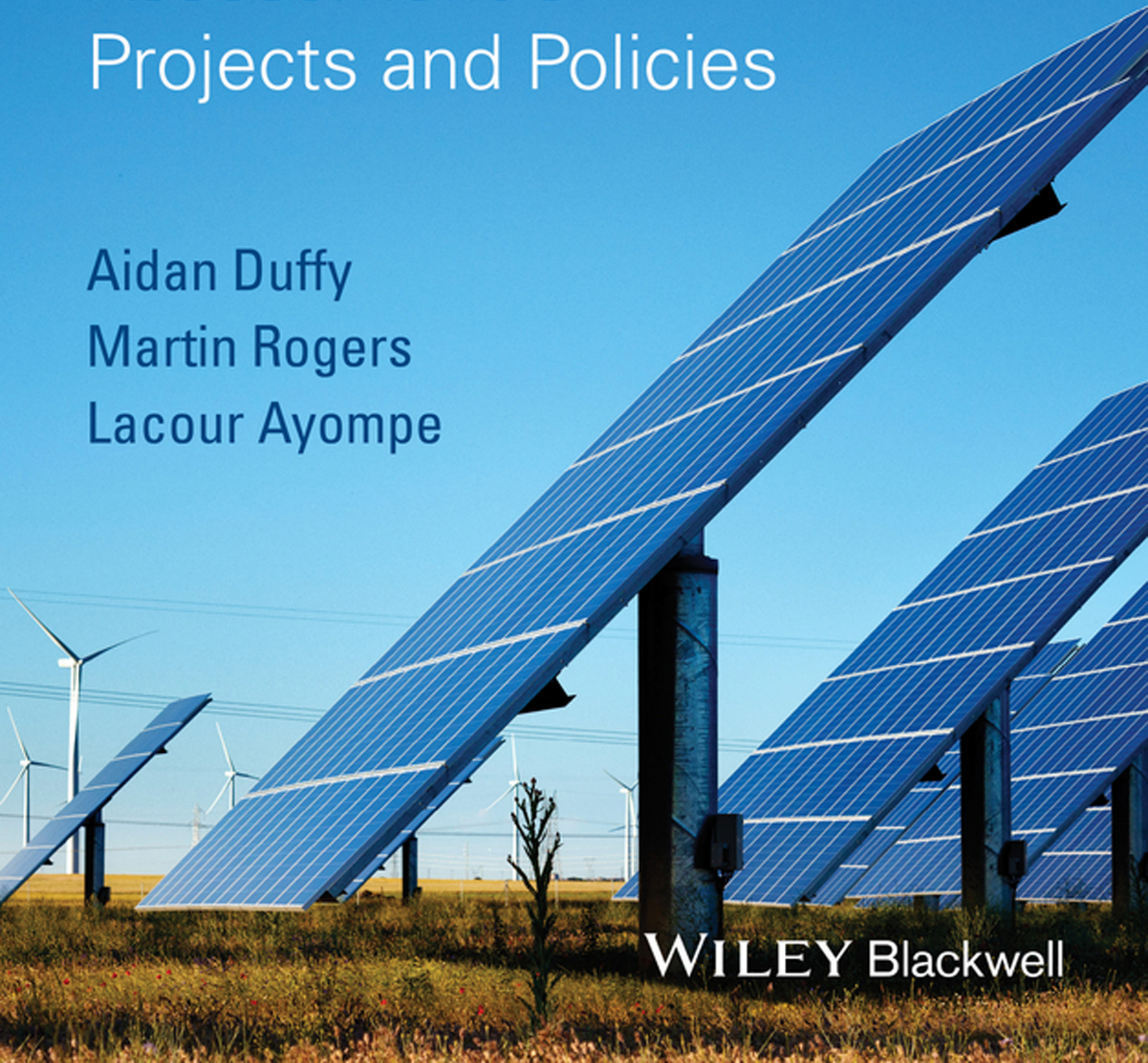
Renewable Energy and Energy Efficiency

Assessment of Projects and Policies



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WILEY Blackwell

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Symbols, Units and Abbreviations

Abbreviations

AC	Alternating Current
AHP	Analytic Hierarchy Process
BAU	Business as Usual
BAWT	Building Augmented Wind Turbine
bbl	Barrel of oil
BOS	Balance of System
CAES	Compressed Air Energy Storage
CAPEX	Capital expenditure
CBA	Cost-benefit Analysis
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CF	Capacity Factor
CHP	Combined Heat and Power
CHPC	Combined Heat and Power and Cooling
CNG	Compressed Natural Gas
CPC	Compound Parabolic Collector
CPI	Consumer Price Index
DC	Direct Current
EDC	Engine-driven Chiller
EIA	Environmental Impact Assessment
ETC	Evacuated Tube Collectors (SWHS)
ETS	Emissions Trading Scheme
FIT	Feed-in Tariff
FPC	Flat Plate Collector (SWHS)
GFA	Gross Floor Area
GHG	Greenhouse Gas
GHP	Gas Heat Pump
GWP	Global Warming Potential
HAWT	Horizontal-axis Wind Turbine
HHV	Higher (gross) heating value
HICP	Harmonised Index of Consumer Prices
HPS	High-pressure Sodium (lamp)
HVAC	Heating, Ventilation and Air Conditioning

IHA	International Hydropower Association
I-O	Input-output (LCA)
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCE	Life Cycle Emissions
LCOE	Levelised Cost of Energy
LED	Light Emitting Diode
LHS	Latent Heat Storage
LHV	Lower (net) heating value
LPG	Liquid Petroleum Gas
MAC	Marginal Abatement Costs
MARR	Minimum Acceptable Rate of Return
MAUT	Multi-attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MIRR	Modified Internal Rate of Return
NHA	National Heritage Area
NPV	Net Present Value
O&M	Operation and Maintenance
OCGT	Open Cycle Gas Turbine
PCM	Phase Change Material
PEM	Proton Exchange Membrane (fuel cell)
PHS	Pumped Hydroelectric Storage
PM10	Particulate Matter (<10μm)
PP	(Simple) Payback Period
PPA	Power Purchase Agreement
PSH	Peak Sun Hour
PV	Photovoltaic
ROC	Renewable Obligation Certificate
ROCE	Return on Capital Employed
RoI	Return on Investment
SAC	Special Area of Conservation
SAW	Simple Additive Weighting
SEA	Strategic Environmental Assessment
SHS	Sensible Heat Storage
SMP	System Marginal Price
SPF	Shadow Price Factors
SWHS	Solar Water Heating System
TES	Thermal Energy Storage
TUoS	Transmission Use of System
TYM	Typical Meteorological Year
VAWT	Vertical-axis Wind Turbine
VSD	Variable Speed Drive
WECS	Wind energy conversion system

Symbols and Units

A	Area	m^2
A	Annuity Factor (Chapter 6)	dimensionless
C	Cost	€
CBR	Cost-benefit Ratio	dimensionless
CDF	Cumulative Discount Factor	dimensionless
CF	Capacity Factor	dimensionless
CF	Net Cash Flow	€
$CO_2\text{-}eq$	Carbon dioxide equivalent	g
COP	Coefficient of Performance	dimensionless
C_p	Power Coefficient (wind turbine)	dimensionless
C_p	Specific Heat Capacity	J/kg °C
CPI	Consumer Price Index	dimensionless
CS	Capital Subsidy	€/W
D	Debt	€
d	Discount Rate	%
DF	Discount Factor	dimensionless
DPP	Discounted Payback Period	y
E	Equity	€
E	Energy (or Electrical Energy)	J or Wh
e	Inflation	%
EAC	Equivalent Annual Cost	€/y
EI	Emissions Intensity	g CO_2-eq/€
F	Cash Flow	€/time interval
FIT	Feed-in Tariff	€/Wh
g	Acceleration due to gravity	m/s^2
G_t	In-plane Solar Radiation	W/m^2
H_{m0}	Significant Wave Height	m
HR	Heat Rate	kJ/kWh
irr	Internal Rate of Return	%
LCC	Life Cycle Cost	€
LCE	Life Cycle Emissions	gCO_2-eq
$LCOE$	Levelised Cost of Energy	€/Wh
LR	Learning Rate	%
M	Mass	g
$\dot{m}$	Fluid mass flow rate	kg/s
MAC	Marginal Abatement Costs	€/gCO_2-eq
MAD	Mean Absolute Deviation	dimensionless
$MAPE$	Mean Absolute Percentage Error	dimensionless
$MARR$	Minimum Acceptable Rate of Return	%
$mirr$	Modified Internal Rate of Return	%
MPE	Mean Percentage Error	dimensionless
N	Number	dimensionless

NPV	Net Present Value	€
P	*Power*	W
P	Cost	€
PI	Profitability Index	dimensionless
PP	(Simple) Payback Period	y
PR	Progress Ratio	dimensionless
Q	Fuel	Wh
Q	Heat	Wh
Q	Quantity	g, l, m^3 ,Wh, etc
r	Return (financial)	%
$ROCE$	Return on Capital Employed	%
RoI	Return on Investment	%
SF	Solar Fraction	dimensionless
SIR	Savings-to-investment Ratio	dimensionless
t	Time	y, h, s
T	Tariff	€/Wh
T	Corporate Tax Rate	%
Ta	Tariff	€/Wh
U	Unit Heat Loss Rate (U-Value)	W/m^{2}K
v	Velocity	m/s
$WACC$	Weighted Average Cost of Capital	%
η	Efficiency	%
ρ	Density	g/m^3
n_p	Payback Period	yrs

Subscript Symbols

aux	Auxiliary
av	Avoided
c	Investment, Capital
$comp$	Compressor
cw	Chilled Water
d	Debt
dem	Demand
dt	Displaced Technology
e	Equity
el	Electrical
ER	Round-trip
ex	Export
f	Fluid, Fuel
fv	Future value
g	Gas
gen	Generator

h	Heat
i, in	Input, Inflows
i,j,n	year
inv	Inverter
loss	Losses
main	Maintenance
n	Nominal
n	Net
no	Net Operating
o	Output, Outflow
out	Output
pv	Present Value
r	Real
s	Sector
s	Saving
sto	Stored
th	Thermal
TUoS	Transmission Use of System
u	Useful

About the Companion Website

This book's companion website www.wiley.com/go/duffy/renewable provides you with case study material to further your understanding of Renewable Energy and Energy Efficiency.

1

Introduction

Energy-efficient projects use alternative technologies, fuels and management systems to reduce heat and electricity consumption. Renewable energy-supply projects produce heat and electricity using sources of energy which are regenerated over short time periods. Their recent rise to prominence in modern society has been driven by their low environmental impacts relative to fossil-fuelled alternatives. However, as they mature, energy-efficient and renewable energy technologies must demonstrate not only their environmental benefits but also their economic competitiveness. This book focuses on the assessment of projects using approaches that take into account the unique economic, environmental and energy characteristics of renewable and energy-efficient technologies.

The global demand for energy-supply and efficiency projects has never been greater. Between 2012 and 2035, the demand for primary energy and electricity is estimated to increase by half and 70%, respectively, mainly in developing countries, while in developed countries the ongoing shift to energy-efficient and low carbon supply technologies are projected to continue. These trends are driven by many – mostly inescapable – factors: a growing global population, increasing wealth, uncertainty of fossil fuel price, security of supply concerns and enhanced policies to combat greenhouse gas (GHG) emissions and global warming. For example, by 2013, China, the European Union (EU) and Japan had adopted emission-reduction targets, while California, Australia, New Zealand and the EU had introduced carbon emissions trading schemes. Assuming the implementation of such existing policy commitments only, it is projected that between 2010 and 2035, a $37tn investment will be required in the world's energy-supply infrastructure and as much as $11.8tn will be spent on energy-efficient measures across all economic sectors (IEA, 2012).

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Aidan Duffy, Martin Rogers and Lacour Ayompe.

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Each of the myriad of energy efficiency and supply projects which will comprise these investments must be identified, shortlisted, modelled and economically assessed before it can be financed and implemented. Some will be very large investments such as nuclear or hydro power schemes; others will be small energy-efficient measures such as the installation of domestic attic insulation. All require a systematic approach to assessing their relative costs and benefits. The intention of this book is to present and illustrate the assessment tools necessary to make these decisions as efficiently as possible.

1.1 Background

The history of assessing the costs and benefits of energy projects is probably as long as humans have been harnessing energy for their needs. Hunter-gatherers must have recognised that the advantages of cooking, light and warmth from fires outweighed the time and effort involved in collecting the necessary fuel. However, it was not until the 18th century that the formal process of investment appraisal (or capital budgeting) emerged as a discipline, which focused on quantifying the benefits of long-term capital investments to companies. Assessing the cost-effectiveness of energy investments became much more important as a result of the 1973 oil and 1979 energy crises, which resulted in real oil prices increasing from a long-term historic average of about \$20/barrel (\$/bbl) to \$60 and then over 100\$/bbl (Figure 1.1). This heralded a much greater level of interest in energy-efficient and renewable

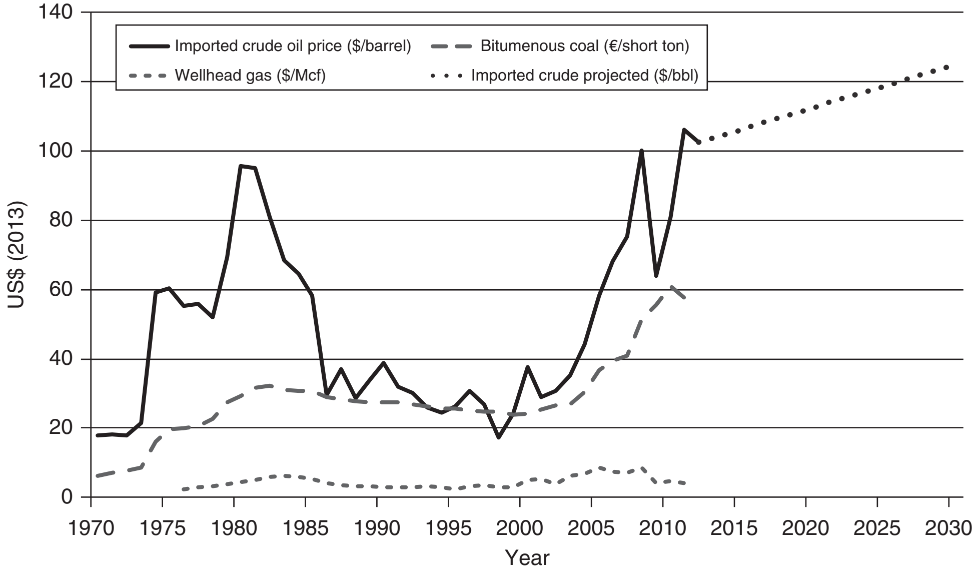

Figure 1.1 Real prices ($2013) of US imported crude oil, wellhead natural gas and bituminous coal, 1970–2012 (US EIA, 2013), and projected oil price in 2030 (IEA, 2012).

energy-supply technologies as economic alternatives to fossil fuels. With the long-term rise in fossil fuel prices since the 1970s and projections for this trend to continue, the investment appraisal of energy projects has continued to become increasingly important (see Figure 1.1).

While the process of investment appraisal has been developed to meet the needs of the private investors of a project, the costs and benefits to the wider community are often ignored, often because they have no market value and are thus difficult to quantify. As energy-supply infrastructure became more widely deployed in developed countries in the mid-20th century and as societies became more environmentally and socially aware, these costs and benefits became more apparent. For example, coal combustion for industrial and domestic heating caused smog, resulting in increased morbidity, higher health costs and lost productivity; hydroelectric dams were built without sufficient consideration of their undesirable impacts on agriculture, fishery and local communities. As these impacts often have no direct market value and are, therefore, difficult to monetise, methods other than investment appraisal become necessary. One solution to this was cost–benefit analysis (CBA or benefit–cost analysis), which was first developed in the mid-19th century but was not used in practice until the 1930s for assessing the attractiveness to society of large infrastructural projects. CBA is typically used to monetise and compare the costs and benefits of large projects or policies that have societal impacts. It attempts to approximate and account for the monetary values of non-marketed goods and services such as air and water quality, employment impacts or displaced local industry. A project is beneficial where its societal benefits outweigh its costs.

However, many large energy projects are complex and have important attributes that are difficult to either quantify or monetise or both. For example, the visual impact of wind turbines on the landscape may affect house prices for the local population and amenity value for tourists: these effects can be difficult to quantify and value. In projects of public importance where environmental and social criteria assume significant importance, purely economic approaches such as CBA or investment appraisal cannot represent all of the attributes which must be considered for an accurate assessment. The emergence of multi-criteria decision analysis (MCDA) in the 1960s and 1970s attempted to address this failure by allowing impacts on different scales to be compared. It breaks the assessment problem in smaller parts to facilitate analysis and aggregates these in a way that allows a project ranking to be made. MCDA is now widely used to shortlist options for large energy projects of public importance such as hydroelectric dams, transmission infrastructure and wind farms.

Energy policies as well as large, strategically important energy projects, which are supported by the state, must be measured not only by their value for money to their investors and wider society but also by their ability to achieve important national objectives such as GHG emission-reduction targets. In February 2005, the Kyoto agreement came into force obliging many developed countries to limit emissions of GHGs. Since then, emission mitigation has become a key energy policy objective for many industrialised countries. In order to develop and monitor policies, project appraisal techniques have been extended to measure the societal cost of climate change mitigation. One widely used metric is the marginal abatement cost (MAC) of a technology, which expresses the cost to an economy of reducing emissions by one unit by switching to a more energy-efficient or renewable energy technology. Initially, only operational emissions were considered when estimating MACs, but the low operational and relatively high production and installation emissions of renewable energy systems led to concerns about the accuracy of this approach. This has led to the increasing adoption of life cycle assessment as a method for estimating the whole life (or "cradle-to-grave") emissions of energy systems.

The development of the aforementioned economic and non-economic assessment techniques (investment appraisal, CBA and MCDA) over the past two centuries has been critical to the effective assessment of energy projects. Two more recent developments are the widespread development of personal computers (PCs) and the collection of large energy-related datasets, many of which are in the public domain. These provide both a wide variety of input data and the necessary processing power for energy-related models. PCs now support powerful programming and data analysis packages that can be configured to simulate a wide range of detailed energy systems. Hourly wholesale electricity data are publically available in Ireland; dynamic wind farm output data are freely available in Denmark, and the advent of smart metering leads to collection of energy demand data at the level of individual buildings. These enable the development of detailed dynamic numerical models which are representative of energy conversion and conservation processes, which, until even a decade ago, were not possible. The resulting ability to model accurate cash flows, pollutant emissions and other outputs provides much more knowledge for decision-making purposes than was possible heretofore.

1.2 Aim

The aim of this book is to provide the reader with the tools to shortlist and economically evaluate energy projects as well as gain an appreciation for aspects of energy policy design. Specifically, students will learn

- approaches to the dynamic modelling of energy inputs and outputs to and from a wide variety of projects employing a range of different renewable and energy-efficient technologies;
- how to extend these models to estimate cash flows and GHG emissions;
- ways of parameterising these results in order to quantify the financial and environmental performances of the projects;

- techniques for assessing and shortlisting complex projects involving non-economic impacts; and
- simple methods for designing price supports for energy technologies.

The book is written for students and practitioners alike. Undergraduate and postgraduate students will be introduced to the economic performances of a variety of technologies and to the basic concepts and frameworks of project financial assessment. Facilities' manager will learn how to provide evidence for business plans outlining their proposals for the energy retrofit and upgrade of their assets. Design engineers will benefit from understanding how to economically optimise their design solutions rather than sizing the plant and equipment to meet peak loads. Planners of large infrastructural projects will be introduced to systematic techniques for site and project screening before undertaking a detailed economic appraisal of a smaller set of project alternatives. Policy makers and planners will be introduced to the fundamentals of subsidy design for renewable and energy-efficient technologies.

The book deals primarily with renewable energy-supply and energy-efficient technologies. Renewable energy supply relates to energy conversion technologies, which use sources of energy that are naturally regenerated on a short (human) time scale, such as solar, wind, ocean, biofuels and geothermal energies. Typical technologies that convert renewable energy sources into electricity include wind turbines, solar photovoltaics (PV), biomass-driven gas and steam turbines, geothermally driven steam turbines, concentrating solar power, tidal barrages and a variety of wave-powered devices. Thermal conversion technologies are very diverse and include solar water heaters, biomass and biogas boilers and stoves and geothermal technologies. Non-renewable energy supply relates primarily to fossil fuels such as oil, coal and natural gas, which cannot be created in a human time scale and typically take many millions of years to form. Fossil-fuelled electricity generation usually employs various gas- and steam-turbine technologies, but also includes reciprocating engines, while heat generation is normally undertaken using boiler technologies and, to a lesser extent, stoves. We do not deal specifically with nuclear power in this book because this is a large topic in itself that, at the time of writing, has an uncertain medium-term future for political, economic and environmental reasons. Nonetheless, many of the principles described here can be directly applied to this technology.

Energy-efficient projects involve the use of alternative technologies, fuels and management systems to deliver the same level of service or output using less energy (irrespective of the energy-supply source). Therefore, any technology, fuel or management system has the potential to be energy efficient, because this classification is gained by comparing it to the displaced alternative. An obvious example is increasing the amount of insulation in a building to reduce heat losses, so that the same level of thermal comfort can be provided using less heat and, therefore, fuel. Burning gas instead of coal in a thermal power station can result in the consumption of less primary energy and, in this situation, may be viewed as an energy-efficient technology. It should be highlighted that although fossil-fuelled technologies are not the focus of this book, the concepts presented are equally valid for their assessment.

The learning approach adopted involves explaining each theory and providing an example in close proximity in order to illustrate and embed the concept. Larger case studies are also included to demonstrate the combination of different concepts for more complex examples. We attempt to give examples for a wide variety of industry sectors and applications to make the book as broadly relevant as possible. Examples are given for the domestic, commercial, energy and industrial sectors using single and multiple electrical and thermal technologies such as PV, solar water heaters, wind turbines, wave power, combined heat and power, boilers and insulation. In addition, a number of policy examples that illustrate feed-in-tariff and capital subsidy design are given. We attempt to make this book as practical as possible, so that the reader is able to easily apply the concepts to projects of personal interest. For this reason, the examples and case studies are made available online (www.wiley.com/go/duffy/renewable), which help the reader to gain a detailed understanding of the techniques used and apply them directly to problems of personal interest.

Finally, this book adopts a bottom-up ‘engineering’ approach to the financial appraisal of renewable energy projects. This involves the modelling, simulation and economic parameterisation of individual energy projects in isolation to the market in which they operate.

1.3 Aspects of renewable energy project appraisal

In general, the appraisal of renewable energy and energy-efficient projects is no different to the assessment of any other capital projects. Although we will see that some project performance measures are specific to the field, the main appraisal techniques described here such as investment appraisal, CBA, and multi-criteria analysis are widely applied to other investments, both large and small. Nevertheless, renewable and energy-efficient projects do have unique characteristics, which the assessor must be aware of in order to undertake a proper assessment.

Many renewable and energy-efficient projects are characterised by high initial investment costs and low operational costs. This is true for technologies such as wind, PV and solar thermal as well as energy-efficient measures such as insulation. Conventional fossil-fuelled plant, on the other hand, has lower capital costs as a proportion of total life cycle costs with relatively higher operational outgoings because of the ongoing need to purchase fossil fuels. This means that renewable energy and energy-efficient supply projects are generally less exposed to fluctuations in variable costs as compared to fossil-fuelled ones due to the high price volatility of fuel inputs, particularly oil and its derivatives. Renewables do remain exposed to fluctuations in revenues resulting from changes in the unit cost of energy outputs, such as electricity and heat, as does conventional plant, although input and output prices tend to move together, thus acting as a natural 'hedge' to revenue risk for fossil-fuelled plant. Often, the 'revenues' in renewable or energy-efficient projects are avoided costs such as the cost of grid electricity displaced by embedded generators. Revenues from many renewable projects may also include long-term price supports such as feed-in-tariffs, which provide a fixed production tariff or tariff floor. However, these can represent a significant risk because a single regulatory decision can greatly alter the basis of an initial investment decision. This political risk is exacerbated by the long payback periods needed for many renewable energy technologies. For example, PV feed-in-tariffs were reduced in the United Kingdom, Spain, Germany and Bulgaria, between 2009 and 2011. Societal imperatives can also shift quickly: the Great Recession of 2009 focused public debate on economic growth and employment while costly emissions' mitigation policies dropped down the priority list. The identification and quantification of project risk are, therefore, an important task in many renewable and energy-efficient project assessments.

The fast-changing energy and renewables landscape results in other risks too. Technology costs are evolving quickly: real capital costs of installed US commercial PV system have more than halved in the 15 years between 1998 and 2013 (Feldman et al., 2012), whereas the development of hydraulic fracturing technology has been associated with a drop in nominal US wellhead natural gas prices from \$6.25 to \$2.66/1000 ft^3 between 2007 and 2012 (US EIA, 2014). Therefore, the timing of investments in renewable energy and energy-efficient projects and policies is particularly important. For example, investing under conditions of strong global growth is likely to be more attractive as energy prices are likely to be higher giving greater certainty to short- and medium-term revenues. Moreover, technology costs in the future are likely to be lower, possibly resulting in better returns to the private investor and lower technology subsidies.

Many renewable energy technologies rely on national subsidies for a variety of reasons, not least because they may not be competitive with conventional alternatives. The approach is controversial as governments do not have a reputation for 'picking winners', particularly in a field as technologically complex as energy conversion, storage, transmission and efficiency. These subsidies include feed-in-tariffs, capital subsidies, tax rebates and renewable obligations certificates. Opponents argue that putting a price on the negative effects of fossil fuels using a carbon tax is a more efficient approach because the market would adopt the technology with the lowest marginal abatement cost, thus resulting in lower overall societal costs as compared with subsidies. However, renewables' subsidies are regarded by others as important in encouraging investment in emerging low carbon technologies, accelerating market growth and reducing technology costs. State investments in onshore wind since the 1990s, for example, have greatly contributed to a decrease of about two-thirds in the real cost of wind power plant over the past two decades. Indeed, the costs of renewable technologies are falling more rapidly than conventional technologies because they are typically less mature. However, while policy supports can result in widespread technological deployment, learning and cost reductions, they can also result in supply constraints and increased market prices. Policy makers must apply project appraisal techniques to answer the questions: What is the minimum support necessary to support a technology? Is this cost-effective in supporting key government policies such as emissions mitigation? It is important that where subsidies are introduced they represent value for money for the taxpayer.

Project assessors should be aware that renewable energy-supply technologies do not always offer identical outputs to the conventional alternatives. A unit of electricity from a wind turbine is not the same as that from a thermal power station because the latter is almost always available when it is needed (i.e. it is 'dispatchable'), whereas the former is only available when the wind is blowing and its availability cannot be guaranteed when needed (and it, therefore, is 'non-dispatchable'). An accurate comparative analysis should always compare like-with-like; for example, storage and backup should be included with intermittent renewable generation when comparing it with dispatchable plant, so that identical levels of service are provided in each case. This approach should be considered when comparing any intermittent technology (wind, solar and ocean). However, when compared to conventional alternatives, renewable energy projects can provide additional benefits to society over fossil-fuelled alternatives, which should be considered as part of the assessment process. These include emissions reductions, local employment as well as increased national security of energy-supply due to reduced import dependency (in net energy importing countries only). Social costs imposed by renewable and energy-efficient projects should also be included.

1.4 Book layout

There are five main chapters in this book that introduce the reader to the techno-economic characteristics of renewable and energy-efficient systems, financial and non-financial project assessment methods and aspects of energy policy. Each chapter includes an initial content overview before describing relevant theory; short examples are provided throughout, which apply this theory to practical applications of renewable energy and energy-efficient projects. Chapters 3–6 include concluding comments, which highlight the key concepts introduced. Case studies are included at the ends of chapters, which illustrate how complete renewable energy projects might be assessed using the main concepts introduced.

Chapter 2, 'Technologies', describes a variety of renewable energy and energy-efficient technologies, which are necessary to understand the examples and case studies described in the book. The descriptions mainly focus on those aspects that are necessary for subsequent modelling and appraisal such as efficiencies and other operational parameters, investment costs, operating and maintenance costs and environmental emissions. This is by no means a comprehensive overview of all relevant technologies because this is not the focus of the book.

The foundation of almost all financial measures of energy project performance is an accurate cash flow. For energy projects, all cash flows are directly related to energy flows to and from the system being considered. For example, the cost of running a gas-fired boiler is related to how efficient it is at converting the gas input into the necessary heat output. Quantities of gas used and heat produced represent the main costs and benefits of the system and, together with capital cost, largely determine its financial performance. Similarly, environmental impacts such as GHG emissions are largely determined by the gas inputs to the system. Therefore, Chapter 3, 'Modelling Energy Systems', is dedicated to system definition, modelling and simulation.

Chapter 4, 'Financial Analysis', uses these cash flows to create financial measures – or parameters – for renewable energy and energy-efficient projects. First, fundamental concepts are introduced, which are necessary for converting project cash flows into useful parameters. A wide variety of parameters are then presented and their strengths and weaknesses in different contexts discussed. Those of particular relevance to assessing renewable energy projects are highlighted.

Not all projects can be compared on purely economic grounds. Many other advantages and disadvantages of a particular project option may be important. For example, social, political and environmental dimensions may be particularly important for large infrastructural projects such as the construction of hydroelectric dams or the routing of large overhead transmission lines. Chapter 5, 'Multi-criteria Analysis', offers alternative methods for shortlisting and selecting projects using MCDA techniques.

Chapter 6, 'Policy Aspects', combines these financial techniques with environmental assessment methods and extends them to introduce basic concepts in policy design. An initial review of policy options for emission mitigation is followed by an overview of life cycle assessment and methods for quantifying GHG emissions from different renewable energy and energy-efficient projects. The chapter explains marginal abatement costs and subsidy design and gives a short introduction to social CBA.

Case studies are provided at the end of Chapters 3–6, which demonstrate the application of many of the key concepts introduced in these chapters. Case studies include energy and cash flow models (commercial PV systems, gas heat pumps for data room cooling, compressed air energy storage), financial appraisals (converting a bus fleet to compressed natural gas fuel, wind farm appraisal), non-economic analysis (wind farm site selection) and policy-related assessments (MAC estimation and domestic PV feed-in-tariff design). Case study spreadsheet calculations can be accessed at www.wiley.com/go/duffy/renewable.

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