Lecture Notes in Energy (LNE) is a series that reports on new developments in the study of energy: from science and engineering to the analysis of energy policy. The series’ scope includes but is not limited to, renewable and green energy, nuclear, fossil fuels and carbon capture, energy systems, energy storage and harvesting, batteries and fuel cells, power systems, energy efficiency, energy in buildings, energy policy, as well as energy-related topics in economics, management and transportation. Books published in LNE are original and timely and bridge between advanced textbooks and the forefront of research. Readers of LNE include postgraduate students and non-specialist researchers wishing to gain an accessible introduction to a field of research as well as professionals and researchers with a need for an up-to-date reference book on a well-defined topic. The series publishes single and multi-authored volumes as well as advanced textbooks.

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Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development
Achieving an affordable, secure and sustainable energy future is one of the central challenges the world faces today. Developing robust strategies to reach these goals requires a comprehensive understanding of the energy system, taking into account the interlinkages between fuels, technologies and policy measures. To inform policymakers on these complex questions, energy modelling and scenario analysis is an invaluable means to explore possible future energy and technology pathways and to evaluate the implications of the various options that are available.

The Energy Technology Systems Analysis Programme (ETSAP) represents a unique network in this field of energy modelling and analysis. Established in 1976 as a Technology Collaboration Programme (TCP) under the auspices of the International Energy Agency (IEA), its two energy system model generators, MARKAL (MARKet ALlocation) and TIMES (The Integrated MARAL-EFOM System), are now used by modelling teams in approximately 200 institutions across 70 countries. While concerns about energy security were the main focus of many model analyses in the 1970s (and remain just as relevant today), their focus has been broadened to also include questions about social and environmental objectives. The model applications today range from the global, regional and national level, down to the local and city level. At the IEA, ETSAP’s modelling tools have been used for more than a decade to help develop scenarios and assess clean energy technologies in the global context. For example, the IEA’s Tracking Clean Energy Progress report consists of a scenario-based assessment of current technology trends against what is needed under a 2-degree pathway.

Following the first book Informing Energy and Climate Policies Using Energy Systems Models, this new ETSAP book provides comprehensive model-based analyses of the overarching goal of the Paris Agreement. It shows that a fundamental transformation of the global energy system is required over the coming decades, driven by rapid and clear policy action to accelerate and scale-up the deployment of clean energy technologies. The analyses in this book highlight how energy models and scenarios can provide invaluable insights into decision-makers
on the interlinked policy dimensions of climate change, energy security and economic development. It also illustrates that technology and system transformations are needed not only in different parts of the energy sector but also at all levels—multilateral, national and local.

I trust readers will find within this book insights that demonstrate both the complexity and usefulness of energy systems modelling in informing technology collaboration and energy policy decision-making.

Paris, France
January 2018

Dr. Fatih Birol
Executive Director
International Energy Agency
This book addresses a number of key questions arising from the transformational global political agreement reached in Paris in December 2015 to ensure human-induced global temperature increases remain well below 2 °C. How far can countries ratchet up the mitigation ambition presented in the Nationally Determined Contributions? What is the magnitude of potential and necessary carbon dioxide removal, more particularly, biomass energy with carbon capture and storage? How can stranded assets be avoided? Is carbon neutrality achievable with technology innovation alone?

These questions are at the core of the global, national and local energy systems modelling analyses in this book that explore the feasibility of roadmaps for a well below 2 °C future. The book is written by more than 20 teams of the IEA Energy Technology Systems Analysis Programme (IEA-ETSAP), a Technology Collaboration Programme supporting about 200 energy systems modelling teams from around 70 countries, which has operated for over 40 years. A key objective of IEA-ETSAP is to assist decision-makers in robustly developing, implementing and assessing the impact of energy and climate mitigation policies with the bottom-up techno-economic models of the MARKAL/TIMES family.

This book constitutes a natural follow-up of the first book *Informing Energy and Climate Policies Using Energy Systems Models*, edited by IEA-ETSAP in 2015, prior to the Paris Agreement on climate change. The methodologies and case studies presented here illustrate how energy systems models have been and are being used to address complex energy and climate policy questions and provide critical insights into the feasibility of enhanced ambition. This responds directly to a requirement of the Paris Agreement and its Talanoa Dialogue to take stock of the collective efforts and determine how we can, all together, move the climate policy agenda forward and turn words into action.

The editors are very grateful to the chapter authors and peer reviewers who willingly shared their expertise and contributed their valuable time, without which this book would not have been possible. In addition, we acknowledge and
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Madrid, Spain
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January 2018

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