Energy Transitions to Modern Renewables: Context, Barriers, and Promises

by Stanislav Vavilov

The world is not running out of fossil fuels, as is often claimed. With technological progress and favorable economic conditions, a process of resource-base expansion occurs through the production of resources that were previously considered economically unviable. Resource-base expansion requires increasing capital investments per unit of energy extracted and an accompanying rise in production costs per unit. The world is running out of cheap fossil fuels, and in the long term, dependence on fossil fuels leads to energy services that are much more expensive and inaccessible. Given other important incentives for transitioning from fossil fuels, such as the need to mitigate global warming and eliminate the geopolitical struggles over the remaining fossil fuel reserves, the only alternative is a decades-long complex transformation of energy systems toward renewables. This brief narrates the evolution of this transition toward modern renewables by drawing on experiences of several countries and argues that these transitions will play a significant role on a global scale, because followers learn from the experience of pioneers.

Rising Production Costs as a Driver for Energy Transition to Modern Renewables

Extraction and processing technologies for most types of commonly used materials were known long before the 20th century. Nevertheless, the ability to extract, process, and transport biomass and minerals has been limited by the amount of available energy supply. The 18th and 19th centuries brought qualitative changes that were the result of two interrelated transitions in energy systems. The first transition was a change in the main source of primary energy from biomass to fossil fuels, initially coal. The second transition was a change in energy converters, or so-called end-use technologies, from human and animal power to machines, which transformed the chemical energy of fossil fuels into useful mechanical power. Energy transitions to fossil fuels and new energy converters imposed fundamental technological changes in most aspects of human activity. Energy consumption per capita, labor productivity, and consumption of materials have risen by several orders of magnitude during the last two centuries. Technological changes were also integral to economic growth and social development.[1] Historically, a higher volume of primary energy consumption meant a higher human development index, higher rates of individual wealth and life expectancy, better nutrition, and lower mortality rates.[2] Estimated at about 50 billion tons per year,[3] the current level of global material consumption would not be possible to sustain without the use of more than 13,000 million tons of oil equivalent (Mtoe) of primary energy, with 80% coming from fossil fuels.[4]

To start transformation of energy systems toward renewables, followers need to have opportunities to learn from the success and failure of pioneers. Thus, cross-national cooperation is necessary.

The total dependence of modern living standards on fossil energy has spurred debates about the long-term availability of energy resources. The assessment of the long-term availability of natural resources is often based on a rather simple reserves-to-production (R/P) ratio. Table 1 presents current R/P ratios for fossil hydrocarbons. In fact, the R/P ratio only illustrates the years it will take to completely deplete the proven reserves of a particular conventional resource estimated for a certain consumption rate at the particular year and does not reflect the fundamental process of resource-base expansion through moving "unconventional resources" to the "conventional" category (explained below). In fact, R/P figures for oil and natural gas have held steady at the level of 40 to 50 years for the past 30 years.[5]

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Table 1. Reserves, Production, and R/P Ratio for Hydrocarbons[6]

Resource	Reserves	Production	Reserves-to-Production Ratio
Oil	1,646 billion barrels (2013)	33 billion barrels per year (2013)	50 years
Natural Gas	6,810 trillion cubic feet (2012)	119 trillion cubic feet per year (2012)	57 years
Coal	980 billion tons (2011)	8.4 billion tons per year (2011)	117 years

"Best first" is a well-established principle in economic theory.[7] Historically, people tend to first use easy and cheap-to-extract (conventional) resources of coal, oil, and natural gas located close to consumers. As initial deposits become exhausted, people start to use unconventional resources, those that generally cannot be extracted with technology and processes used for conventional resources, because of lower concentrations, different geological or geographical settings, or different chemical compositions.[8] Thus, the future accessibility of unconventional resources is a question of technological progress.[9]

The difference in production costs between easy-to-access and difficult-to-access resources characterizes every energy system, even biomass-based ones.[10] Extraction of oil and natural gas from unconventional resources is characterized by higher production costs as well. Thus, inventions that allow exploitation of unconventional resources could be widely adopted only under favorable economic conditions. Given higher costs per unit of energy produced and mammoth fixed costs to install complex engineering infrastructures, expansion of the resource base by moving unconventional resources into the conventional category occurs in periods of high commodity prices, which provide economic incentives for territory expansion and innovative activity in exploration, extraction, transportation, and processing. When the flow of energy resources from unpacked unconventional deposits gluts the market, prices fall dramatically, providing economic incentives to reduce the costs of production from unconventional resources. Even under strong competitive pressure, however, producing a barrel of oil or a cubic foot of natural gas from unconventional resources costs more than producing it from conventional ones. The shale revolution in oil and natural gas production provides a great example of the process described above: costs per unit produced increased substantially when unconventional resources were involved in operations.[11]

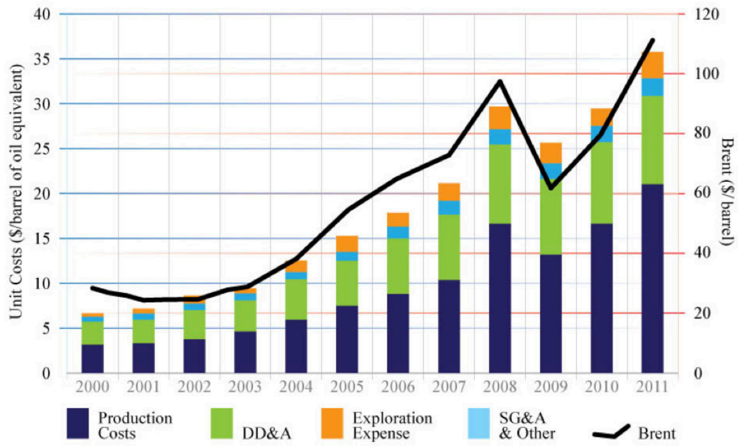
Production costs per barrel of oil increased dramatically in the last decade. In 2011, the 50 largest oil companies (except those in OPEC and former Soviet countries) were spending $35.9 to produce one barrel, almost a sevenfold increase in just one decade (see Figure 1). Unconventional resources are only a part of the reason for such a cost surge. Costs of production from conventional oil reserves also soared. Steven Kopits, managing director of Douglas-Westwood, pointed out the following:

> In 2005–2013 we [the world] have spent about $4 trillion on finding and getting the oil. Of this, $350 billion were spent on US and Canadian unconventionals, $150 billion on liquid natural gas, and $3.5 trillion were spent on maintaining the legacy of oil and gas systems in the last seven years; $2.5 trillion were spent on crude oil production alone, and that bought a decline in production of 1 million barrels per day (mbpd) compared to 2005. For comparison, in 1998–2005 we spent $1.5 trillion and added 8.6 mbpd crude production. We have historically added a lot more in production for a lot less money… [In 2005–2008] we spent an unbelievable amount of money to try to hold down the front on the legacy system of 2005.[12]

Moreover, instead of higher production costs, replacing easy-to-access resources with difficult-to-access resources requires extensive capital investments on the national level. Fatih Birol, the executive director of the International Energy Agency (IEA), stated that "to keep at the current level of oil production, Russia needs to invest more than $700 billion in its oil industry by 2035 and to provide a more favorable tax regime for businesses."[13]

Summarizing, energy is a depletion-based business that must replace its reserves. Capital expenditures to expand resource base are gigantic, production costs from unconventional resources are very high, and costs of production from conventional reserves also increase over time. Energy is available, but could we pay a price to cover permanently increasing costs? If a price is lower than marginal costs, as at the beginning of 2016, there are no incentives for expansion and investments in exploration plummet, which in the long term leads to shortages and price spikes. When a price is high, energy becomes even more inaccessible for many; social consequences are obvious—economic poverty goes hand in hand with energy poverty. Keeping in mind other important incentives for transitioning from fossil fuels, such as mitigating global warming and eliminating the geopolitical struggles over remaining fossil fuel reserves, the solution also seems obvious—a transition from fossil fuels to a new energy mix based on renewable energy resources.

Figure 1. Increasing costs of oil barrel production. Global unit costs increased to a record high of 35.9 $/boc.



Brent – A type of sweet crude oil that is used as a benchmark for the prices of other crude oils.
DD&A – Depreciation, Depletion and Amortization expenses, reflect the costs of finding and developing reserves.
SG&A – Selling, General and Administrative expenses, include the day-to-day expenses not directly related to producing the product.

Source: Bernstein Research (2012). Era of Cheap Oil Over As Secular Growth in Upstream Cost Inflation Underpins Triple Digit Oil Prices. Bernstein Energy. p. 11

Barriers to Transformation

At first glance, the transition from fossil fuels to modern renewables appears to be in a very active phase. Over the last decade, most countries have set long-term renewable target goals[14] and have started to use modern renewables, mostly sun and wind energy, as the source of primary energy. More than 130 countries have become members of the International Renewable Energy Agency (IRENA), which focuses on doubling the share of renewables by 2030.[15] China is the world's largest wind market with more than 100 gigawatts (GW) of wind capacity, equivalent to about 65,000 turbines, and is currently adding more than 30 new turbines per day.[16] Germany is the leading solar photovoltaic (PV) nation with about 36 GW of installed capacity.[17] However, these are just the first small steps on the thorny road to providing the current level of energy consumption without burning fossil fuels. Achieving quick success in energy transition to renewables is a significant challenge for at least three reasons.

First, the supply of renewable electricity is still tiny compared to the amount of energy consumed globally. The amount of installed capacity of modern renewables that is required to supply enough energy to satisfy all current energy needs could be analyzed through power densities of different energy supply technologies. By "power density," Vaclav Smil, a distinguished professor emeritus at the University of Manitoba, means the number of usable watts that can be produced per square meter of land (or water) by a given technology.[18,19] Fossil fuel–based supply infrastructures are characterized by a power density of 100–2,000 W/m^2, compared to 0.5–9 W/m^2 for modern renewables. Smil notes that supplying the current amount of primary energy with high-density infrastructures requires a total area equal to the territory of Belgium. To produce the same amount of energy with low-density infrastructures requires "roughly an equivalent of the entire territories of the United States and India, an area more than 400 times larger than the space taken up by all of modern energy's infrastructures."[20] A shift away from fossil fuels is the first transition in the industrial era from high-density fuels to low-density fuels, and it is likely to be a generations-long process. Moreover, the substitution of capital-intensive fossil fuel–based infrastructure would be economically feasible only at the end of that infrastructure's 30–50 year life cycle.

Second, there are no ready markets where renewable electricity can be used in providing many of the essential energy services. Renewable electricity can substitute the electricity produced by burning coal, but it cannot yet substitute coal as the energy carrier in cement production or diesel in sea transportation. Current end-use energy technologies, such as heat technologies, transportation, and industrial processes, absolutely depend on fossil-based energy carriers; the share of coal in global final energy consumption is 10%, natural gas 16%, and products of oil refineries 41%.[21] In 2012, the share of electricity in global final energy consumption was only 18%, which actually is the maximum share of final energy consumption that could be supplied with renewable electricity today without massive substitution of current end-use technologies and without fundamental changes in the design of many of them. Energy transition to modern renewables requires new end-use infrastructures such as turbines, engines, boilers, furnaces, kilns, and new industrial processes for the production of steel, cement, stone, plastics, and paper, among others. Such technologies and processes first have to be designed to use renewable electricity as the energy carrier, and then be scaled globally. Scholars emphasize that energy transitions on a supply side are driven precisely by technological shifts in end-use technologies.[22] In reality, mostly opposite tendencies prevail. End-use technologies that use energy carriers produced from fossil fuels are growing in scale. The number of motor vehicles will likely double by 2050, and the share of electric vehicles will remain relatively small;[23] similarly, the number of aircraft will likely increase from 21,000 to 42,000 by 2033.[24]

Third, energy transitions are not only a matter of technological change. Social innovations, along with technological innovations, have been core drivers of historical energy transitions and remain so in future scenarios.[25] To conduct an energy transition, many significant changes would need to occur in the economy, financial and social institutions, politics, and even ideology. As Smil notes, "A careful investigation of energy transitions always reveals that their progress requires a specific sequence of scientific advances, technical innovations, organizational actions, and economic, political and strategic circumstances. Missing a single component in such a sequence, or delaying its introduction or effects because of some unforeseen events, results in very different outcomes and in lengthier transition periods."[26] Naïve statements[27] that single inventions lead to a bright future usually overestimate the importance of technology improvements and underestimate the significance of intangible elements of energy systems.

Obstacles are significant, and a world powered by modern renewables in 2050 or earlier is more a fantasy than a reality. It would be a mistake, however, to evaluate efforts to transform energy systems from a global perspective. As examples of the past illustrate, technological change occurs by clusters of radical innovations forming successive and distinct revolutions[28] that erupt in a particular country or region and then spread across the world. Several countries have already begun unique and complex transformations of their energy systems with very clear goals of keeping the current level of welfare, reducing consumption of primary energy, changing energy supply technologies, adapting end-use and supplementary technologies to new energy carriers, and initiating huge social change in order to overcome dependence on fossil hydrocarbons. An inspiring lesson from the history of energy transitions is that adopters have implemented the experience of the pioneers.[29]

Energy Transitions in Pioneering Countries

Denmark is the first country that has aimed to supply 100% of its energy demand (not just electricity!) with renewable energy. Following the ambitious *Energy Strategy 2050—from coal, oil and gas to green energy*,[30] the Danish government aims, by 2050, to substitute the current energy system, which has a total primary energy supply of 18 Mtoe and 75% share of fossil hydrocarbons,[31] with an energy system that has a total primary energy supply of 10 Mtoe and 0% of fossil energy in the mix.[32] Such transformation is possible without a decrease in consumption of energy services only if very bold goals in efficiency on both supply and demand sides are achieved—if electricity demand in households is decreased by almost 50% by 2050 and if electricity demand in industry and services is reduced by 45%. Other meaningful milestones on a path to a 100% renewable-energy society by 2050 include 100% of vehicles being either electric or hybrid; railroads and trams meeting approximately 40% of the transportation demand, compared to 15–20% today; more than 60% of electricity produced by wind; and individual heat provided mostly by heat pumps (60%) and solar thermal (20%).[33]

Germany is the first country with a relatively large territory and significant energy consumption (313 Mtoe in 2012[34]) to announce that it has already started an energy transition, Energiewende, to renewables in the power sector. One of the main prospective achievements of the energy transition is to increase the share of final energy supply provided by renewables to about 60% by 2050 from less than 10% in 2011.[35] In order to reduce overall costs, the transition would have to be based on existing technologies but not on technologies that are far from scaling and that require large subsidies.

With 115 GW of wind and 28 GW of solar PV, China is the global leader in installed capacity of wind and second (after Germany) in installed capacity of solar PV.[36] China doesn't have an official national strategy for energy transition toward renewables. But, the China National Renewable Energy Center published road maps that provide insights on China's long-term energy vision for transforming its energy system by 2050: more than 80% of electricity would be provided by renewable energy; installed capacity of solar PV would be 1,000 GW; installed capacity of wind would be 2,000 GW; 400 million out of 500 million passenger vehicles would be electric; and China would rely on renewables for more than 60% of its total energy needs.[37]

Another important example of energy-systems transformation toward renewables is the ambitious strategy launched in Japan in 2013. The Strategic Road Map for Hydrogen and Fuel Cells[38] envisions a completely new energy infrastructure (both on the demand and supply side) based on local zero-carbon energy supply and carbon-free energy consumption. According to the road map, the first phase of creating a hydrogen society starts in the mid-2010s and focuses on the expansion of hydrogen applications, such as fuel cells for households and fuel cell vehicles. Actually, the first phase of the Japanese transition is focused precisely on creating multiple markets for hydrogen as an energy carrier. The focus of the second phase, which starts in the mid-2020s, will be establishing a hydrogen supply system, first using imported natural gas as a feedstock. In order to reduce environmental impact, hydrogen production plants will include carbon-capture and storage technology. In the early 2040s, in the third phase, when demand has matured on import-based supply, the main focus will be on creating a carbon-free hydrogen supply system and substituting natural gas–based supply systems with a new supply system based on technologies that produce hydrogen using modern renewables, such as wind-to-gas technologies.

Establishing energy systems based on modern renewables in the developing world is vital for the economic and social development. One of the major development goals is to provide access to modern energy services (electricity and clean cooking facilities) for about 3 billion people, mostly in Africa and South Asia, who use mainly biomass to satisfy their energy needs. Solutions to fight poverty and to provide universal access to modern energy services for all could come with a transition to renewables because of four factors.

On a global level, energy transition to renewables is very much at its beginning, and it would be misleading to expect fundamental changes in a short period of time.

First, given recent technological progress, the developing world's technological potential for modern renewables is significant. Most developing countries have an irradiance level much higher than in Germany.

Second, modern renewables are relatively cheap for consumers in the developing world. According to the 2015 Africa Progress Report, because they are isolated from modern energy technologies, millions of Africans pay nearly the highest prices in the world for energy. These prices can reach as much as U.S.$10/kWh for lighting alone, which is approximately 100 times the amount spent in the United States (U.S.$0.12/kWh).[39]

Third, strategies that worked in twentieth century for developed countries, which became industrialized using fossil fuels, will not work for the developing world. Fossil fuel–based energy systems are not a solution to providing universal access to energy in the developing world. Fossil fuel reserves are distributed extremely unevenly. For instance, 90% of all proven African natural gas reserves exist in four countries (Nigeria, Algeria, Egypt, and Libya), and 97% of African coal reserves reside in only two countries (South Africa and Zimbabwe).[40] Moreover, even developing countries with abundant energy resources do not prosper. Oil-rich Nigeria simply exports about 95% of its oil and uses mainly biomass for its own energy consumption (82% of the total primary energy supply).[41] Developing countries lack end-use technologies, such as cars, and complementary infrastructures, such as roads, that would allow them to use their natural resources in providing energy services. Such improvements usually come with institutional changes.

Fourth, policy adoption is critical for developing countries, and there is no deficit of cases from which to learn: India, Kenya, Bangladesh, Indonesia, and many other countries provide cases of adoption.[42] For instance, the Indian government extends household solar projects with massive subsidies allowing every home to run two lightbulbs, a solar cooker, and a television.[43] India also offers a great example of adoption of modern renewables in agriculture, swapping out 26 million fossil-fuel–powered groundwater pumps with solar-powered ones.[44]

Energy transition toward modern renewables in the developing world is no longer a question of technological development but of policy adoption. For developing countries, it may be hard to learn from examples in Denmark or Germany. But, they could learn from India, Bangladesh, or other pioneer countries in the developing world, which could enable them to leapfrog over traditional physical energy infrastructure by focusing on individual access to electricity using modern renewable technologies.

Conclusion

With policy support and multibillion-dollar investments, over the last four decades wind and solar PV energy technologies mostly reached grid parity in pioneering countries. At least in the power sector of developed countries, energy transition to renewables is not a question of technological development. For further success in transitioning from fossil fuels, pioneering countries have to focus on creating markets to adopt renewables in transportation and industry sectors. Examples of past energy transitions illustrate that clusters of new breakthrough technologies were first adopted by progressive societies, and only after that, followers implemented the experience of pioneers. Thus, the meaning of modern energy transitions in pioneering countries—Denmark, Germany, China, India, and Japan—is hard to overestimate.

International diffusion of renewable energy technologies has typically been preceded by the international diffusion of regulation.[45] To start transformation of energy systems toward renewables, followers need to have opportunities to learn from the success and failure of pioneers. Thus, cross-national cooperation is necessary. There are several international organizations that already focus on facilitating cross-national learning about renewable energy, such as IRENA, the Sustainable Energy for All initiative (SE4All), and their numerous partners. Collaboration between Denmark and China in the form of the Sino-Danish Renewable Energy Programme is a perfect example of an instrument through which an adopter is directly acquiring expertise and experience from a pioneering country and then, in turn, is becoming a pioneer in its own region. Due to a positive correlation between the level of economic development and the amount of energy consumption, efforts to transform energy systems in the developing world from biomass toward modern renewables could act as a driving force to eliminate energy poverty.

On a global level, energy transition to renewables is very much at its beginning, and it would be misleading to expect fundamental changes in a short period of time. Due to the large scale of current fossil-fuel–based energy systems, their interconnectedness with other technological systems, and their ubiquity throughout societies, energy transitions toward modern renewables have incarnated the Lampedusa principle that "everything must change in order that nothing change." Transformation of energy systems toward modern renewables is a long-term process of complex technological and societal changes that can be accomplished through a determined effort of many generations.

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Endnotes

[1] Arnulf Grubler and Charlie Wilson, *Energy Technology Innovation: Learning from Historical Successes and Failures* (Cambridge: Cambridge University Press, 2014): 5.

[2] Vaclav Smil, chapter 2 "Energy Linkages," *Energy at the Crossroads: Global Perspectives and Uncertainties* (Cambridge: MIT Press, 2005): 63–120.

[3] Vaclav Smil, *Making the Modern World: Materials and Dematerialization* (Sussex: John Wiley & Sons, 2013): 81.

[4] IEA, *Key World Energy Statistics 2014* (IEA, 2014): 8. Accessed November 19, 2015. http://www.iea.org/publications/freepublications/publication/KeyWorld2014.pdf.

[5] Data from BP website at http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy/review-by-energy-type/oil/oil-reserves.html.

[6] EIA, International Energy statistics, Reserve statistics. Accessed November 19, 2015. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm.

[7] David Ricardo mentioned "best-first" principle in *On the principles of the political economy and taxation* (1821) regarding farmers, who tend to plant crops where those crops grow best

[8] GEA, *Global Energy Assessment – Toward a Sustainable Future* (Cambridge: Cambridge University Press, 2012): 434.

[9] The term *unconventional* is usually used in relation to resources when indicating a particular level of technological development. For instance, in the 1960s, oil resources in the North Sea were considered unconventional. With technological progress (off-shore oil platforms) and under favorable economic conditions (the oil crisis of the1970s), North Sea oil resources were in production in 1970s. In the 2000s, tight gas, coal bed methane, shale gas, shale oil, heavy oil, tar sands, and methane hydrates were considered unconventional.

[10] Astrid Kander, Paolo Malanima, and Paul Warde, "Energy Transitions in Europe: 1600–2000," *CIRCLE Electronic Working Papers* 2008/12 (Centre for Innovation, Research and Competences in the Learning Economy, 2008): 5.

[11] For costs of shale oil and gas, see Magnus Nysveen and Leslei Wei, "Cost deflation and the effect on 2015 breakeven prices," *Oil & Gas Financial Journal* (July 8, 2015). Accessed November 19, 2015. http://www.ogfj.com/articles/print/volume-12/issue-7/features/unconventional-resources.html.

[12] Quote from presentation of Steven Kopits "Global Oil Market Forecasting: Main Approaches & Key Drivers" at Columbia SIPA. See p. 18. Accessed November 19, 2015. http://energypolicy.columbia.edu/events-calendar/global-oil-market-forecasting-main-approaches-key-drivers.

[13] Quote from Fatih Birol's interview in Gazeta.ru (in Russian). Accessed November 19, 2015. http://www.gazeta.ru/business/2012/01/23/3971841.shtml.

[14] REN21, *Renewables 2014 Global Status Report* (REN21 Secretariat, 2014): 116. Accessed November 19, 2015. http://www.ren21.net/ren21activities/globalstatusreport.aspx.

[15] IRENA, "Doubling the Global Share of Renewable Energy: A Roadmap to 2030," Working paper (2013). Accessed November 19, 2015. https://www.irena.org/DocumentDownloads/Publications/IRENA%20REMAP%202030%20working%20paper.pdf.

[16] Bloomberg New Energy Finance. A multibillion dollar opportunity – service for wind farms in China. October 20, 2014. Accessed November 19, 2015. http://about.bnef.com/press-releases/multibillion-dollar-opportunity-service-wind-farms-china/.

[17] REN21, *Renewables 2014 Global Status Report* (REN21 Secretariat, 2014): 106. Accessed November 19, 2015. http://www.ren21.net/ren21activities/globalstatusreport.aspx.

[18] The concept of "power density" is explained in detail in Vaclav Smil's article "Power Density Primer," May 8, 2010. Accessed November 19, 2015. http://www.vaclavsmil.com/wp-content/uploads/docs/smil-article-power-density-primer.pdf.

[19] In Arnulf Grubler, "Energy: Profile of power," *Nature* 523 (2015): 32–33, the author argues that Smil incorrectly uses the term *power density* and that it should be substituted with a term *energy density*, but for the purpose of this issue brief the term is used as in Smil's publications.

[20] Vaclav Smil, *Energy Transitions: History, Requirements, Prospects* (Santa Barbara: Praeger, 2010): 117.

[21] IEA, *Key World Energy Statistics* 2014 (IEA, 2014): 28. Accessed November 19, 2015. http://www.iea.org/publications/freepublications/publication/KeyWorld2014.pdf.

[22] Charlie Wilson and Arnulf Grubler, "Lessons from the history of technological change for clean energy scenarios and policies," *Natural Resources Forum*, 35 (2011): 165–184.

[23] Karen Ward, Nick Robins, and Zoe Knight, *The World in 2050. From the Top 30 to the Top 100* (HSBC Global Research, 2012): 10.

[24] Boeing, *Current Market Outlook 2014–2033* (Boeing, 2013): 4. Accessed November 19, 2015. http://www.boeing.com/assets/pdf/commercial/cmo/pdf/Boeing_Current_Market_Outlook_2014.pdf.

[25] Arnulf Grubler and Charlie Wilson, *Energy Technology Innovation: Learning from Historical Successes and Failures* (Cambridge: Cambridge University Press, 2014): 39.

[26] Vaclav Smil, *Energy Transitions: History, Requirements, Prospects* (Santa Barbara: Praeger, 2010): 20.

[27] Peter Diamandis And Steven Kotler, *Abundance: The Future Is Better Than You Think* (New York: Free Press, 2012).

[28] Carlota Perez, *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages* (Chentelham: Edward Elgar, 2002): 10.

[29] Arnulf Grubler, "Energy transition research: Insights and cautionary tales," *Energy Policy* 50 (2012): 8–16.

[30] The Danish Government, *Energy Strategy 2050 – from coal, oil and gas to green energy* (Denmark. Danish Ministry of Climate, Energy and Buildings, 2011). Accessed November 19, 2015. http://www.ens.dk/sites/ens.dk/files/dokumenter/publikationer/downloads/energy_strategy_2050.pdf.

[31] IEA Statistics. Accessed November 19, 2015. http://www.iea.org/stats/WebGraphs/DENMARK4.pdf.

[32] Brian Vad Mathiesen, Henrik Lund, and Kenneth Karlsson, "100% Renewable energy systems, climate mitigation and economic growth," *Applied Energy* 88, no. 2 (2011): 488–501.

[33] Henrik Lund and Brian Vad Mathiesen, "Energy system analysis of 100% renewable energy systems – The case of Denmark in years 2030 and 2050," *Energy* 34, no.5 (2009): 524–531.

[34] IEA Statistics. Accessed November 19, 2015. http://www.iea.org/stats/WebGraphs/GERMANY5.pdf.

[35] The German Energiewende website. Accessed November 19, 2015. http://energytransition.de.

[36] REN21, *Renewables 2014 Global Status Report* (REN21 Secretariat, 2014). Accessed November 19, 2015. http://www.ren21.net/ren21activities/globalstatusreport.aspx.

[37] See Management Office of RED Programme, China Wind, Solar and Bioenergy Roadmap 2050 from December 2014. Accessed November 19, 2015. http://www.cnrec.org.cn/english/publication/2014-12-25-457.html.

[38] See for more information this website of Japan Ministry Of Economy, Trade, and Industry. Accessed November 19, 2015. http://www.meti.go.jp/english/press/2014/0624_04.html.

[39] African Progress Panel, *Power, People, Planet. Seizing Africa's energy and climate opportunities* (2015). Accessed November 19, 2015. http://www.africaprogresspanel.org/publications/policy-papers/2015-africa-progress-report/.

[40] Data Workbook BP Statistical Review of World Energy 2015. Accessed November 19, 2015. http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html.

[41] See IEA Sankey diagram of Nigeria energy balance. Accessed November 19, 2015. http://www.iea.org/Sankey/index.html#?c=Nigeria&s=Balance.

[42] Peter Meier, Maria Vagliasindi, and Mudassar Imran, *The Design and Sustainability of Renewable Energy Incentives. An Economic Analysis* (Washington, DC: World Bank, 2015) highlights the case studies for Vietnam, Indonesia, Sri Lanka, South Africa, Tanzania, Egypt, Brazil, and Turkey.

[43] See generally e360 Digest. India's new Prime minister plans to make a major push on solar energy. May 19, 2014. Accessed November 19, 2015. http://e360.yale.edu/digest/indias_new_president_plans_to_make_major_push_on_solar_energy/4152/.

[44] See generally Bloomberg. Solar Water Pumps Wean Farmers From India's Archaic Grid. February 8, 2014. Accessed November 19, 2015. http://www.bloomberg.com/news/print/2014-02-07/solar-water-pumps-wean-farmers-from-india-s-archaic-grid.html.

[45] Juliana Subtil Lacerda and Jeroen van der Bergh, "International Diffusion of Renewable Energy Innovations: Lessons from the Lead Markets for Wind Power in China, Germany and USA," *Energies* 7 (2014): 8236–8263.

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