Virtuous Cycles of Expanding Production and Lower Costs in Renewables Through Economies of Scale: Lessons from the Information Economy

Roberto Verzola

Executive Director, Center for Renewable Electricity Strategies (CREST), Quezon City, Philippines; Lecturer, Institute of Mathematics, University of the Philippines, Diliman Campus, Quezon City, Philippines

rverzola@gn.apc.org

Abstract

By expanding production to levels that made significant economies of scale possible, industries in the information economy were able to trigger virtuous cycles of declining costs and expanding markets. Thus, they managed to attain such low costs and universal reach that they became deep game-changers, changing the rules of the game not only within these industries but also within society as a whole. The solar PV industry is already going through a similar trend, while other renewables like wind and hydro are showing promise of following these earlier trends in the information economy. By deriving lessons from the information economy that can be transferable to renewables, it may become possible for the emerging renewable economy to launch its own virtuous cycles of market and production expansion and thereby lead us in the future to a new abundance of clean energy sustainably harvested from renewable sources.

Keywords: renewable energy, economies of scale, micropower

1. INTRODUCTION

Renewable sources of energy such as the sun, wind, flowing water, hot underground rocks and biomass are highly preferred because they depend on local resources that are easier to secure; they are more environmentally benign and less harmful to human health compared to fossil-fuelled and nuclear plants; and—except for biomass—they require no fuel and therefore incur very low marginal costs. Appropriately sized, they can be tapped directly by small communities and even households. Thus, renewables can help resolve the world's triple dilemma of energy security, environmental sustainability and energy equity.

The use of renewable energy can become more widespread by making them more affordable to ordinary people. Affordability was a major factor in turning oil into the dominant source of energy and power in the late 19th and the 20th century; affordability was also the factor that turned the small computer and its variants into the dominant tool of the 21st century [9]. This paper explores how renewables can attain lower costs and better affordability that can turn them into the dominant source of energy and power in the 21st century.

2. ATTAINING ECONOMIES OF SCALE

Affordability means a low price. Conventional economic wisdom asserts that low prices encourage consumption but discourage production, both of which exert an upward pressure on price. Thus a drop in price creates economic forces that tend to raise it back. This negative feedback creates a balancing mechanism towards an equilibrium point of price and quantity that tends to maintain itself.

Under certain conditions, however, the negative feedback can turn positive. Instead of tending towards an equilibrium of price and quantity, the feedback can lead instead to exponential growth in quantities traded, and exponential decline in prices.

This positive feedback can happen, for instance, when higher demand encourages greater production among suppliers, and the increased volume of production enables some suppliers to attain economies of scale. The economies of scale in turn allow them to maintain and even improve their profit margins through lower costs and higher sales. Under such conditions, producers who are able to take advantage of economies of scale can find themselves in a virtuous cycle of increasing production and lower costs, putting them in a position to bring down their prices further and keep the virtuous cycle going. Belatedly, economists have been looking at theories that analyse economies of scale, including the economics of increasing returns to scale [1].

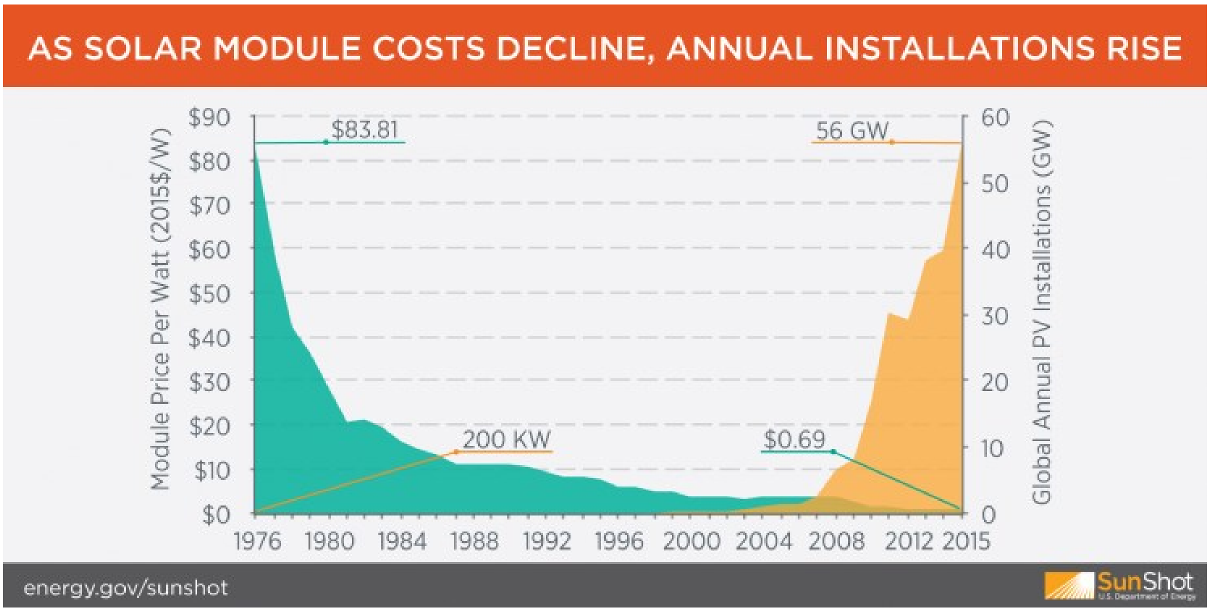

Fig. 1. The solar PV industry is showing a virtuous cycle of declining costs and growing markets (Image credit: Earth Policy Institute/Bloomberg).

Such virtuous cycles of exponentially declining prices and growing markets can already be seen in the solar PV industry, as Figure 1 shows. [2]

It is easy to understand why small systems like solar panels enjoy economies of scale much better than big power plants like mega-dams or coal plants.

Coal plants come in sizes of 100-1,000 MW; big dams in 10-100 MW sizes. Solar projects use 100-250-watt panels for their building blocks.

Raising generation capacity by 1,000 MW would need 1–10 coal plants, 10–100 dams, or 4–10 million solar panels. In fact, because solar power plants generate in 24 hours only one-fifth the output of their conventional counterparts of the same capacity, some 20–50 million panels would be needed to provide the same amount of kWh that a 1,000-MW coal or hydroelectric plant will provide. Finally, since a typical 100-watt panel may consist of 72 individual solar cells, *some four billion solar cells have to be manufactured* to provide the same amount of electricity as ten 100-MW coal plants or one hundred 10-MW hydroelectric plants.

Clearly, the solar PV industry can benefit from learning curves and economies of scale in ways that are simply not possible when only ten or a hundred units have to be built. Decreasing costs are *inherent* in the technology of solar PV. [19]

The challenge for other renewables is how to attain market sizes large enough to trigger economies of scale that can bring about virtuous cycles similar to those we have seen in the computer industry, the Internet, and the solar PV industry.

This paper proposes the following measures learned from the information economy that the renewables industry can adopt in order to expand their markets and attain production levels that can realize economies of scale.

2.1. Downsizing

Downsizing means making smaller marketable units or building blocks that can be sold at lower prices. Scaling down towards smaller and lower-priced units creates new markets consisting of those who previously could not afford the higher price. Priced lower, they become affordable to more people. The larger market enables producers to expand production towards operating levels that allow mass production methods to be applied, bringing down their costs further. This in turn can make products even more affordable. Once economies of scale are activated, a virtuous cycle of lower prices and higher production becomes possible.

A simple example of this approach is the packaging of shampoo, toothpaste and similar products in small sachets to reach lower-income brackets. Downsizing, however, can go much further than this.

It was the downsizing of the mainframe computer to the mini-computer, and later to the microcomputer, that launched the computer mass market, which in turn made the global Internet possible. This process is not over yet, as CPUs, memories and storage continue to be downsized for the smartphone market. The resulting affordability of the microcomputer—and its various reincarnations—has made it a deep game-changer, by changing the rules of the game not only in the computer industry but also in the whole economy and in society as well. [20]

Downsizing should not be pursued for its own sake. It must be pursued if the smaller version results in a significantly lower-cost product. Lower prices result in larger markets, which require larger production volumes. The goal of downsizing is to reach production levels that activate new economies of scale, which lead to new rounds of price reductions—this time, not simply because of a smaller, lower-priced product, but because of higher productivity. Under the right conditions, the lower prices can trigger another round of market and production expansion, which can then launch a virtuous cycle of lower prices but greater production. This positive feedback process trumps conventional economic wisdom, which presumes negative feedback leading to an equilibrium of supply and demand.

Sizing Solar Panels

Scale economics is working well in solar production, as Figure 1 shows. In many parts of the Philippines, solar rooftops—which avoid the cost of transmission, distribution, system losses and other costs—are already the cheapest source of electricity today [19]. Rooftop solar will pass grid parity in each distribution utility service area over the next few years as solar PV costs continue their decline. Within a few years, rooftop solar will become the cheapest source of electricity nationwide. A similar trend can be expected in other countries.

Solar manufacturers sell products based on the solar cell—the building block of solar panels, solar arrays and solar farms. Solar cells already enjoy the benefits of economies of scale. The production and price history of solar cells, in fact, already shows the recognizable features of an exponential rise in production and fall in prices—typical marks of the virtuous cycle we are after.

But the urge to upsize remains a temptation, like the mainframe manufacturers who sought growth by building super-computers.

Solar panel assemblers today, however, are starting to show a hint of the “bigger is better” bias. Solar panels are getting larger, and 300-watt panels are now being sold commercially. It is easy to imagine suppliers thinking of super-sized 500-watters down the line. Perhaps one-kW giants are already on the planning board.

Look on the other hand at the downscaling that computers went through—from mainframes to mini, micro, desktop, transportable, portable, laptop, notebook, netbook, tablet, embedded, etc. It is not hard to imagine, in the not-so-distant future, a similar transformation for solar, opposite today’s trend.

This paper suggests that solar panels should be kept small and light enough for one person, working alone, to lift and carry comfortably. To keep within this limit, solar panels should stay below, say, one square meter in size. To get higher wattage, just use more panels or use more efficient ones. At two m^2, the 300-watt panel is definitely too big and too heavy for a single person to carry. These panels will require additional labor costs due to their unwieldy size. If solar suppliers want to reach the household market and its millions of rooftops, they had better stick to solar panel sizes that a homeowner, working mostly alone or with some occasional help, can comfortably lift, carry and install. Remember the “transportable” computer? It was not light enough.

Grid-tie inverters are showing a similar “bigger is better” trend, handling 12-36 volts of DC input in the early days to a thousand volts and greater today. This paper suggests that the one-panel/one-inverter approach taken by microinverter manufacturers lends itself better to economies of scale through circuit integration. Millions of panels will require millions of microinverters, making it economic to put the microinverter controller on a single integrated circuit chip, which can then be mass-produced very cheaply. The same microinverter design can be used not only with solar panels but, in the future, with solar *roofing*, placing the solar panel itself within the well-established AC ecosystem.

Sizing Wind Towers and Turbines

It is the wind industry that flaunts its giantist approach. Starting with turbines in the hundred-kilowatt range more than two decades back, progressing to 1-2 MW wind turbines on 50-80 meter hub heights at the turn of the century, wind designers graduated rapidly to 3 up to 5-MW turbines. Monsters with 7 MW and higher capacities are starting to come online [13], and 10-MW and above super-monsters are probably not far behind, on towers exceeding 150 meters.

Wind designers cite very good reasons for this giantism.[7] Higher towers allow for longer blades. Since the power that can be extracted from the wind is proportional to the square of the blade length, this does argue for taller towers that can accommodate longer blades. More important, taller towers enable wind turbines to reach heights where winds are faster, steadier and less turbulent. And since the power that can be extracted from the wind is proportional to the cube of the wind speed, this is an even bigger reason in favor of taller towers.

But that is just one side of the argument. After all, mainframes did have their justifications too.

Let us look at the other side. Higher towers are heavier. So, they must be supported with a larger base. Assuming that the best materials and structural designs possible are already being used, then strength will vary with the cross-sectional area. To double the strength, this area must be doubled. But doubling the area doubles forthwith the weight of the structure. Thus, the extra strength is just enough to carry the additional weight. Because the structure usually tapers with height, some additional height can be attained from the additional area, but not much. In fact, for a given structural material and design, a height limit exists. Beyond it, the risk of structural failure goes up.

The second point is the length of the blades. The tip speeds of very long blades can easily approach the speed of sound, setting an upper bound on wind speeds that big turbines can harvest from. But more massive blades also require higher wind speeds just to start, setting a lower bound on harvestable wind speeds. In short, as turbines get bigger, their operating range tends to get narrower.

In the lingo of Internet design, tower height and wind turbine size *do not scale up very well*. Without doubt, the scaling direction they are taking today will eventually mire the future wind industry in the economics of diminishing returns.

This paper suggests that giant wind turbines are bound to follow a similar trajectory as computer mainframes—they will get larger and larger, but they will eventually be surpassed by their micro-sized counterparts.

Research on making small wind turbines vastly more efficient—so that they can extract energy better from turbulent as well as from laminar flow—are easily justified if the costs can be amortized over millions of units. This paper suggests that the potential of downsizing wind turbines to attain better economies of scale through quantity rather than size offers better promise for the expansion and growth of the industry.

Sizing Hydroelectric Plants

Another good candidate for downsizing is the hydroelectric plant. One can think of extracting hydroelectric power from a stretch of sloping water flow either by extracting power from the full length of the resource in a single mega-project, or by splitting the resource into shorter stretches that can then be developed separately. Again, it is easy to understand the argument in favor of one big project: a single feasibility study, a single financial arrangement, and a single mega-effort to implement the mega-structure [14]. Just like a mainframe.

Given the lessons we have learned from microcomputers, the Internet, mobile phones and solar PV panels, however, it makes sense to check whether the same downsizing trend can also be applied to the hydroelectric sector to create the conditions for a mass market of microhydro facilities, services and components and bring about potential economies of scale.

For instance, by downsizing towards operating pressures that are low enough, a hydro project can shift from stainless steel and other expensive metal penstocks to plastic-based and other lighter and lower-cost penstock materials. [8] This change can result in a significantly lower material costs. And if the penstock material becomes significantly lighter, it can also result in lower labor and installation costs.

2.2. Piggy-back on Existing Products and Standards

Market leaders in the information economy are masters in piggy-backing on existing products. Early microcomputers, for instance, piggy-backed on audio cassettes and later the standard 8-inch floppy disk for storage. Thousands of new products were piggy-backed on the Apple II and IBM PC ecosystems. It is the cascade of new products built on top of earlier ones that built the Internet and the Web of today. The best of them eventually took over these markets.

In the early stages of the renewable economy, many new concepts and products have to be developed, and R&D costs will tend to be very high. By piggy-backing on existing, off-the-shelf items which are already mass-produced, development times can be shortened and development costs lowered.

In the hydro sector, good examples of piggy-backing include the pump-as-turbine approach [4] [5] [21] and the induction-motor-as-generator approach [4] [11] [12] [16] [17]. Many more water pumps are made than turbines; the same is true with induction motors, compared to synchronous generators. By using centrifugal pumps with integral induction motors, it may be possible to trim a huge chunk from the cost of turbine-and-generator R&D and fabrication. Although somewhat lower in efficiency, this off-the-shelf combination can be significantly lower in cost. It will also shorten the project timeline and reduce financing and other time-related costs. If the lower overall costs lead to significant market growth, the market expansion can eventually fund the R&D to bring the system's efficiency back to the usual industry standards.

Another example of piggy-backing is the use of electric posts and off-the-shelf vehicle parts—particularly the differential, axle and wheel hubs—to build wind mills for water pumping [6]. The dramatically lower costs of this approach can create a secondary market for ageing gasoline and diesel-fueled vehicles that are scheduled for phase out, especially as electric vehicles go mainstream. A third example is the proven wind technology for converting "wild alternating current" to direct current and subsequently clean AC. Adapting this technology for run-of-river microhydro facilities, for instance, can help the microhydro industry reduce costs further by bypassing the need for more expensive hydraulic and mechanical controls to maintain frequency and voltage output.

A fourth is to apply maximum power point tracking (MPPT), routinely used in solar panel inverters, to microhydro facilities.

In the Philippines, my organization, the Center for Renewable Electricity Strategies (CREST) is currently experimenting with some of these possibilities to dramatically bring down the cost of micropower.

Adapt Existing Standards

Standards help propel competition, cost reduction, and market growth by enabling the interchangeability of parts, components and even systems. Going back to the pump-as-turbine example, standard off-the-shelf pump sizes can give microhydro developers a good head-start, compared to competitors who insist on designing made-to-order turbine-and-generator combinations that uniquely fit each individual site.

Once a mass market for microhydro emerges and establishes itself, the industry can then design more efficient turbine-generator combinations for this growing market to replace the less efficient centrifugal pump-and-induction motor combinations as soon as they pay for themselves or as they reach the end of their useful life. This time, however, these micropower turbo-generators should be able to show features typical of mass-marketed commodities: standard sizes, a low-cost bare-bones set-up, optional accessories that are interchangeable across different systems, and so on. One can imagine a secondary market of add-ons eventually growing around the basic micropower installation.

The electric vehicle industry is starting to show its own virtuous cycles of increasing production and declining prices. This huge industry will be adopting its own standards particular around battery storage: standard voltages, testing protocols, charging practices, battery sizes, cable connectors, and so on. The EV industry tends to replace batteries when they have lost 20% of their storage capacity, because maximum range is an important selling point for electric vehicles. These discarded batteries can still serve as perfect storage for rooftop solar and other renewables. By unifying their battery standards early in the game, the EV and the renewables industry can both enjoy a vastly larger market for their products, and possibly trigger more economies of scale. The purchase by EV manufacturer Tesla of SolarCity should make it easier for the two industries to adopt common battery standards.

An interesting case in standards is the reprise of the supply-side debate between Edison and Tesla on direct current versus alternating current supply. The debate today is between DC and AC on the demand side. Given the DC output of solar panels as well as wind turbines that convert "wild AC" to DC, the DC requirements of LEDs lamps, laptops, and mobile phones, and the DC nature of battery storage, strong arguments exist in favor of demand-side DC. However, the supply from the grid is AC and most appliances require AC. The development of the AC battery also helps strengthen the argument in favor of AC. An AC battery contains built-in electronics to take care of the AC-to-DC as well as the DC-to-AC conversion. Thus, it can directly charge itself from as well as supply power to the AC line. Putting the required controller into a single chip for mass production will eventually make the cost of conversion relatively insignificant, especially if the chip can be used for both batteries and solar panels.

Although DC standards for cars and trucks as well as AC standards for household electricity already exist, buyers who are shifting to renewables still face the risk of early obsolescence should they pick the standard that eventually loses out.

But betting on a standard that loses out in the long run is still better than getting stuck with non-standard, one-off components and designs.

2.3. Rely More on Digital Hardware, Integrated Circuits and Software for Flexibility, Lower Cost and Programmability

An important key in the development of the early information economy is digital electronics and the mass production of the 7400 series of low-cost digital integrated circuits. This led to a rapid decline in the cost of building electronic control systems and devices. Culminating in the development of microprocessors and microcontrollers, digital electronics made computing power, memory, and built-in intelligence available at a dramatically lower cost to industrial machines, including micropower plants. As these machines become cheaper and easier to use, these can turn into consumer appliances, expanding their potential market dramatically. It is already possible to imagine solar home systems as appliances that exchange electricity with the grid and making their own decisions to optimize income and savings for their owners. Further down the line, as their costs decline further, solar panels can then be embedded within other consumer items, creating entire new markets and triggering more virtuous cycles.

Another approach that can drive down costs in the renewable economy is to gradually replace hydraulic, fluidic, mechanical and analog electrical control equipment with digital electronics, which will allow the benefits of scale economics that are already in place in the information economy to spill over into the energy sector, especially for markets large enough to justify medium- and large-scale circuit integration.

Digital electronics have a further built-in advantage: they can be designed to be highly flexible and easily programmable. Program changes can be made quickly, distributed easily and even installed remotely. Software reproduction and distribution also entails lower costs, compared to the fabrication of hardware. The advantages of digital electronics can be further enhanced by providing machines with built-in logic and arithmetic processing power as well as memory and storage—already very cheap thanks to developments in the information economy.

Once the market for these control electronics become large enough, circuit integration can put them into a single chip. The ensuing mass production can lead to new rounds of cost reductions and market expansion.

This approach can be done not only on the supply-side, but also on the demand-side. Behind-the-meter equipment can acquire the same built-in low-cost intelligence. This will enable rapid ramping up or down of demand in response to sudden changes in supply that will happen more often as variable sources like solar and wind increase their share in the electricity mix.

2.4. "Killer Apps"

The first commercial killer-application in the microcomputer industry ran on the Apple II microcomputer. It was Visicalc, the very first spreadsheet software. This killer-app transformed the Apple II—and subsequently other microcomputers as well—from a hacker's toy to a business machine that any accounting operation had to have. Visicalc was the first in a long series of killer-apps which helped ensure the continuous growth of the nascent microcomputer industry. The term is less frequently used today, but the concept continues to propel innovations on the Internet. The hypertext mark-up language (HTML) was the server-side killer-app that spawned the World Wide Web. The first graphical browser, Mosaic, was the user-side killer-app which turned the Web into a mass phenomenon. These were quickly followed by search engines, peer-to-peer methods, wikis, blogs, and then social media. The growth of smartphones also relies on new generations of killer-apps.

To propel growth in demand, the renewable economy must think in terms of killer-apps. The low-power solar lamp and cellphone charger is a killer-app in off-grid areas. The first battery-solar panel combination that passes grid parity will be a killer-app where the grid is unreliable and power outages as well as severe voltage fluctuations are common. The solar panel that is designed to be installed as roofing material will be a killer-app. The first affordable roof-mounted wind microturbine that can harvest energy from the slightest whiff of wind and turbulence will probably be a killer-app. For consumers to shift to renewables in droves, applications must meet needs that are so compelling that the consumer must simply have them.

2.5. "Plug-and-play"

Killer-apps open up new markets because users feel compelled to buy them. But less compelling applications may also open up new markets through ease-of-use. Some products involving old, time-tested applications became best-sellers anyway because they were so intuitive and easy to use. A plug-and-play solar PV system will probably open up new markets, just as plug-and-play microturbines for wind and flowing water will.

2.6. Pricing "Sweet Spots"

Producers should be sensitive to what economists call the reservation prices of consumers, the price point at which a significant number will enter the market. These are often called pricing "sweet spots". Priced above the sweet spot, a product may move sluggishly. But priced below the sweet spot, it may enjoy brisk sales. In the U.S., for instance, the sweet spot for newly-introduced entry-level desktop computers stood for a long time around a thousand dollars.

Microhydro systems may exhibit a higher sweet spot for local government projects, and a lower one for farm owners with access to fast-flowing water. Just as solar panels had to drop in price by an order of magnitude or more, before they found those sweet spots that appealed to mass markets, microhydro vendors may need to strive for further price reductions, until the market responds strongly enough to activate economies of scale. Micropower suppliers who are able to pinpoint these sweet spots and manage to reach them through heroic R&D efforts can expect ample rewards from responding consumers in terms of greater market share. Identifying sweet spots will require detailed market studies and long-term test marketing. To start off the discussion, this paper offers these initial suggestions: a

microhydro project for a municipality should cost less than a low-cost single-family house. For farms, it should cost less than a cheap car. And for the do-it-yourself crowd, less than the price of a computer. With such prices, one can almost imagine an impulse to buy—if only to try—the new technology.
Imagine microwind turbines that turn at the slightest whiff of air, accumulating their micro-output in microbatteries and powering intelligent microdevices in homes and buildings. In fact, these microturbines do not even have generate electricity. If they can move air, they can find applications in residential and commercial structures. If they cost about as much as a lighting fixture and its bulb, would not consumers be interested?

2.7. Make the Product Multi-functional

The incredible value of today's computers is measured not only by their high benefit-to-cost ratio and the extent of their connectivity but also by the sheer variety of things that they can do. The number of functions that a computer can be used for today is limited only by the number of different applications one can download for it. Likewise, today's smartphone is not just a phone. It is also an audio recorder and player, a camera, and video recorder and player, a browser, an alarm clock as well as timer, and many more. It can measure distance, determine location and count steps like a pedometer. To expand their markets, energy products must provide more functions and meet more needs, while becoming more affordable.
Let us apply the multi-function idea to solar panels: they can become the roof itself, or part of the wall that faces the summer sun. The new round of construction savings can trigger more virtuous cycles. Then, as solar prices drop further, one can imagine new products such as solar tablets and solar wearables like hats, shirts, wrist bands, etc.
With the proper stainless steel or copper tubing in place, a solar array can also be a water heater. As a bonus, the lower operating temperatures will further increase the array's solar conversion efficiency. As a further bonus, the attic will be cooler too.

2.8. Plan for Interconnectivity

The electricity grid, which is in fact an internet of energy sources and sinks, antedates the Internet by more than a hundred years. Electric utilities should therefore be the first to recognize the benefits of interconnectivity. Unfortunately, they are blinded by their fear of distributed generation as a threat to their business model and are fighting hard to delay if not stop its spread. Perhaps, reviewing the history of the Internet can help utilities relearn this basic lesson—that interconnectivity adds value to stand-alone, isolated systems. This network effect is also called demand-side economies of scale. [3]

Things that do a lot in isolation can do much more—and in a much better way too—when they are interconnected. The network effect of positive externalities as more interconnections are added to a network leads to new virtuous cycles of increasing benefits and declining costs. When personal computers got connected to the Internet, new rounds of market expansion and cost reductions occurred. The mobile phone industry recognized from the beginning the value of interconnectivity and embraced it—starting with texting, then bluetooth, and finally wifi. As a result, the Internet today has become a platform for all kinds of new businesses and value-creating activities not only for computer users but also for smartphone users.

The physics of electricity requires supply to equal demand at all times. Any mismatch can cause overheating and eventual damage to either utility equipment or consumer appliances. If the output of a stand-alone PV, wind or hydroelectric plant exceeds demand, it often has to be wasted through a “dump load”. Or it can be stored in batteries, but at a significantly higher cost. If the in-house supply is not enough, the consumer will have to find another source to provide the balance. If the supply as well as demand vary often, unpredictably and in big increments, an isolated stand-alone system will find it next to impossible to balance the two.

Connected to a grid, however, a system can share any excess output with the grid, and cover any shortage by importing power from the grid. When the grid itself has too much supply—or does not have enough—the cost of storage and/or peaking plants can be shared among the many grid users. Consumer-side economies of scale—also called the network effect—takes over.

Thus, renewables must plan for interconnectivity. In the future, households will be exchanging electricity with the grid in a peer-to-peer manner, exporting energy to the grid some of the time and importing from the grid at some other times. New business models and peering arrangements must be developed for this purpose.

If utilities see their future from this perspective, they might perhaps learn to encourage and embrace emerging off-grid, microgrid and mini-grid solutions as potential markets that will want energy connectivity in the future. Who knows what kinds of new businesses and value-creating activities will come out of them and the new energy interconnectivity platforms?

Utilities who can appreciate these developments and prepare for them will have a promising future. Those who cannot will go the way of mainframes and landlines.

The grid will definitely continue to play a major role in energy systems of the future.

2.9. Try Peer-to-peer Business Models Too

The grid has until recently always patterned itself after the highly-centralized, top-down, client-server model of big power plants providing electricity to a mass of consumers. It was probably the grid that inspired the computer industry's business model of dumb terminals connected to large mainframes. This model continues to find expression on the Internet through big mail servers, Web servers, database servers, search engines, etc. that provide highly-centralized services to millions of clients.

However, Internet business models based on more decentralized, bottom-up, peer-to-peer exchanges—also called "co-provision" [15]—have emerged and proven their effectiveness too. These include the free/open source model of software development, the bit-torrent method of file exchanges, crypto-currencies patterned around Bitcoin and its block-chain technology, and others. These have even found expression in hardware development, scientific and academic publishing, and other fields.

As more and more homes and business establishments put solar panels on their rooftops, ushering a wave of distributed generation that can also include microwind, microhydro and other forms of micropower, most will want to keep their grid connection. They will often have excess production, which they might want to sell to the grid or to share with others; or they might need more power than what their existing sources and storage devices can provide. Business models that can keep close track of and fully account for these peer-to-peer exchanges can avoid unnecessary wastage of excess power. In fact, net metering as it was originally developed and practiced in the U.S. provides the best mechanism so far in accounting for these energy exchanges, especially when neighbors become willing to pool their energy surpluses into a commons.

In the future, the quality of the energy exchanged on the grid may lead to price differentiation among different sources—based for instance on their carbon-content or toxicity of by-products—leading to entirely new markets for energy. Electric vehicles, for instance, may want to rent their batteries out as storage and ancillary services when they are garage-bound. These possibilities can turn the grid into a universal platform for sharing or trading energy and power, just like the Internet today has become a universal platform for trading information. It is not far-fetched to imagine accumulating credits for net energy uploads, just as uploaders today earn credits in file-sharing sites. Markets can later arise where these credits can be bought and sold for cash or perhaps using crypto-currencies.

2.10. Let the Government Do the Resource Assessment and the Bulk of the R&D

Aside from their basic role in providing a supportive policy and legal environment, governments can play another positive role in the ongoing shift to renewables by shouldering the responsibility for comprehensive resource assessments of the renewable potential of their country and various sub-national territories. Detailed community-level solar, wind and river atlases must be produced, and low-cost resource maps must be made available to the public, to generate community and household enthusiasm for micropower.

Governments did much of the early research on computer networking and the Internet. The government can also help by conducting the bulk of research and development and absorbing their costs, and then making the results available for exploitation by businesses. This in turn provides a level playing field for all and avoids the growth of monopolies that can stunt these virtuous cycles of declining prices and expanding production.

3. THE ECONOMIC AND SOCIAL CONSEQUENCES OF DECLINING COSTS

The declining prices and growing abundance that accompany the virtuous cycle of increasing demand and supply generates a powerful economic force called substitution [18]. As goods and services that decline in price compete with similar but more expensive goods, a steady replacement process occurs. Old expensive ways of doing things are replaced by newer lower-cost ways of doing so. Sooner or later, as the substitution process relentlessly takes effect, the lower-cost product or service becomes the dominant—if not the universal—way of doing things. The mainframe gives way to the small computer. The landline gives way to the mobile phone. The shopping center gives way to the Internet. The expensive and the scarce give way to the lower-cost and the abundant. Similarly, oil and coal will eventually give way to microrenewables.

The new products and services that take over require their own unique procedures and practices as well as new business models. Their consumers will acquire new habits and new ways of thinking and doing. Economic change begets social and cultural change. If the changes are deep enough, a new social system—a new civilization even—emerges.

Thus low-cost, abundant goods carry the potential to become deep game-changers. They can change the rules of the game not only within their own industrial sector, but within society as well.

Although scarce items may be highly-prized in society, it is the affordable and the abundant that become the foundational building blocks of societies and civilizations [10].

The abundance of wood and other biomass fuelled humanity's early use of fire. Subsequently, the abundance of fossil fuels and metals propelled the Industrial Revolution. It is the abundance of silicon, transistors and integrated circuits that launched the information revolution and continues to propel it today. These foundational materials of civilizations are deep game-changers, but their abundance makes it easy to take them for granted. It also makes them less interesting to most economists, who prefer to focus their attention on economizing scarce economic goods which are poor universal material and energy sources for building societies and civilizations precisely due to their scarcity. [19]

If the measures suggested here manage to trigger virtuous cycles of increasing production together with declining costs through economies of scale, then renewables may yet turn into one of the foundational building blocks of 21st century societies.

4. CONCLUSIONS

When market sizes and production levels become large enough, producers may reach a point where economies of scale are activated. With economies of scale activated and their costs further reduced, producers are then enabled to respond to the increased demand with higher production instead of getting discouraged by the low prices. Negative feedback turns positive, and a virtuous cycle of increasing production and declining prices is triggered.

This is how the computer industry grew. As computers became cheap enough, they started replacing older and more expensive ways of doing things, causing a new round of virtuous cycles in other sectors of the economy too.

Cascades of activation of economies of scale and virtuous cycles of increasing production and declining prices led to the rapid growth of the Internet, creating new virtuous cycles in many other sectors of the economy.

As the effects of substitution rippled outwards, they were accompanied by further social and cultural upheavals, changing the rules of the game not only in the computer industry and the information economy but the rest of society too.

The emerging renewable energy industry shows promise of going through a similar phenomenon of expanding markets, declining prices and increasing production. In the process, it promises to resolve the triple dilemma of ensuring energy security, energy equity and environmental sustainability.

Learning from the lessons of the information economy, this paper suggests ways by which markets can be expanded and costs reduced in the renewable energy sector. These include: 1) downsizing; 2) piggy-backing on existing products and standards; 3) relying more on digital hardware and on software; 4) developing “killer-apps”; 5) making products “plug-and-play”; 6) identifying pricing “sweet spots”; 7) make products multi-functional; 8) planning for interconnectivity; 9) exploring peer-to-peer business models; and 10) letting governments do the resource assessment and the bulk of the R&D.

Under the right conditions – including the appropriate technologies that make economies of scale possible, the right business models, and a responsive market – things may fall into place. Then, the ensuing virtuous cycles of growing markets and declining prices driven by economies of scale can create a cascade of abundance that causes deep changes in society and improves the lives of millions.

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