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PART I

INTRODUCTION

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1 Energy Technology Innovation

Charlie Wilson and Arnulf Grubler

1 Introduction

1.1 What is Energy Technology Innovation?

Asked to "vision" their ideal future, schoolchildren agree almost invariably on one common feature of the year 2050: solar-powered flying skateboards.[1] What better example of *energy technology innovation*? Materials and knowledge combined in a novel application containing an energy conversion chain in miniature. An energy supply technology (solar panel) converts an energy resource (solar radiation) into an energy carrier (electricity). An end-use technology (electric motor and fan) converts the energy carrier into a useful service (aerial mobility). A novel combination of technologies; a novel energy service. And a very satisfied end user (schoolchildren).

The useful services provided by energy underpin life. Mobility – particularly of the flying skateboard kind – is a prominent example. Others include heating, cooling, cooking, cleaning, entertaining, communicating, information processing, industrial processing, manufacturing – the list of energy services goes on. Energy technologies are used to extract, capture, process, convert, transport, and distribute energy in its myriad forms through the transformation chains that provide us these services.

Energy technology innovations range from radical new inventions to marginal performance improvements, and encompass social and behavioural changes alongside more visible material changes in technological hardware. Innovation is most simply conceived of as novelty. Unlike natural resources, innovation originates from human endeavour or inspiration, so is an entirely human-made resource. Despite popular conceptions of the visionary genius, innovation is more sweat and application than eureka and ease. Innovation success typically means widespread diffusion and commercial uptake. But this outcome is the culmination of an often lengthy process that runs from research and development through demonstration and trials to early market formation and then diffusion. There are countless pitfalls along the way. The majority of innovation journeys end in failure, some abject, others marginal (Edgerton, 2011). Innovation is neither costless nor certain.

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[1] From the author's experience in Canadian classrooms with eight to ten year olds as part of a climate change–related lesson. The aerodynamically questionable assumption of onboard electric motors is the author's interpretation.

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1.2 Global Energy Challenges and the Rationale for This Book

First and foremost, this book is about what we have learnt about energy technology innovation based on successes and failures recorded in the pages of history. The book is developed around a varied set of twenty case studies of energy technology innovation. At the risk of disillusioning readers at such an early stage, what follows is not a lengthy treatment of solar-powered skateboards nor other technologies from the realms of science fiction. Our interest is rather more earthbound, but still far from prosaic. We are concerned with energy technology innovations ranging from solar photovoltaics in Kenya to appliances in Japan to wind power in Europe to hybrid cars in China. What we do share with solar-powered skateboards is an interest in alternatives: technological innovations largely at the fringes of our current energy system, but hoped and heralded to play an ever-greater part in our future.

Why is technology innovation important? It has played and continues to play a central role in economic growth and development. Likewise, energy technology innovation has been key in historical transformations of energy systems and services and is central to future sustainability. The context for this book is the enormous challenges facing the global energy system in mitigating climate change, in providing universal access to modern energy carriers like electricity, and in ensuring the supply and distribution of energy is secure and resilient. The *Global Energy Assessment* sets out these challenges as well as the possible pathways describing how they can be surmounted (GEA, 2012). This book is a companion volume to a chapter in the *Global Energy Assessment* that covers energy technology innovation (Grubler et al., 2012). The *Global Energy Assessment* develops the theory and practice of energy technology innovation, and explains the integral role that energy technology innovation can and will play in addressing global energy challenges. This book enriches and deepens this assessment, and offers detailed empirical support for the analysis and arguments of the *Global Energy Assessment*.

1.3 Aims and Intended Audiences

The aim of this book is twofold. The first is to develop and validate a comprehensive, integrated framework for thinking about and for analysing energy technology innovation. The second is to identify critical elements of successful innovation efforts as a basis for informing and supporting the wide range of innovation activities and policies in the energy technology innovation system.

These two aims – analysing energy technology innovation from a systemic perspective and developing insights to support successful innovation outcomes – makes this book of potential interest to a broad audience: researchers and students of innovation processes; social scientists and engineers working on energy technologies; policy makers in the domains of innovation and technology policy as well as within the energy sector; scenario developers and system planners concerned with energy transitions and technological change; financiers in the clean technology and "green" energy space; and concerned citizens curious with what we know and don't know about the role energy technologies and innovation may play in the context of future sustainability.

The historical case studies around which the book is developed require a familiarity with energy technology and an understanding of innovation concepts and terms. While the book is pitched at the informed reader, these introductory sections should provide the necessary background to understand what follows.

The policy community is one of the key constituencies for our findings. Policy can and does strongly shape the various interrelated stages of the innovation process, particularly in the case of energy technologies given their environmental and social implications. The concluding sections of the book apply the analytical framework developed to abstract generalisable policy guidelines that should work in favour of innovation success and guard against innovation failure.

2 Energy Technology Innovation: An Overview

2.1 Energy Technology Innovation Historically

Technological change has long been recognised as integral to economic growth and development (Freeman and Perez, 1988; Solow, 1957). Moreover, technological change and social change are inseparable, caught in lockstep by a web of mutual interdependencies. These change processes have played a driving role in past energy transitions from preindustrial, traditional practices, through the coal and steam era, and to the infrastructure of today (Grubler, 1998; Smil, 1994). Technological change also plays a central role in future scenarios of climate change mitigation (Halsnæs et al., 2007; Nakicenovic et al., 2000). One of the case studies in this book synthesises the "grand patterns" of technological change in the energy system, drawing parallels between historical evidence and future expectation. Four of these patterns are summarised here as they provide important context for what follows.

Firstly, the history of energy transitions is predominantly characterised by changing types and amounts of energy end-use services. The characteristic large-scale features of the energy supply – mines, rigs, pipelines, grids, power plants, refineries, dams, and turbines – are ultimately driven and shaped by growth and changes in the demand for energy services. End-use applications and their contribution to the proliferating array of consumer goods and services are the most important markets for new energy technologies.

Secondly, many technology innovations, including in the energy field, tend initially to be crude, imperfect, and expensive (Rosenberg, 1994). But they gain a market foothold by offering a novel energy service attractive to a distinctive set of users in a particular market niche. Thus shielded from the winnowing force of full market competition, technologies undergo an iterative process of testing, improvement, adaptation, even redesign, until the costs of providing the particular energy service fall to the point at which they become attractive to the wider market. Such technologies may then enjoy widespread commercialisation and diffusion: the ultimate outcome of innovation success. But attractiveness beats cheap, at least initially.

Thirdly, technological change from innovation through to widespread diffusion is generally slow, lasting as a rule many decades. The innovation process itself is constantly iterating back and forth. Moreover, a technology is not adopted and used in isolation. Dependent on related technologies and infrastructures, but also business models and wider market and social institutions, an energy technology's diffusion is contingent and necessarily gradual (Hughes, 1983). But these same

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interdependencies, which take considerable time to develop, also give rise to a self-reinforcing process by which successful technologies reach a position of dominance and so themselves become entrenched, a condition known as "lock-in" (Cowan and Hulten, 1996; Unruh, 2000).

Fourthly, the transformative potential of energy technologies arises through clustering and spillovers (Grubler, 1998). Clustering means combinations of interrelated technologies. Spillovers mean applications of technologies beyond their initial designation or use. In short, technologies operate more effectively as "gangs" than as individuals. This again implies slower potential rates of change, exacerbated by the capital intensiveness and long-lived nature of many energy technologies and their associated infrastructures.

These four "grand patterns" observed historically are reflected clearly in the treatment of energy technology innovation developed in this book. Indeed, as we will argue, the importance to historical energy transitions of end-use services, of performance and cost advantages, of interdependencies and inertia, and of clustering and spillovers, underscores the need for a *systemic perspective* on energy technology innovation.

2.2 Energy Technology Innovation: Concepts and Terms

Like any field of study, energy technology innovation has its own particular concepts and terms. While we have tried to ensure the writing is accessible to those with a general grounding in energy and innovation studies, these introductory chapters go over the key ideas and define the key terms needed to engage with the case study chapters that follow (see also Table 1.1).

Figure 1.1 starts by introducing and organising the key elements of energy technology innovation. These are: (i) the stages of the innovation process; (ii) the flows and feedbacks between these stages; (iii) the influence of both technology-push and market-pull drivers; (iv) the relevance of both energy supply and energy end-use technologies.

Technologies move sequentially through a "life cycle" from birth (invention, innovation), to adolescence (growth), maturity (saturation), and ultimate senescence (decline driven by competition from newer and more attractive innovations). Models of innovation describe the drivers and mechanisms behind this technology life cycle. Their intellectual history goes back to the nineteenth century and Marx's conceptualisation of technological innovation in his economic theories. In the early and mid twentieth century, Schumpeter (1942) emphasised the importance of radical, disruptive, or "breakthrough" technologies driven by entrepreneurship and competition, while scholars such as Usher (1929) pointed to the compounded effects of numerous, small, "incremental" innovations.

Early models of the innovation process, such as those formulated in the influential U.S. report, "Science the Endless Frontier" (Bush, 1945), emphasised the role of basic, publicly funded science in a linear innovation process from basic research to applied development, then demonstration in a commercial setting, concluding with widespread diffusion.

These innovation stages are shown in the centre of Figure 1.1. The innovation processes are the linkages from stage to sequential stage. But as can be seen, the

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Table 1.1. Definition of key terms used to describe energy technology innovation.

	Key term	Definition as used in this book
Innovation Processes & Stages	invention	origination of an idea as a technological solution to a perceived problem or need
	innovation	putting ideas into practice through a (iterative) process of design, testing, application, and improvement
	research & development (R&D)	knowledge generation by directed activities (e.g., evaluation, screening, research) aimed at developing new or improving on existing technological knowledge
	demonstration	construction of prototypes or pilots for testing and demonstrating technological feasibility and/or commercial viability
	research, development & demonstration (RD&D)	a commonly used grouping of the main precommercial stages of the innovation cycle
	niche markets	application of a technology in a limited market setting (or niche) based on a specific relative performance advantage (or on public policy incentives) and typically protected in some way from full market competition
	market formation	activities designed to create, enhance, or exploit niche markets and the early commercialisation of technologies in wider markets
	diffusion [also: deployment]	widespread uptake of an energy technology throughout the market of potential adopters
	innovation or technology life cycle	the sequence of processes and stages of an innovation's journey from invention right through to senescence or obsolescence
Types of Innovation	radical innovation [also: breakthrough, disruptive]	a novel technology that strongly deviates from prevailing norms and so often entails a disruptive change over existing commercial technologies and associated institutions
	incremental innovation [also: continuous]	an improvement in performance, cost, reliability, design, etc. to an existing commercial technology without any fundamental novelty in end-use service provision
Drivers of Innovation	technology-push [also: supply-push]	forces driving the generation of innovations (e.g., by reducing innovation costs)
	market-pull [also: demand-pull]	forces driving the market provision of innovations (e.g., by increasing innovation payoffs)
Types of Energy Technology	energy supply technologies	technologies used to extract, harness, transport primary energy resources (e.g., coal, uranium, sunlight) and convert them into secondary and final energy (e.g., petrol, electricity)
	energy end-use technologies	technologies that convert final energy into a useful service to end users (e.g., heating, mobility, entertainment)

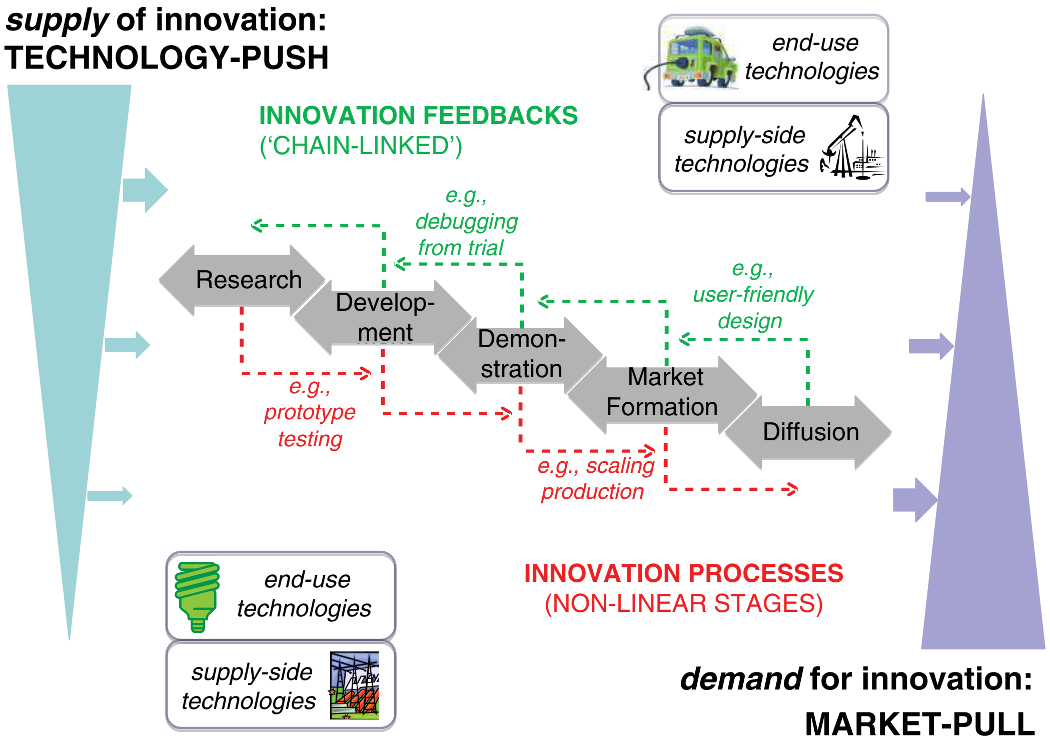

Figure 1.1. Key elements of energy technology innovation.

innovation life cycle is no longer considered linear nor unidirectional (Freeman, 1994; Mowery and Rosenberg, 1979). This has given rise to the term *chain-linked model* (Brooks, 1995; Kline and Rosenberg, 1986) shown in the centre of Figure 1.1 with the stages of innovation linked in both directions by innovation processes and innovation feedbacks. So, as an example, knowledge does not just flow from basic scientific research to technology development and commercialisation; technological applications can also enable breakthroughs or discoveries in basic scientific research. The sequence of stages is also not prescriptive. Some technologies are successful without having proceeded through each stage in the innovation process (Grubler, 1998).

Related to these bidirectional flows and feedbacks is a recognition that the innovation process is driven by forces of both supply and demand, reducing the costs of innovation on one hand, and increasing the payoffs from innovation on the other (Nemet, 2009). These are shown on the left and right sides of Figure 1.1. Supply-side forces push technologies through the development process to commercialisation, hence also "technology-push." The supply of innovation emphasises the interests and roles of scientists, researchers, prototypers, product developers, engineers and designers, and venture capitalists seeking to promote and provide new goods and services. In contrast, demand-side forces signal a market appetite that pulls technologies through the development process, hence also "market-pull." The demand for innovation emphasises the interests and roles of consumers, end users, and public institutions expressing their needs or desires for new goods and services. As we will see, these "technology-push" and "market-pull" drivers do not work in isolation; not only are they complementary, they are also both necessary.

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Figure 1.1 also includes an additional stage of "market formation" that separates widespread diffusion from the key innovation stages of research, development, and demonstration (RD&D). The specific inclusion of market formation recognises the major hurdle faced by technologies as they start to compete with their incumbent rivals in a market environment. Apparently successful innovations may fall in this "valley of death" if they are too expensive, offer too indistinct performance advantages, are too difficult to scale up, or lack a clear perceived market demand. Market formation activities support new technologies through this early competition. In some cases, natural market niches are formed if a particular group of end users is less price sensitive and accords particular value to the relative advantages of the new technology (Kemp, Schot, and Hoogma, 1998).

Finally, Figure 1.1 highlights that this simple model of the innovation process in an energy context applies both to energy supply technologies and to end-use technologies. Energy supply technologies are used to extract, process, transport, and convert energy resources into a form useful to end users. Examples include solar panels, oil refineries, natural gas pipelines, and nuclear power plants. End-use technologies are used to convert final energy into useful energy and then to services like heating, mobility, or communication. Examples include boilers, cars, and mobile phones. The relevance of this energy supply and end-use distinction is discussed further in the next chapter.

2.3 Energy Technology Innovation in a Nutshell

So what is energy technology innovation? The simple definition with which the chapter opened captures its essence: materials and knowledge combined in some novel application involving energy conversion and the provision of a useful energy service. More formally, energy technology innovation can be regarded as the embodied result of institutionalised research, development, and collective learning processes involving both suppliers and users of energy technologies operating within specific incentive structures and adoption environments. The "embodied result" is most easily visualised in physical terms (capital stock, hardware, gadgets), but can also be in the form of new social arrangements or patterns of behaviour associated with end-use services. As a general rule, technological change involves changes in hardware as well as in social or institutional settings. The "innovation environment" thus ranges from research laboratories and testing facilities for the suppliers of technologies to households or consumer goods markets and social networks.

This working definition of energy technology innovation points to the importance of the actors and institutions involved in the development and commercialisation of an energy technology innovation. This is one of the additional dimensions to the innovation processes and feedbacks shown in Figure 1.1 that we set out in the next chapter.

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