This draft: September 20, 2010
First Draft: July 2010

Green Revolution 2.0

Nalin Kulatilaka*

Abstract

It is imperative that a cornerstone of a prudent development strategy be a vibrant and sustainable energy sector. First, I draw insights from the implementations of the Green Revolution 1.0 that averted a global food crisis in the mid 20th Century but left us with a myriad of new problems. I then propose an energy strategy built around a smart electricity network formed by merging the physical energy infrastructure with a modern cyber infrastructure. By bridging the glaring information gaps, such a strategy can create a platform to spawn innovations in green technologies, accelerate their adoption, and induce prudent behavior in energy use. This approach, I contend, will realize a Green Revolution 2.0 without falling into some of the traps of the 1st Green Revolution. Vital to harnessing our economic growth potential, such a strategy can be best achieved through a public-private partnership.

1. Role of Energy in Sustainable Development

Economic development depends on the availability of factors of production that are often in scarce supply, and energy is often the most critical factor. Having access to a reliable and cost effective supply of energy is a vital ingredient for economically sustainable development. But development often also comes with negative spillovers in the form of congestion and environmental externalities that can have far reaching impact on quality of life, and ultimately impose a heavy drag on development itself.[1] The challenge is to devise an energy strategy that is both economically and environmentally sustainable.

Transitioning from our fossil fuel driven economy can be a slow and costly process that requires careful management. Most of the world's current capital stock and social systems are designed to function with fossil fuels that are in limited supply. Even with improvements in exploration and extraction technologies, the scarcity of fossil fuels will act as a drag on growth and add to global insecurities and exacerbate wealth imbalances. As the "peak oil" literature argues, it is not a question of if, but when and at what levels the production levels peak and begin to decline.[2] The resulting uncertainty is sufficient reason to base long-range growth plans on renewable sources of energy. A diversified energy portfolio will have significant short-run benefits as well. Reducing disruptions arising from geopolitically driven supply uncertainty and improving trade imbalances

---

* Wing Tat Lee Family Professor of Management, School of Management, Boston University. email: nalink@bu.edu. I thank Martha Amram, John Baillieul, Michael Caramanis, Jim Ciriello, Robert Kaufmann, John Henderson, Nitin Joglekar, Mandy Kulatilaka, Tudor Kulatilaka, Bruce Kogut, John Leggate, Paul McManus, Adil Najam, Venkat Venkatraman, and David Weil for valuable discussions and suggestions on earlier drafts of this paper. Any remaining errors, however, are mine alone.

[1] See Garrett Hardin (1968), "Tragedy of the Commons", Science and Robert Stavins (2005), Economics of the Environment, Norton.

[2] For a recent review of peak oil research, see Steve Sorrel, S. J. Speirs, R. Bentley, A. Brandt, and R. Miller (2009), "Global Oil Depletion: An assessment of the evidence for a near-term peak in global oil production", UK energy Research Centre.

due to heavy dependence on foreign energy sources further strengthens the case for seeking energy independence.

With supply constrained, improving efficiency becomes a natural path to a sustainable energy future. A large fraction of primary energy is lost before its final use.[3] As economies work their way up the development ladder, industrial sectors tend to improve in energy efficiency. Unfortunately, the accompanying higher standards of living lead to more energy consuming human activities that also rely on more 'refined' forms energy like electricity. The development challenge then is to raise standards of living while keeping energy intensity low.[4]

The energy mix (the type and form of the energy) to a large extent also determines the spillover effects. The complicated inter-dependencies between energy use in human systems and natural systems can have harmful side effects on human health and natural ecosystems. Most complex and far-reaching spillovers are due to greenhouse gas emissions from burning fossil fuels and its impacts the global climate. This climate externality from fossil fuel use increases the urgency to wean our economies from fossil fuels. Although there is significant uncertainty about the exact levels of climate change, there is mounting scientific evidence of anthropogenic climate change over the next century. The resulting global warming, rise in sea level, and extreme weather events will lower the value of existing capital that is well adapted to the present climate and destroy wealth.[5] As the global political community unites around this problem, it is inevitable that the social costs of the climate externality will be internalized in the price of carbon emissions and reflected in cost of fossil fuels.

Weaning an economy from the dependency on fossil fuels and replacing with a portfolio of renewable energy sources positions a country strongly in the face of scarcity and negative environmental spillovers. A prudent and sustainable growth strategy, therefore, must recognize the realities of scarcity, spillovers, and equity. In other words, a sustainable development strategy must include a *sustainable energy future* – one that harnesses a diverse mix of plentiful energy sources, in ways that are economically sustainable, minimize environmental harmful side effects, and addresses distributional concerns across nations and populations within nations.

The challenge for the 21st Century is to find a path to such an energy future. I argue doing so calls for addressing a wider complementary system for "green energy" that includes not only less polluting energy sources, but also more efficient ways to transport, store, and use energy. Transitioning from an oil dependent, carbon-emitting, legacy capital stock to one that depends on renewable sources is a costly and time consuming task. This paper takes a complementary network view of the energy challenge. In complementary systems the proliferation of one component (hardware) leads to innovation and variety in other complementary components (software) in subsequent time periods. Hence, the transition away from a fossil fuel-based ecosystem must consider changes to the traditional energy sector as well as complementary sectors including energy using appliances; incentives that affect individual habits and business practices; and reforms to regulations and institutions. For instance, small investments can induce efficiency improvements in the short run. Larger infrastructure investments and behavior

[3] DOE/EIA estimates find that globally only 45% of primary energy reaches end users in the form of useful energy. In other words, 55% is lost in the various steps involved in harnessing, transporting, and converting processes. Additionally, end use appliance inefficiencies too can be significant leading to even more wasted energy.
[4] In economic terms this would imply increasing per capita GDP while keeping down BTU per dollar of GDP. See updated pubic domain source.
[5] IPCC Fourth Assessment Report: Climate Change 2007.

changes are needed to sustain these efficiency gains and to facilitate the inclusion of clean energy sources. But the value from the complementary system grows non-linearly with the size of the network.[6]

Here I argue that the heart of transforming the energy sector will be a modern electricity network. With its growing pervasiveness in modern society, 'smart' electricity network is a central asset to growth. By building ubiquitous measurement, monitoring, and communication capabilities to complement the energy generation and distribution infrastructure, such a smart electricity network can catalyze a Green Energy Revolution. It will increase system efficiency by driving down waste and lead to superior cost economics. Pervasive information will endow consumers with situational awareness and adjust their behavior to be more prudent users. Distributed energy sources can be more readily integrated into the network. Restructured regulations and public policy will create an environment where businesses can flourish through innovation of new products and services. What results could consist of a resilient network consisting of 'Islands of Power' where electricity would be produced closer to where it is consumed, is consumed more efficiently, in a system that is less vulnerable to cascading failures. Such a distributed system forms a platform for introducing a diverse mix of generation sources.[7]

In order to fix ideas and draw insights, I will first look at another Green Revolution from recent history.[8]

2. The First Green Revolution (Agriculture)

During the middle part of the 20th Century, countries around the world were grappling with the challenges of feeding their rapidly growing populations. In his best seller "The Population Bomb", Paul Ehrlich (1968) predicted that programs aimed at increasing food production would be unable to avoid mass starvation.[9] Such arguments leading to limit to growth do not take into account price responses and hinge on the assumption that technological change would be slower than population growth. The Green Revolution debunked this notion.

The term "Green Revolution" is most often associated with the development of high yielding grains that were developed through scientific research. Norman Borlaug, who was awarded the 1970 Nobel Peace Prize and considered the father of the revolution, headed a team at Mexico's *International Maize and Wheat Improvement Center* (CIMMYT) that developed dwarf varieties of wheat which flourished in a wide range of climates and produced four-fold yield increases. Meanwhile, the *International Rice Research Institute* (IRRI) in the Philippines developed hybrid varieties of rice that had shorter crop cycles (allowing more crop seasons); grew in submerged conditions (opening flood-prone land for rice cultivation); were disease and pest resistant (better suited for tropical climates). The hybrid rice IR8, which became the poster child of this

---

6 This issue has been raised in the clean energy context in an earlier paper. See Martha Amram and Nalin Kulatilaka (2009), "The Invisible Green Hand: How Individual Decisions and Markets Can Reduce Greenhouse Gas Emissions," California Management Review, 51:2.

7 A similar notion is advanced in Jim Woolsey, Rachel Klienfeld, and Chelsea Sexton (2010), "No Strings Attached: The Case for a Distributed Grid and a Low-Oil Future", World Affairs, September/October.

8 Rebecca Henderson and Richard G. Newell (2010), Accelerating Innovation in Energy: Insights from Other Sectors, University of Chicago Press for National Bureau of Economic Research (forthcoming) provides a collection of papers that apply insights from a number of different sectors to the innovations process in the energy sector.

9 Paul Ehrlich (1968), Population Bomb. Ehrich's thesis was based on the Malthusian premise that a world with limited resources would be unable to meet the needs of a growing population.

innovation, more than doubled the per acre yields. But developing better seed technology was only the first step.

Much else, however, was needed to realize high crop yields. The new seeds had to be made available to farmers in developing countries; new farming techniques ranging from better irrigation, fertilizing, and the use of pesticides needed to be demonstrated; risk had to be managed through crop insurance and agricultural price supports; and capital provided through agricultural banks and futures markets.

Achieving higher production at the farm was only the second step. Getting the crops from the farms to consumers required fundamental changes to various complementary services. Countries that experienced true Green Revolutions saw parallel investments and innovations in agricultural markets, transportation infrastructure, and logistics.[10] Good harvests didn't always mean piles of rotting produce or even, rock bottom prices. Storage and food processing technologies allowed the crops to be efficiently distributed over not only geographic distances but also over time. Some have even counted the avoided deforestation as a benefit of this green revolution.

The Green Revolution is not without its critics. Some point out that the heavy use of fertilizer and irrigation caused long-term degradation of the soil. The use of chemical fertilizers contributes to increased dependency on oil and adds the problem of green house gas emissions. In fact, some estimates claim that the modern farming techniques have resulted in a tenfold increase in the amount of energy used in food production. Green Revolution may have prevented conquering more land for farms but it conquered more oil fields. A case can also be made that the primarily beneficiaries were large commercial farms with ready access to fertilizer, pesticides, and modern equipment, thus rendering smaller farms uneconomical and worsening inequities in income and asset distribution. [11]

What relevant lessons can we glean from this discussion of the first Green Revolution as we prepare for the Second Green (Energy) Revolution? Firstly, success wasn't based simply on the development of new technologies – hybrid seeds and modern farming techniques. A much broader set of capabilities had to be built around these technologies: dramatic changes were needed in the transportation infrastructure and storage systems that moved food from farms to population centers; development of markets where farmers could not only get a fair price for their crops but also provided access to financing through rural banking networks. In other words, success came through the creation of a business platform that connected the consumers with producers and the network of stakeholders in the wider complementary system.

---

[10] The success stories from Mexico, India, Pakistan, the Philippines, and China are often attributed to their better infrastructures including stability of government institutions that permitted better diffusion of technology and more effective ways of brining crops to market. In contrast, many countries in Africa, where governments were unstable and roads and water resources were less developed did not reap the full benefits. Charles Mann (1997) "Reseeding the Green Revolution" Science, Vol. 277, documents a case contrasting the success in corn production in the stable, northern Mozambique against the rotting crops found in the southern region that is stricken with political strife and a crumbling transportation system. See also R. E. Evenson* and D. Gollin (2003), "Assessing the Impact of the Green Revolution, 1960 to 2000" Science, Vol. 300:5620.

[11] Exceptions were in countries like Taiwan and Sri Lanka where the new agricultural practices were accompanied by land reform that addressed equity issues.

Table 1 Green Agricultural Platform			
Technology	**Infrastructure**	**Markets and Financial Institutions**	**Public Policy**
Seeds	Roads/Railway networks	Commodity markets (e.g., eChaupal[12])	Price supports
Fertilizer and Pesticides	Irrigation	Insurance	Land reform
Farm equipment	Logistical systems	Credit markets	Crop Insurance
Food processing and storage technologies		Agricultural/Development Banks	

Before applying these insights to the energy sector, I will frame the energy challenge and highlight the central role played by the electricity sector. The parallelism comes from the dependent variables. Whereas a well-executed Green Agricultural Revolution provided food security and self-sufficiency, a Green Energy Revolution has the potential to bring about energy independence, reduced carbon emissions, and higher power quality needed for a growth in the 21st Century.

3. Designing a Smart Electricity Network as a Platform for a Green Energy Revolution

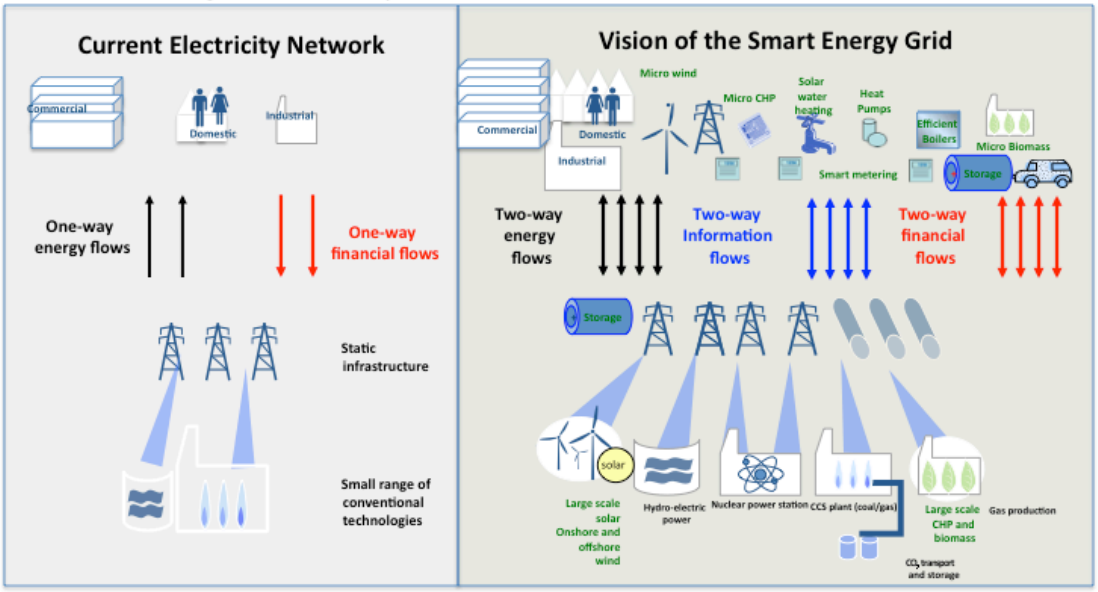
"The Smart Grid", used as a proper noun, refers to a particular vision for the technical design configuration -- a smart *technical* grid comprising of a cyber-physical system resulting that overlays intelligence (sensing, communication, information processing) on the physical electric power system. My notion of a Smart Electricity Network takes a broader view. It includes the institutional and governance structures to build capabilities and launch new services.

Much like the folk story of the elephant and the six blind men, the impact of the smart grid depends on your vantage point. But the most salient feature of the smart grid for our discussion is that it bridges the information gap between various stakeholders in the system. The cyber system will enable information to flow in both directions – to and from customers. Figure 1 compares the current electricity network with the vision for a smart electricity network.

[12] See http://www.itcportal.com/default.aspx

Realizing the full potential of the smart grid needs more than technology. It calls for parallel

Figure 1: Electricity Network Transformation Reaches Far and Wide



changes to markets, business models, and public policy. Only then will the smart grid be able to provide the requisite power quality for the digital economy; enable efficient operation leading to lower cost structures; build resiliency by anticipating and responding to disturbances; and accommodating environmentally friendly generation and storage options. Such a smart electricity network becomes a *business platform* to innovate and launch a wide variety of end-user services.[13] Consequently, the challenges and opportunities offered by the smart grid affects a much broader set of institutions.

As with high-yielding varieties of corn and rice, there are many challenges to overcome. Vested interests, old habits and work practices, and legacy capital makes disrupting the status quo a no easy task even when a superior system is available. The challenges include:

1. Integration of the existing energy technologies and innovations in new information and communication technologies including the Internet.
2. Providing incentives for behavior changes in key actors (individuals and organizations) needed to best use the newly enabled capabilities.
3. Developing decision support and control systems to manage end user appliances and realize synergies between intermittent generating resources and interruptible loads.
4. Developing new markets that signal timely price information to the various participants (including end users) of the widely distributed network.
5. Creating new financing vehicles and contracts to facilitate investments in distributed energy resources (environmentally friendly loads, storage, and generation).

[13] See Bruce Kogut and Nalin Kulatilaka (1994), "Options Thinking and Platform Investments: Investing in Opportunity", California Management Review, 36:4, and Bruce Kogut and Nalin Kulatilaka (2001), "Capabilities as Real Options", Organization Science, *12:6*.

6. Restructuring policies and the regulatory environment to facilitate the transition and value capture.
7. Developing new services and revenue models to deliver them to end-users.

Table 2 summarizes the components of the Green Energy Platform and draws parallels to the Green Agricultural Platform. It also offers opportunities to a broad ecosystem of firms and institutions. In the rest of the paper I will examine several specific applications.

Table 2
The Green Energy Platform

Technologies	Infrastructure	Markets and Financial Institutions	Public Policy
Sensors, smart meters, and other grid technologies	Smart Technical Grid – incorporating ubiquitous connectivity, sensory capabilities, and intelligence in electricity distribution network	Wholesale Power markets	Building Codes Appliance Standards Transportation fleet standards
Control and decision support tools		Ancillary service markets	Emissions limits, carbon prices, renewable portfolio Standards (RPS) and other incentives for clean generation
Renewable generation (PV, wind) and storage (fuel cells, flywheels, batteries) technologies		Cost reflective rates and retail power markets	Restructured utility regulation: e.g., 'decoupling', net metering and feed-in tariffs,
Smart Appliances		Performance contracts	Direct subsidies or tax incentives

4. Who Will Build the Smart Electric Network? A Public-Private Partnership

An important characteristic of network economics is that creating value requires large up-front investments. Since network effects increase with it size, benefits begin accruing at a slow low rate but accelerate more-or-less exponentially. These immense opportunities come with equally large uncertainties mechanisms for value capture and depend on evolution of technical standards, regulatory policies, and business models. Private capital markets are, therefore, ill equipped to navigate the risks of platform building. Yet, the social value potential and the strategy urgency make this an appropriate target for public investment.

History is rife with examples of industries where public-private partnerships successfully developed new platforms and 'tipped' systems away from inefficient legacy network systems. Besides creating the necessary regulatory policies, public funds and leadership through R&D for seed technology, educational and awareness programs for new farming technologies, and building the physical distribution infrastructure was crucial for success in the green agricultural revolution. Public investment in the highway system forms a platform for private investment in trucking and transportation services to evolve. In both cases, the public intervention catalyzed private investment.

Build It and They Will Come: Investing in infrastructure ahead of determining the uses of the infrastructure is an effective transformation strategy when a single entity controls most aspects of the complementary network, when new technology is incremental, and choices are few. There is little uncertainty about how value is created and captured. Cases in point are phone companies that were either state-owned or function as regulated natural monopolies, like AT&T of the old. Operating within a 'walled garden', there was little uncertainty about how to capture value: Networks built; standards established; end-user equipment and applications introduced; new services offered. Customers came, but innovation was slow and gradual.

The challenge in sustainable energy is different. Innovation is drastic. Technology choices are vast and rapidly obsolete existing systems. Applications and services are uncertain and may need changes to behavior. Competition is fierce and global. Much social value, economic competitiveness, and security is at stake. Exacerbating the problem are time dynamics of network systems evolution. Individuals and institutions make decisions about energy using capital goods based on available information at the time of the decision, with less than perfect foresight. Early decisions can lock patterns of usage and lead to a "tipping tendency" where some times inferior technologies may be chosen. The resulting path dependency is akin to the extreme sensitivity to initial conditions found in chaos theory and to evolutionary paths in biology.

Co-evolution: I argue that a more apt strategy for sustainable energy is to seek changes in a modular fashion where technologies and institutions co-evolve. The installed base of capital, business practices, behavior, institutional arrangements, and existing ecosystems of firms can be used to earn short-term benefits, while innovating new modules, and keeping alive valuable growth options. Under such a strategy, government investment seeds innovation and thereby allows for exploration of many potential technologies in various parts of the value network. Then public policy can create regulatory climate that would induce commercialization and wide-spread adoption. It takes advantage of design principles of modularity.[14] An example would be the development of mobile navigation services. It required public investments in the Global Positioning System, private investments in digitized maps, and a proprietary interface for the service provider.

4. Towards a Green (Energy) Revolution

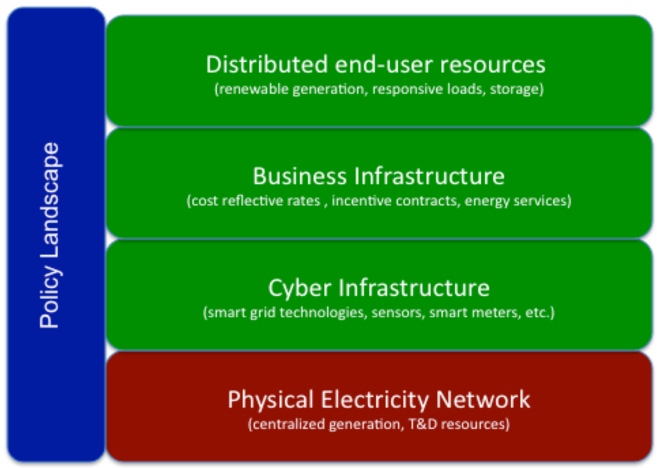
In this paper I advanced the notion of a smarter electricity network as a central building block of a sustainable growth strategy. Such a network will reduce the need for investments in polluting power generation plants. However, large investments will be required in complementary cyber infrastructure. We can think of this strategy as substituting polluting (brown) capital with clean (green) capital investments.

---

[14] Carliss Baldwin and Kim Clarke (2000) Design Rules, Vol. 1: The Power of Modularity, MIT Press (Cambridge, MA).

At its core is a smart grid business platform that calls for coordinated actions through a public-private partnership. Investments in *smart technologies* creating a robust cyber-physical infrastructure will form the backbone. A modern distribution system that turn the grid into a resilient dynamic system that can deliver the power quality needed for modern industry and a rapidly modernizing society. In parallel, consumer-side technologies that can respond to information about energy prices and grid conditions by adjusting energy consumption will increase efficiency and lower customer bills. But realizing value needs much more. Introduction

Figure 3:
Smart Grid Business Platform Substitutes Brown Capital with Green Capital



of s*mart rates*, either through markets or institutional proxies, must provide opportunities for consumers to recognize and receive rewards for shifting risk through demand response and scheduling smart loads. Smart technologies and smart rates create opportunities. But it takes informed consumers/agents to make *smart decisions* and harness the value of those opportunities. A well functioning system must have *smart organizations* with a governance structure that changes relationships between utilities, customers and regulators and induce broader changes to business/work practices, behavior and habits. Such an environment will spawn *smart services* that can differentiate quality of service at a granular level of segmentation. For instance, demand-side response will smooth out peak loads and reduce the need for investments in expensive and environmentally harmful generation plants. Leading the energy strategy with a smarter electricity network has other benefits too.

Modern industry and sophisticated consumers place a high premium on 'quality of power'.[15] The performance levels of appliances fall and their lifetime shrinks as the voltage and frequency move outside allowable ranges. Quality must also take into account the resiliency of the power system to ensure reliable delivery in the face of extreme weather events, demand spikes, and various supply interruptions. A smart grid not only enables the provision of higher quality power but also measures and conveys the quality and cost to consumers so that new services based on quality can be offered. The notion of quality extends beyond the technical characteristics into risk

[15] The concept "energy quality" refers to the ability of a energy to produce goods and services for human use and is combination of physical, technical, economic, and social attributes. As Cutler Cleveland writes in the Encyclopaedia of the Earth, these attributes include gravimetric and volumetric energy density, power density, emissions, cost and efficiency of conversion, financial risk, amenability to storage, risk to human health, and ease of transport.

management and other financial attributes. One can even imagine developing services around "packets" of energy that can be valuable in serving interruptible loads such electric vehicles.

It is important to note that smart grid business models can foster significant network effects. The real time information flow created by intelligent systems that span both the T&D infrastructure and the user communities will enable new workflow designs, spawn highly distributed service based organizations, sustain innovation at the product level, and perhaps most critically, give rise to new market structures that use price signals to facilitate more efficient behavior.[16] The combination of the new products, services and related markets will lead to a significant transformation across the entire energy value chain. The resulting ecosystem will adopt clean energy technologies while fostering new businesses, creating new jobs and ultimately empowering society to reach new heights in energy conservation and sustainability.

Bill Gates has coined an instructive terminology to describe the transformation needed in the energy sector.[17] He calls our current energy sector as dependent on "*energy factories*". These are efficient (due to scale economies) and, for the most part, resilient in the face of adverse weather conditions. The conventional energy factories emit environmentally damaging greenhouse gasses and increase the dependence on imported fuels. In contrast, renewable generation is more like "*energy farming*". These farms, although dependent on local resources, are vulnerable to the vagaries of weather.

One can argue that the Green Agricultural Revolution turned small farms into factory farms that concentrated production in few locations and reduced the diversity of crops. A Green Energy Revolution, centered on a smart electricity network, takes a different path: By enabling rich information flows, it allows for diversity of energy sources. By conveying more accurate cost signals, it creates incentives to reduce levels of consumption and shift consumption to reduce the peak capacity needs. By bringing energy farms closer to demand centers, it reduces losses.[18] By improving the quality of power, it enables the creation of valuable new services.

[16] For instance, Enel in Italy has installed nearly all their customers with smart meters that offer price signals. Appliance makers have since introduced various responsive appliances that can.
[17] "Q&A with Bill Gates", Technology Review, September/October 2010.
[18] In cases of onsite generation, such as rooftop solar, production and consumption is co-located eliminating the need for any special movement.