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SUSTAINABLE  
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INSIGHTS

# Green Revolution 2.0: A Sustainable Energy Path

## Nalin Kulatilaka

The Green Agricultural Revolution greatly increased crop yields and averted mass starvation, but it also turned small farms into factory farms that concentrated production in few locations and reduced the diversity of

## Role of Energy in Sustainable Development

Economic development depends on factors of production that are often in scarce supply, and energy is often the most critical factor. Having access

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The author has benefited from valuable suggestions from many friends and colleagues. Special thanks go to members of the Clean Energy & Environmental Sustainability Initiative (CEESI), which engages university-wide resources to help prepare for a world where increasing demand for energy resources must be balanced with environmental, economic and social sustainability.



crops. In this paper I propose a strategy for a Green Energy Revolution, centered on a smart electricity network, that 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 shifts consumption patterns to reduce the peak capacity needs. By bringing energy farms closer to demand centers, it reduces losses. And by improving the quality of power, it enables the creation of valuable new services.

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. The challenge is to devise an energy strategy that is both economically and environmentally sustainable.

Transitioning from our fossil fuel driven economy will be a slow and costly process that requires careful management. Most

*Sustainable Development Insights* is a series of short policy essays supporting the Sustainable Development Knowledge Partnership (SDKP) and edited by Boston University's Frederick S. Pardee Center for the Study of the Longer-Range Future. The series seeks to promote a broad interdisciplinary dialogue on how to accelerate sustainable development at all levels.

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

higher standards of living lead to more energy-consuming human activities that also rely on more refined energy forms like electricity. The development challenge then is to raise standards of living while keeping energy intensity low (Corless 2005).

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 on the global climate. This climate externality 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

Weaning an economy from dependency on fossil fuels and substituting a portfolio of renewable energy sources positions a country strongly against 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, minimizes environmentally 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

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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. According to the U.S. Department of Energy/ Energy Information Administration's estimates, more than 55 percent is lost in the various steps involved in harnessing, transporting, and converting processes. As economies work their way up the development ladder, industrial sectors tend to improve in energy efficiency. Unfortunately, the accompanying

scientific evidence that anthropogenic climate change will occur 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 (IPCC 2007). 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.



investments can induce efficiency improvements in the short run. Larger infrastructure investments and behavior 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 (Amram and Kulatikika 2009).

I argue that the heart of transforming the energy sector will be a modern electricity network. With its growing pervasiveness in modern society, the “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 be a resilient network consisting of “Islands of Power” where electricity would be produced closer to where it is consumed and 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 (Woolsey et al 2010).

For ideas and insights, let’s look at another Green Revolution from recent history.

## The First Green Revolution

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. Such arguments leading to limits 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.

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); and were disease and pest resistant (better suited for tropical climates). The hybrid rice IR8, which became the poster child of this innovation, more than doubled the per acre yields.

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

**Table 1: Green Agricultural Platform**

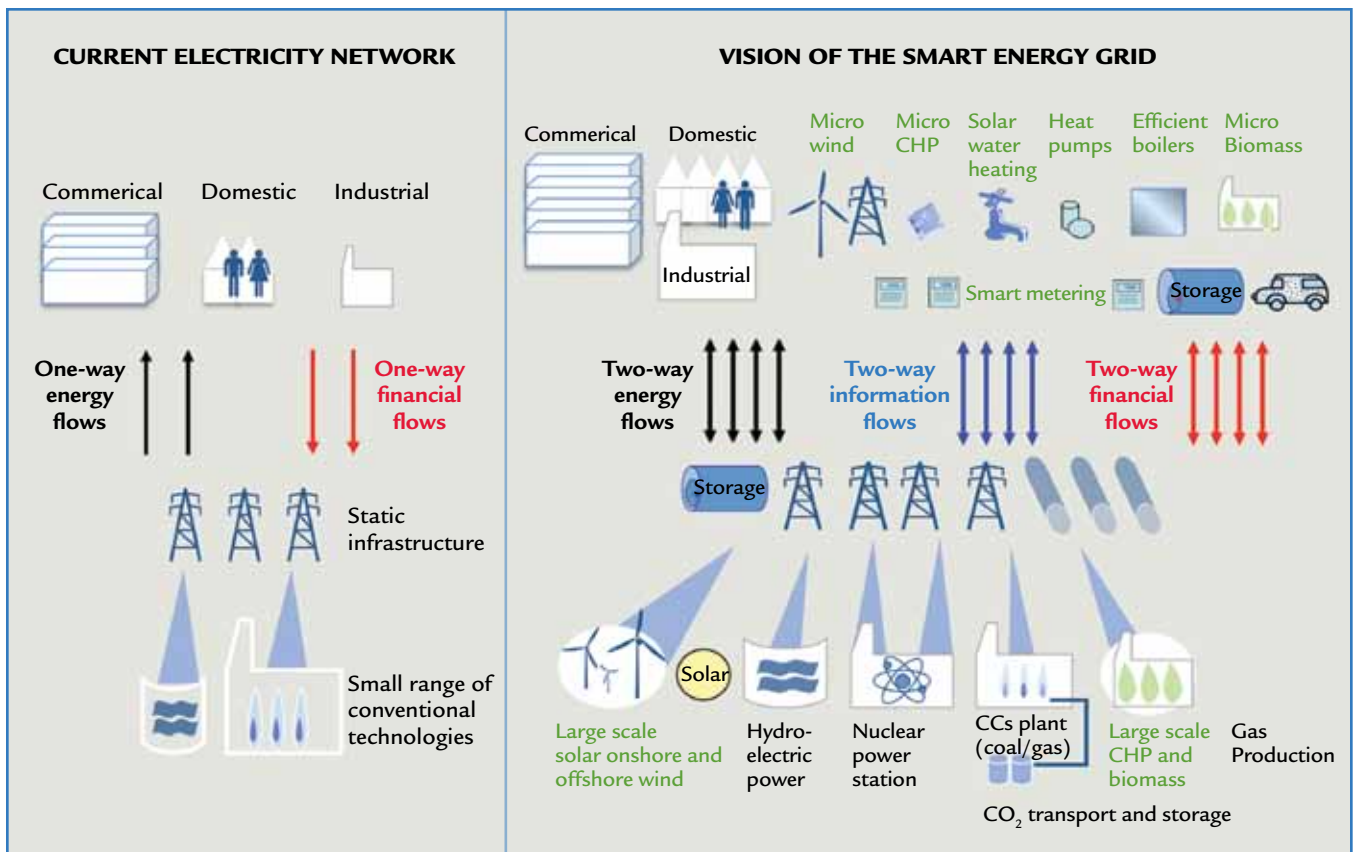
Technology	Infrastructure	Markets and Financial Institutions	Public Policy
Seeds	Roads/Railway networks	Commodity markets (e.g., eChoupal)	Price supports
Fertilizer and Pesticides	Irrigation	Insurance	Land reform
Farm equipment	Logistical systems	Credit markets	Crop Insurance
Food processing and storage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

The term “Green Revolution” is most often associated with the development of high yielding grains that were produced 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 that flourished in a wide range of climates and produced four-fold yield increases.

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 had to be provided through agricultural banks and futures markets.

In addition, getting the crops from the farms to consumers required fundamental changes to various complementary services. Countries that experienced true Green

**Figure 1: Electricity Network Transformation Reaches Far and Wide**



Revolutions saw parallel investments and innovations in agricultural markets, transportation infrastructure, and logistics (Mann 1997; Evenson and Gollin 2003). 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.

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. The Green Revolution may have

prevented consuming more land for farms but it also created more oil fields. A case can also be made that the primary 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.

What relevant lessons can we glean from this discussion of the first Green Revolution as we prepare for the Second Green (Energy) Revolution? First, 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; markets had to be developed where farmers could not only get a fair price for their crops but also could get 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.

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 growth in the 21st century.



## Designing a Smart Electricity Network

“The Smart Grid”, used as a proper noun, refers to a particular vision for the technical design configuration – a smart technical grid comprised of a cyber-physical system 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 tale 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 this 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.

Realizing the full potential of the smart grid needs more than technology. It calls for parallel 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 accommodate 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. 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 difficult task even when a superior system is available. The challenges for implementation of the smart electricity network include:

1. Integrating 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).
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 (see page 6) 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.

## Who Will Build the Smart Electric Network?

An important characteristic of network economics is that creating value requires large up-front investments. Since network effects increase with the network’s size, benefits begin accruing at a slow, low rate but accelerate more-or-less exponentially. These immense opportunities come with equally large uncertainties for value capture and depend on evolution of technical standards, regulatory policies, and business models. Thus, private capital markets are 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

**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

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 formed 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 functioned as regulated natural monopolies, like the AT&T of old. Operating within a “walled garden”, there was little uncertainty about how to capture value: networks were 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 existing systems rapidly become obsolete. 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 sometimes 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 a regulatory climate that would induce commercialization and wide-spread adoption. It takes advantage of design principles of modularity (Baldwin and Clarke 2000). 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.

## Towards a Green Energy Revolution

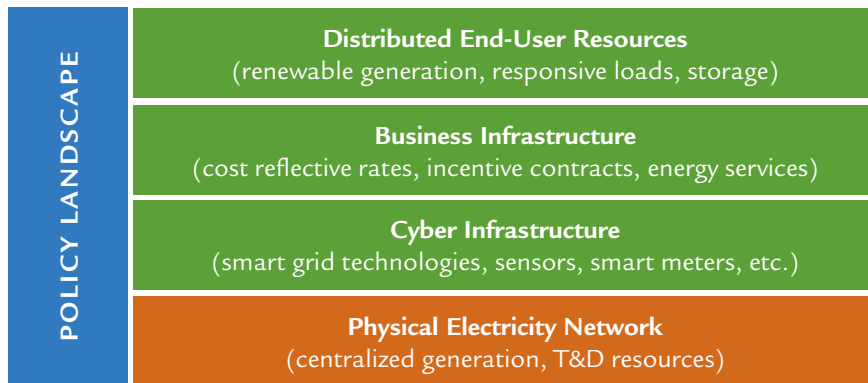
In this paper I advance the notion of a smarter electricity network as a central building block of a sustainable growth strategy. Such a network will reduce the need for investments in polluting power generation plants. However, large investments will be required in complementary cyber infrastructure.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

At the network's 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. Also key is

Introduction of *smart 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 induces 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

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 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.

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



a modern distribution system that turns the grid into a resilient dynamic system capable of delivering 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.

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” (Cleveland 2010).

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 transfer and distribution (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. 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. ●



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brings together governments, individuals, institutions, and networks engaged in the production and dissemination of knowledge on sustainable development, including research institutions and sustainable development expert networks. Its aim is to organize knowledge on sustainable development and make it available to policy makers and practitioners. The Partnership is supported by the Division for Sustainable Development of the United Nations. *Sustainable Development Insights* is a contribution of The Frederick S. Pardee Center for the Study of the Longer-Range Future at Boston University to the SDKP.

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