min},i}(k) = \max [u_{\text{gen}} \cdot (ξ^\text{min} - w^\text{max} - v_x - Cx), u^\text{min}_{\text{gen},i}]_{k,i} - u^0_{\text{gen},i}(k) 
\]

in which the terms \(w^\text{min}_i(k)\) and \(w^\text{max}_i(k)\) define the minimum/maximum allowable curtailment for this generation unit. In case the primary fuel supply is controllable, the terms \(ξ^\text{min}_i(k)\) and \(ξ^\text{max}_i(k)\) define the minimum/maximum allowable primary power provision. Please note that sign of the storage power term \(Cx\) is negative when providing positive flexibility, i.e. discharging, and positive when providing negative flexibility, i.e. charging (\(Cx\) > 0).

This flexibility assessment for the power metric \(π\) (Eq. 4–6) can be extended to the other two metrics, \(ρ\) and \(ε\), via time-differentiation and integration, respectively. The flexibility assessment for all other power system unit types can be accomplished in a similar fashion. Please note that in this way, the maximum available flexibility is calculated without any consideration of how long a certain power system unit would need to reach a new operation point that allows the provision of this flexibility.

The three thus calculated flexibility metrics span a so-called flexibility volume, which can be represented in its simplified form as a flexibility cube for a generic power system unit \(i\), with the terms
\{\pi^+_i, \pi^-_i, \rho^+_i, \rho^-_i, \epsilon^+_i, \epsilon^-_i\} as its vertices or extreme points. A qualitative illustration of this is shown in Fig. 5, where the flexibility volume is cut into eight separate sectors.

**Figure 5** Flexibility cube of maximum available operational flexibility of a generic power system unit.

The evolution over time of the (maximum) available operational flexibility from a generic storage unit with both load and generation terms, \(u_{\text{load}}(k)\) and \(u_{\text{gen}}(k)\), is illustrated in Fig. 6. The plots show that the available operational flexibility is highly time-variant due to the actual storage usage over time.

**Figure 6** Time-evolution of maximum available operational flexibility (\(k = 1\)h, 12h, 24h, 48h).
However, when taking into account the internal double-integrator dynamics, the flexibility volume becomes a significantly more complex polytope object. An illustration of the more realistic but significantly more complex polytope flexibility volume is given in Fig 7. Here, the information of how long it takes to reach a certain new operation point providing a required set \( \{\rho, \pi, \epsilon\} \) of operational flexibility is explicitly given. The set of reachable operation points providing additional flexibility (green) becomes larger when the available time span is longer. The flexibility set remains, however, always smaller or becomes at most equal to a set of maximal flexibility (red) as defined by the underlying technical constraints of a given power system unit. Calculating the available set of operational flexibility that is achievable after a given number of time-steps \( k \) is equivalent to a reach set calculation, which is in general more computationally expensive than the analytic approach sketched out by Equations (6).

![Figure 7](image-url) Time-evolution for reaching available operational flexibility from a generic storage unit at the nominal operation point \((k=0)\). (Green: Evolution of available flexibility after \( k = 3h, 5h, 10h, 15h, \) Red: maximum available flexibility \((k\to\infty))\).
For the sake of simplicity in representing flexibility volumes we will stick to the simplified flexibility cubes for the remainder of this chapter.

5. Aggregation of Operational Flexibility

An important question in power system analysis is how a group or pool of power system units act together in achieving a given objective, i.e. delivering a scheduled power trajectory or providing ancillary services by tracking a control signal. Pooling together different power system units to provide a service that they cannot provide individually is an active research field. A prime example is to combine a dynamically slow power plant with a dynamically fast, but energy-constrained storage unit to provide fast frequency regulation that neither of the units could provide individually [10] due to the lack of one flexibility metric, i.e. the missing fast ramping capability $\rho$ of the power plant, or another, i.e. the small energy capability $\varepsilon$ of the storage unit.

Obtaining the aggregated operational flexibility that a pool of different power system units provides, is equivalent to aggregating the flexibility volumes of the individual units. Since these are given by more or less complex polytope sets, depending on the chosen calculation approach presented in the previous section, a well-known polytope operation, the Minkowski sum, can be employed for calculating the aggregated flexibility of the pool. In the following, we illustrate the aggregation of a slow-ramping power plant together with a fast-ramping but energy-constrained storage unit in Fig. 8. The aggregation of two or more power system units leads to the addition of individual flexibility metrics:

$$\{\rho, \pi, \varepsilon\}_\text{agg} = \{\rho, \pi, \varepsilon\}_\text{slow} + \{\rho, \pi, \varepsilon\}_\text{fast}$$

(7)

The aggregation of the operational flexibility of both units, given individually by polytope objects, is accomplished via the Minkowski sum approach

$$\rho^-_{\text{agg}} = \sum_i \rho^-_i, \quad \rho^+_{\text{agg}} = \sum_i \rho^+_i$$

$$\pi^+_{\text{agg}} = \sum_i \pi^+_i, \quad \pi^-_{\text{agg}} = \sum_i \pi^-_i$$

$$\varepsilon^+_{\text{agg}} = \sum_i \varepsilon^+_i, \quad \varepsilon^-_{\text{agg}} = \sum_i \varepsilon^-_i$$

(8)
The slow-ramping unit, e.g. a thermal power plant, with \{ρ, π, ε\}_slow, is assumed to have an unlimited fuel supply, which implies that no energy constraints exist and that the energy storage capability is infinite ($ε_{\text{slow}} \rightarrow \infty$). Also, the potential power output $ρ$ is large. Dynamically slow means in this context that the power ramping $ρ$ is small. The fast-ramping storage unit, e.g. a fly-wheel or battery system, with \{ρ, π, ε\}_fast, has a limited run-time bounded by energy constraints of the storage unit and thus only a limited energy storage capability exists (0 < $ε_{\text{fast}}$ << $ε_{\text{fast}} < \infty$). As is often the case for storage units, ramping $ρ$ is large whereas power capability $π$ is comparatively small. Depending on the storage technology in use, time-dependent storage losses, $v(x)$, can be significant. This is notably the case of fly-wheel energy storage systems, where storage losses become large when going beyond a storage cycle duration of a few minutes due to bearing friction.

**FIGURE 8** Aggregation of maximum operational flexibility of individual power system units (yellow: flexibility of conventional unit with no energy constraint; blue: flexibility of energy-constrained storage unit; green: aggregated flexibility of both units).
6. Conclusion

The here presented techniques allow in a first phase the modeling and definition of operational flexibility of individual power system units by building up on our previous work on the Power Nodes modeling framework [6-7] and combining it with the valuable work of others, notably in [5].

In a second phase, the analysis and visualization of the operational flexibility of individual power system units is presented for some illustrative examples. The approaches are, however, also applicable for more complex, larger-scale power system setups.

In a third phase, the aggregation of operational flexibility from several, different individual power system units is explained and illustrated. This allows notably the analysis of the overall flexibility properties of unit pools, in which different power system units are aggregated and work together to achieve a common control objective.

References