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First Principles: Technology as an Enabler for Productive Power Markets

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EXECUTIVE SUMMARY

In this paper, we look at the advantages that decentralized energy (DE) systems offer to the Asia-Pacific as compared to the traditional power generation model and provide insights to governments, utilities, and developers looking to electrify poor and/or remote areas of the region.

Main Argument

Power generation in the developed world has been built around the concept of large, centralized plants connected through long distances of transmission and distribution infrastructure. While this conventional wisdom is embedded in most utilities, a new mindset may be helpful for developing regions in the Asia-Pacific. Smaller decentralized energy systems may offer the best way forward to electrify poor or remote communities without incurring significant delays or infrastructure costs. Within the right regulatory frameworks and employing the correct business models, DE systems can provide long-term socioeconomic and environmental benefits to local communities at relatively low cost. In this paper, we consider how developments in technologies such as solar, wind, and biomass have increased their feasibility for DE systems while ongoing convergence between the energy and information technology sectors is removing previous operational barriers.

Policy Implications

- Constantly changing social, economic, and technology landscapes should encourage leaders to periodically revisit their energy strategies, and look at the question of whether DE systems can be utilized in order to realize their potential benefits, and if so, where and how?
- The development of DE systems is often constrained by limited access to capital. Many technologies have relatively high upfront capital costs per kilowatt (kW), but subsequently benefit from modest operating costs. Governments should create an environment where public, private, or combined funds can be used to overcome any initial financing hurdles
- Market liberalization is often required to promote DE system development. Smaller, regional players are inherently more efficient at creating small-scale plants than are the large incumbents; however, market regulation frameworks must be designed to remove any major barriers that smaller generators would face.

How Centralized Power Became the Conventional Wisdom

One hundred thirty years have passed since Thomas Edison first built a central power station in Manhattan to provide electricity to various offices on Wall Street. Edison's vision was to provide localized power generation on an as-needed basis and make it more affordable for companies to access. Edison, the first independent power producer (IPP), was the pioneer of the electricity generation and supply business model, which for many years prevailed in the United States and parts of Europe. During World War I, electricity became a strategic commodity, and many authorities in the United States and Europe started grouping their electricity suppliers into districts in order to control supply. However, it was not until World War II that governments took this consolidation a step further and centralized most of their countries' infrastructures and, in many cases, nationalized the entire system. This drive toward consolidation, alongside advances in technology, led to ever-larger power plants being built, supported by economies of scale; the bigger, the better.

In the 1960s, developed countries started to commission large nuclear, coal, and heavy fuel oil (HFO) power plants that were by themselves small villages. These power plants were constructed near the primary energy source—in the case of coal plants, near the mines and railheads, and in the case of HFO, near the refineries. Sites were also purposely chosen to be far away from population centers to minimize the impact of their heavy pollution. The state was, in many cases, the owner of these plants and thus held a monopoly position regarding the sale of electricity. As such, the centralized model, where large power plants were connected by extensive transmission and distribution infrastructures, became the norm and the conventional wisdom for the industry.

Due to their relatively low costs, coal and HFO were the chosen primary energy sources for power generation. However, during the 1970s, when successive oil price shocks caused oil prices to increase dramatically, governments became concerned with the security of their supplies and started to look into new resources. But it was only in the 1980s that the role of the IPP, a non-utility generator, was introduced in countries that until then had been dominated by the centralized state system. For many years, IPPs were associated with the development of small-scale combined heat and power (CHP)[1] plants; but it did not take long for them to start participating in large-scale deployments such as the introduction of Combined Cycle Gas Turbines (CCGT) in the United Kingdom in the late 1980s and early 1990s. At the same time, the United States and a number of countries in Europe began to liberalize their power markets.

As an established business model, this centralized power mindset has been exported to many emerging markets, where large combustion plants, as in the case of China, are connected over long distances though an extensive transmission infrastructure. Even renewable systems, when they are deployed, are based on the model of large-scale deployment. For example, the Three Gorges dam power station complex in China with an installed capacity of 20,300 megawatts (MW) and the Itaipu dam power stations in Brazil and Paraguay with an installed capacity of 14,000 MW are the two largest power station complexes in the world, and while they might help reduce CO_2 emissions, this is not without causing other environmental damage such as changes in the landscape and the flooding of, in many cases, whole communities.

Due at least in part to a certain “legacy mindset” in the power sector, the large-scale centralized system has kept its predominant position until recently. However, governments and operators are beginning to realize that “the bigger, the better” maxim is not always true. With an expanded agenda that, in addition to providing the lowest-cost electricity, also includes environmental and security-of-supply concerns, leaders in many regions are now targeting a larger penetration of decentralized energy systems. While the conventional wisdom of the centralized system is still embedded in most large utilities, many governments and operators have recognized that the lowest total cost to the consumer, together with security of supply, can in some cases be better provided by small decentralized plants closer to the point of consumption. Even though a certain element of infrastructure lock-in will exist, decentralized energy systems present a potential alternative to future grid reinforcement or expansion.

[1] In some literature, CHP is also referred to as “co-generation.”

The Role of Decentralized Energy

As highlighted in Mitra et al.,[2] there appears to be no consensus on the definition of decentralized generation (DG).[3] This is often defined in terms of generation capacity, proximity to demand sources, or connection point into the grid. Dondi et al. view decentralized generation as the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system.[4] For the purposes of this paper, we use the concept of decentralized energy (DE) systems that expands on these definitions for DG to include energy storage and CHP applications.

As mentioned in the previous section, electricity grids first began as decentralized systems with local generation supplying local demand. While modern grids moved to a centralized structure, DE systems continued to be utilized for providing electricity to remote sites, such as farms, mines, or lumber mills, where due to the terrain it was either too expensive or too difficult to build the required transmission and distribution infrastructure. In most cases, these generators were privately owned with little, if any, power supplied to nearby communities.

As grid connectivity in most OECD countries is close to 100%, the majority of existing DE capacity is for standby purposes during power outages. However, the most beneficial application of DE lies in parts of the developing world that are still not connected to an electricity network. Many studies have shown that a lack of electricity exacerbates poverty by limiting access to education and reducing worker productivity. Yet it was estimated by the International Energy Agency (IEA) in 2011 that 1.3 billion people worldwide still lack access to electricity, of which 99.7% are in developing

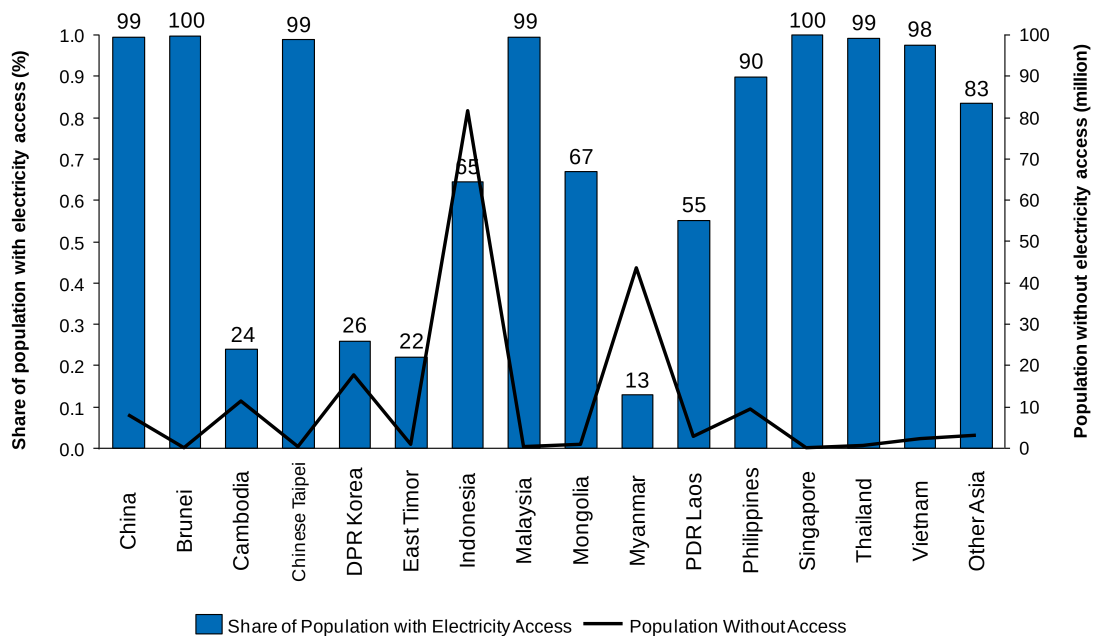
[2] I. Mitra, T. Degner, and M. Braun. "Distributed Generation and Microgrids for Small Island Electrification in Developing Countries: A Review," Solar Energy Society of India, 2008.

[3] Some literature refers to "distributed" generation rather than "decentralized." We have used the latter term to provide a clear differentiation with centralized generation.

[4] P. Dondi, D. Bayoumi, C. Haederli, D. Julian, and M. Suter, "Network Integration of Distributed Power Generation," *Journal of Power Sources* 106, 1–9.

countries.[5] The Asia-Pacific has over 180 million inhabitants who are not connected to the grid, despite huge progress in electrification over the last twenty years, particularly in China. As **Figure 1** below demonstrates, the rate of electrification varies quite significantly between countries. Furthermore, this number vastly underestimates the full magnitude of the problem by not including inhabitants who, while connected to the power grid, are underserved due to outages or power quality issues.

Figure 1: Access to electricity in the Asia-Pacific



Source: IEA; and World Bank.

The leaders of these countries are faced with the challenge of producing a technically feasible, environmentally conscious, and sustainable framework to supply electricity to rural and poorer areas in order to promote economic and social development. The correct business model should take into consideration local growth prospects and act as an enabler to growth and prosperity. The system design should be tailored to local needs and to the creation of socioeconomic benefits in the area, also

[5] *Energy for All: Financing Access for the Poor*, Special early excerpt of *World Energy Outlook 2011*, International Energy Agency, 2011, http://www.iea.org/papers/2011/weo2011_energy_for_all.pdf.

taking into consideration potential growth in demand for electricity, and where possible it should exploit local resources and sustain local employment. Against these criteria, DE systems potentially offer the best way forward to electrify these areas without incurring significant delays or infrastructure costs.

Comparison of DE Systems with Grid Electricity

Benefits of Decentralized Energy Systems

Due to technical advances and structural changes, DE systems have seen a resurgence over the past decade. The IEA suggests five key drivers for growth in DE systems:[6]

1. Developments in DE (and communications) technologies
2. Constraints on the construction of new transmission lines
3. Increased customer demand for highly reliable electricity
4. Electricity market liberalization
5. Concerns about climate change

As this list highlights, the decision of whether to deploy DE relies on many other considerations besides which option provides the lowest cost electricity. In this section we look at some of the key benefits and drawbacks of DE systems as compared with the alternative of an expansion of centralized grid electricity.

Overall, there are eight primary benefits that DE systems can provide over the conventional centralized power generation model. These are listed below and described in the following paragraphs:

1. Increased security of supply
2. Ability to utilize renewable energy technologies
3. Potentially lower levelized cost of energy[7]

[6] International Energy Agency, *Distributed Generation in Liberalised Electricity Markets* (Paris: OECD, 2002).

4. Improved competition in the power sector
5. Shorter time to deployment
6. Reduction in transmission and distribution losses
7. Opportunity for local employment
8. No "infrastructure lock-in"

Energy security can be improved in two ways from deploying DE systems, namely through diversification of primary energy supply and from improved system reliability. First, at a national level, imports of fossil fuels can be partially offset by the use of local and/or renewable resources in decentralized systems. Second, a power system based on a large number of small generators can operate with the same or higher reliability as a system of a smaller number of large generators. In fact, the reliability of the centralized power generation grid is due to the fact that a significant degree of excess capacity is maintained in order to compensate for disruptions, such as the planned or unplanned shutdown of a plant.

While many renewable energy technologies are best utilized in DE systems, one does not necessarily imply the other. For example, large solar and wind farms connected to the transmission system would qualify as centralized generation while small fossil-fueled generators are considered decentralized. Solar photovoltaic (PV)[8] power provides the best example of a technology best suited to DE systems. PV panels generate low-voltage, direct current (DC) power that must be inverted and stepped up to high-voltage alternating current (AC) in order to connect to a transmission or distribution network. This conversion process incurs substantial losses relative to the power initially generated. As economies of scale are minimal or even nonexistent for solar PV systems, they are optimally deployed at the required demand source. Indeed, this is what has been occurring in the majority of on-grid applications in developed markets.

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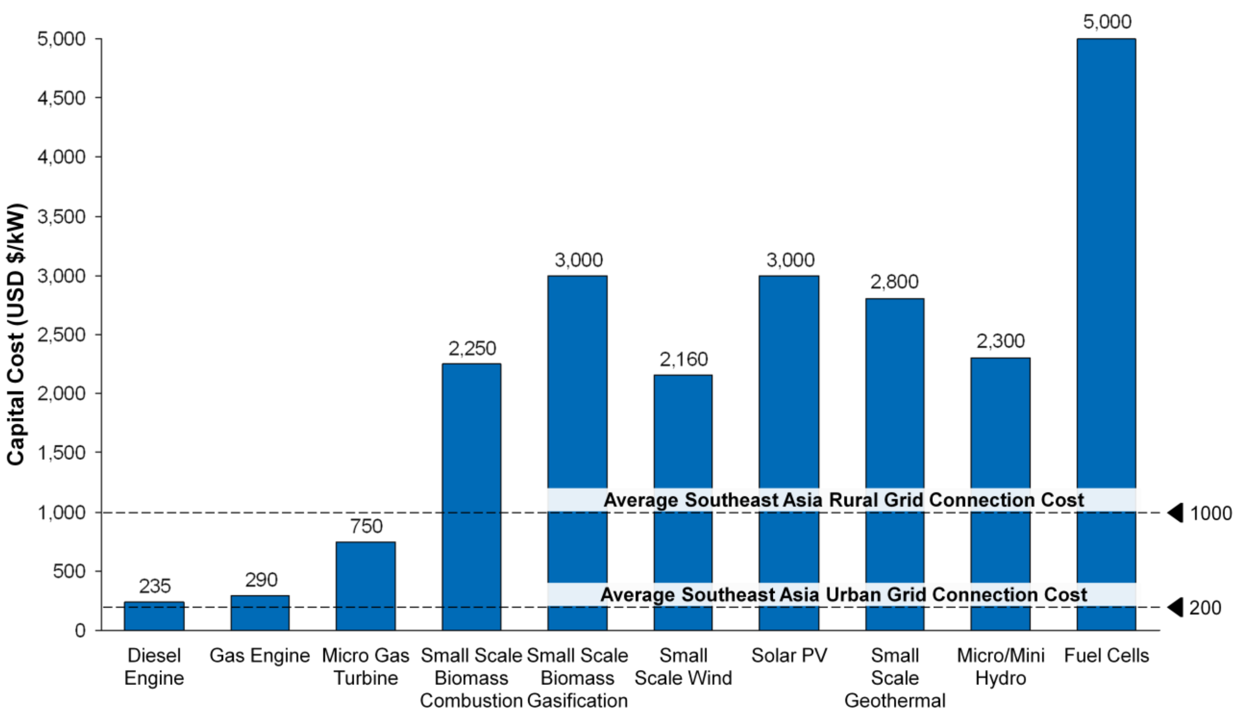
[7] The "levelized" cost of energy includes all costs of generation such as the initial capital investment depreciated over its lifetime, plus any recurring costs such as operation, maintenance, and fuel. It proves a way of comparing disparate technologies.

[8] It is important to distinguish solar photovoltaic (PV) from concentrated solar power (CSP) as the latter is geographically specific and not suited to distributed applications.

Continued advances in DE technologies have produced dramatic reductions in both their capital and operating costs. As shown in **Figure 2**, in many cases, it may be more economical to install diesel- or gas engine–based DE systems than to extend grid connections to remote rural areas. However, most renewable technologies still remain at a higher cost per kW. But, whereas centralized systems require a "pre-investment," building in many cases a few hundred megawatts more capacity than initially needed, DE systems are modular and can be built to match the actual development of load. This greatly reduces project cost and simplifies the financing structure for DE projects.

Figure 2: Capital costs for DE technologies vs. grid connection



Source: Ricardo.

While many governments have taken great steps to liberalize their energy markets, the large amount of capital needed to build a centralized power plant limits the number of organizations that are able to participate. By contrast, DE systems have a significantly lower capital requirement, which removes a major barrier to entry for new players and allows for a more competitive power market. For instance, a rural community underserved by the existing grid could have the option of working with a developer to build a local power system instead, thus providing residents with potentially more reliable and/or lower cost electricity.

The smaller size and modular nature of DE systems also enables faster deployment. Small-scale decentralized power plants can be built in between nine and eighteen months, as compared to the two years or more for a grid-connected system.

By situating large power plants far from populated areas, a significant amount of electricity is wasted through transmission and distribution (T&D) losses, which in the United Kingdom as an example, account for over 7% of the power generated (approximately 29 TWh), which translates into roughly 15 million tons of CO_2 emissions (roughly 3% of total UK emissions). By comparison, T&D losses across the Asia-Pacific vary significantly, with some countries like Malaysia and Korea below 5%, and others such as the Philippines and Indonesia with rates above 10%. However, as distribution lines in rural areas typically have high resistance, they lead to much greater energy losses than these averages would suggest. As DE systems are located at or near the demand source, distribution losses are negligible.

Providing a community with reliable power improves its economy by both raising the productivity of current residents and allowing new industry to move in. However, electrifying with DE allows for even further job creation; aside from the initial construction of the plant, labor will be required for operation and maintenance and, if needed, for the supply of an input fuel such as biomass. As many of these DE systems can and will be built in poorer areas, these additional jobs would be created where they are needed the most.

Finally, as opposed to centralized power plants, which are developed with excess capacity built in over a lifetime of 30–50 years, DE systems are developed to meet a specific load in a specific location. As they are small and modular, there is little risk of “infrastructure lock-in” should environmental or energy market circumstances change in the future. An example of this type of risk would be in nuclear energy, which was heavily built up in countries like Germany and Japan at great expense, but may be decommissioned ahead of plans as a result of public opposition to the technology.

Limitations of Decentralized Energy Systems

While the aforementioned benefits are numerous, particularly for underdeveloped regions, there are also some notable limitations of DE technologies. These are mentioned at a high level here and presented in detail in the next section on technology.

As discussed above, sufficient access to electricity is necessary to raise the standard of living in poorer areas; however, it will not by itself bring about economic development without other conditions in place. These other prerequisites include transportation infrastructure; market mechanisms for local industry, education, and health services; and communications services. Simply providing a DE system to a poorer community without addressing these other factors will not provide lasting economic benefits, and in many cases will not be sustainable itself. A prime example of this occurrence was the 1998 joint venture between Shell and Eskom, the South African national electricity company, which aimed to provide solar power to 50,000 homes in poor, rural areas. This program eventually failed, as it was not built around improving the local economy and residents were not adequately trained on how to maintain their systems. In many cases, solar panels were stolen shortly after being installed, often being reused as simple building materials.

And while there is a range of technologies available for DE systems, many of these technologies might not be suitable for a given area. For instance, a reliable source of natural gas must be available for gas-powered plants. As gas is difficult to transport, a supply infrastructure must already be in place to make this option feasible. Other technologies such as hydroelectric and geothermal are geographically restricted. Yet while Indonesia and the Philippines are located in the geothermally active “Pacific Ring of Fire,” both countries have problems accessing most of their resources due to other location issues, environmental concerns, and in some cases, public aversion. The Bedugul project in Bali, which aims to develop up to 175 MW of power, or approximately half of the resort island’s needs, is now on hold because local residents fear it could damage a sacred area and affect water supplies from nearby lakes. In the Philippines, the world’s second-largest geothermal producer, environmental concerns such as the high acidity associated with active volcanoes, which can corrode pipes, constitute a significant obstacle to developing the reserves.

When trying to bring power closer to the point of consumption, policymakers and developers alike have faced some public aversion, what is known as the NIMBY (Not in My Back Yard) effect, driven in many cases by misleading reports and a general lack of awareness. This is often the case with wind projects, which provide no ill effects other than their appearance, because their tall towers can be viewed from a considerable distance. By comparison, transmission infrastructure together with large power plants has a much greater impact on the overall landscape. Locating DE systems near residential areas will likely raise concerns over appearance, noise, air pollution, and safety depending on the technology chosen; these are problems that must not be ignored, but rather managed by a proactive approach based on awareness of local sensitivities and appropriate communication policies to address them in a transparent manner.

It is often the case that the efficiencies and economies of scale enjoyed by centralized plants do not apply to their DE equivalents. Electrical efficiencies, for example, tend to be higher when technologies like CCGT are utilized in centralized plants. The net outcome is usually a higher cost per unit of electrical capacity for smaller-scale plants. But this statistic can be misleading; when full levelized system costs and socioeconomic and environmental benefits are taken into account, the result is often more favorable.

One final drawback of DE systems is their effect on power quality and reliability. When demand exceeds supply on a network, voltage levels drop, creating brownouts, which can damage or reduce the effectiveness of electrical equipment. Indeed, this occurs already in fringe-of-grid rural networks without proper balancing in place. In larger systems, this effect is diminished through the averaging out of a large number of sources and loads. This issue is exacerbated in DE systems employing significant amounts of variable[9] generation technologies like wind and solar. Furthermore, DC generators like PV and fuel cells, and the varying speeds of wind turbines, can cause issues with harmonics and reactive power on a network that must be compensated for. Another potential issue arises from the asynchronous nature of power flows when DE systems are connected to a central grid. These networks have been largely designed for one-way flow

[9] This characteristic is often termed “intermittency;” however, “variability” is a more accurate description.

of power from a generator to a final user. When the potential exists for users to also supply power, many of the meters, switches, and safety controls on the network become inadequate, and the role of distribution system operators (DSO) becomes more difficult.

Technology Advancements in Decentralized Energy

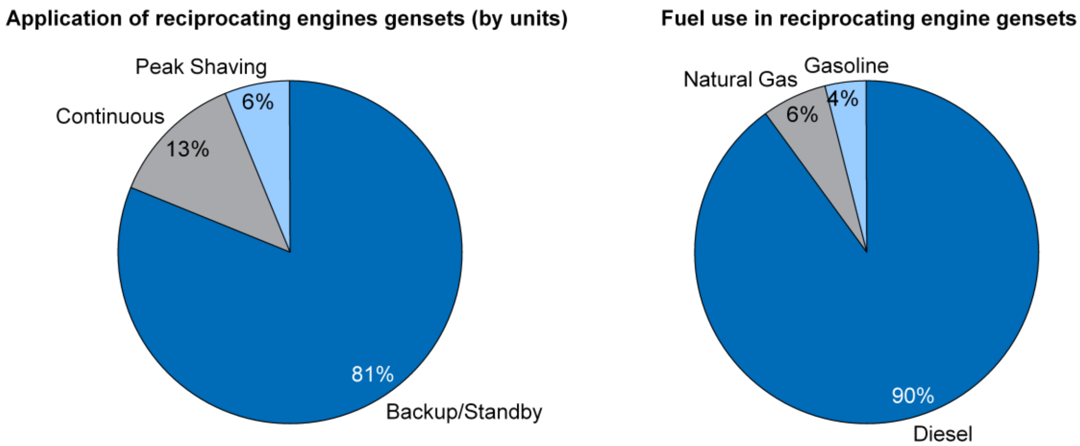
Distributed energy encompasses a wide range of technologies and fuels, each with its own set of benefits and drawbacks. A thorough understanding of where and how each technology fits into the energy landscape is needed to ensure a system is optimized for a particular region and purpose. This section highlights some key characteristics of current decentralized energy technologies.

Reciprocating Engines

By far the most commonly deployed decentralized energy technology globally is reciprocating engines, powered by diesel or gas. As shown in **Figure 3**, they are normally used for back-up applications and predominantly diesel. Reciprocating engines offer many benefits, including relatively low capital cost, good reliability, an ability to be dispatched,[10] and fast start-up times. However, their dependence on fossil fuel is the primary drawback for remote applications where fuel supply logistics may be limited. In addition, price volatility causes operating costs to vary with market prices and requires a constant fuel supply to be available. Furthermore, reciprocating engines emit a relatively high level of CO_2 and particulate emissions, and in many cases, are much noisier than competing technologies. As many of these engines can be modified to use vegetable oil, some of these drawbacks can be partially mitigated, making them a potentially viable option for remote farming areas.

[10] "To be dispatched" is the ability to generate more or less power on demand over a relatively short period.

Figure 3: Application and fuel used in reciprocating engine gensets



Source: Diesel & Gas Turbine World; Frost & Sullivan; and Ricardo.

Gas Turbines

Although developed with the promise of being a decentralized technology, gas turbines have typically been used in centralized power generation due to a legacy mindset in the sector. The capacity of small gas turbines ranges from approximately 1 to 10 MW, but microturbines present the opportunity to extend gas turbine technology to smaller-scale applications. Microturbines were originally developed for transportation applications, but are applicable for DE systems in the range of 25 kW–250 kW. Microturbines for stationary power generation are a relatively new technology that has only recently been available commercially.

Biomass Power

Biomass power generation is a thermal process in which solid fuel is burned to produce steam to power a turbine and produce electricity. Biomass gasification is a related process that offers improved efficiency but at a much higher cost. Currently for DE applications, biomass gasification is not cost-competitive with biomass combustion technologies.

In practice, solid biomass is a sustainable resource that is in abundance in many rural parts of the Asia-Pacific and, in particular, the areas that are most likely to be underserved by electricity grids. Feedstocks can range from municipal and animal wastes to forestry and agricultural residues. The economical availability of these feedstocks is a common constraint, limiting biomass power for large-scale applications; however, this technology becomes more practical when both feedstock supply and power demand are local to the plant.

Small-Scale Wind Turbines

Small wind turbines, typically under 100 kW, although easy to install, have a high capital cost compared to large-scale turbines (+1 MW). The United States is currently the largest market for small wind turbines, with over 144,000 turbines providing 179 MW of installed capacity (AWEA 2010).

A key drawback of small wind turbines is that their power generation is highly variable. Whereas large-scale wind is typically deployed with high hub heights near or above 100 meters (m) and in optimal wind areas, small-scale installations are much lower to the ground and often installed in less optimal locations. Systems require a minimum average wind speed of between 3 and 4 meters per second. Furthermore, small-scale wind typically comprises single turbines, not a farm, so their capacity factor is typically 15%–20%, which is much lower than large-scale wind installations (c. 25%–30% capacity factor).

Solar Photovoltaic

Solar photovoltaic (PV) systems have long been viewed as one of the most promising technologies for electrifying underserved rural areas. They are less dependent on economies of scale and are often deployed as low wattage, single-home systems. As the solar resource is free and PV systems require relatively low maintenance, they have a very low operating cost once installed. However, the initial capital investment per kW still remains very high relative to other technologies.

Driven previously by generous feed-in subsidies and large, grid-connected deployments in developing countries, global solar PV manufacturing capacity has increased dramatically over the past twenty years. This has decreased installation costs significantly, and systems are close to approaching cost parity with retail electricity prices in many developed markets.

Off-grid applications represent a much smaller portion of the market, but one with much more upside potential. Future cost reductions in solar PV, together with its easy deployment and maintenance, will drive an increase in its use as a key decentralized solution.

Other Technologies

A host of other technologies are available as potential options for DE systems. Some, like geothermal power or small-scale, "run of river" hydroelectric systems are geographically determined, while others like hydrogen fuel cells still have a high cost, as well as substantial technical hurdles to overcome. These technologies are briefly described in this section.

Geothermal power utilizes heat from the earth's interior to generate steam to power an electrical turbine. It is used for power and heat applications in over 60 countries, although for power generation it tends to be better suited to large-scale plants of up to 100 MW.[11] Smaller-scale plants (less than 5 MW) are currently in use in China, Mexico, and Thailand, with the potential for many more in the Asia-Pacific along geologically active fault lines. As an example, it is estimated that Indonesia has a potential of over 25 gigawatts (GW). Efficiencies for geothermal plants tend to be around 20%–30%, and they are able to produce constant electricity, with capacity factors above 80%.

Mini or micro "run of river" hydroelectric utilizes the natural flowing current of a river to drive a turbine and produce electricity.[12] By comparison to large, hydroelectric plants, these systems are quick to install and do not require dams that interfere with the natural surroundings. However, they must be scaled to the minimum river flow during the dry season, which often leads to an overcapacity for the remainder of the year.

[11] The World Geothermal Congress estimated that 11 GW of geothermal capacity exists globally.

[12] The definition for scale changes by region, Brazil defines small-scale as 1–30 MW, but uses mini-hydro (100 kW–1 MW) and micro-hydro (under 100 kW) categories.

Fuel cells come in several varieties, the most common of which are proton exchange membrane (PEM) and solid oxide fuel cells (SOFC). Fuel cells use an electrochemical process to turn hydrogen gas into electricity and heat. They are fully dispatchable and offer efficiencies above 85% when the heat is also utilized. The key drawbacks are the requirement for hydrogen, which is not widely available, and high capital costs. In spite of much hype, fuel cells are expected to remain a small niche technology for transport and stationary applications for the foreseeable future.

Combined Heat and Power Applications

Combined heat and power (CHP) systems generate electricity using a standard thermal process while capturing the waste heat to use for domestic or industrial applications. Industries that typically utilize CHP include agriculture, forestry, and wood products; pulp and paper; mining; glass; petroleum; chemicals; metals; and food and beverage. Most systems are heat-led, meaning that the plant is sized for the heat requirements and the electricity is a secondary output. In many cases, the electricity is excess and exported back to the grid.

By capturing heat, the overall process becomes much more efficient, with a combined efficiency of 70%–80%. However, these projects are only cost-effective when demand for heat already exists. Most developing regions and rural areas tend not to be industrialized and thus have limited demand for process heat. As heat cannot be efficiently transported over long distances, it essentially must be used at or near the source.

Energy Storage

Energy storage is beneficial to help balance supply with demand. Storage technologies do not generate electricity, but rather capture excess electricity and dispatch it as needed to an end user. As such, they are only useful as part of a larger system, particularly one using solar power or wind power because their production cannot be scheduled and is not well synchronized with peak demand.

Energy storage has been utilized for balancing purposes since the first power grids were deployed. In Edison’s time, most of the distribution grids were DC, and large battery banks were directly coupled to the system to buffer differences between supply and demand. Many solar PV systems have been integrated with batteries in order to store unused electricity. Some systems, like the solar battery charging stations (SBCS) in Nicaragua, allow families to periodically charge a portable battery at a central site and then take it home to power low-wattage lighting. However, the storage of electricity can potentially go beyond simple batteries.

As power grids moved to AC, storage options like pumped hydro became commonplace. In fact, there are a wide range of technologies available that can be used to store electricity; however, the availability of some, like pumped hydro or compressed air, are dependent on geography. Others, like hydrogen, cannot yet be economically produced.

Table 1: Key specifications for DE technologies

Technology	Capital cost ($/kW$_e$)	Efficiency (%)	Emissions (gCO_2e/kWh)	Scale (kW$_e$)	Dispatchable
Reciprocating engines – diesel	95–500	36–43	650	1–2,000	Y
Reciprocating engines – gas	110–650	28–42	500–620	5–5,000	Y
Micro gas turbines	500–900	20–30	720	25–250	Y
Small-scale biomass combustion	1,500–3,000	15–35	0–100	300–5,000	Y
Small-scale biomass gasification	3,000–4,000	30–40	0–100	10–1,000	Y
Small-scale wind	1,350–3,850	10–20	0	1–50	N
Solar PV	2,200–5,000	5–12	0	0.5–25	N
Small-scale geothermal	2000–3000	20–30	0	300–5,000	Y
Micro/mini hydro	1,600–3,500	70	0	50–1,000	Y
Fuel cells	3,500–8,000	25–55	0–490	0.5–15	Y

Notes: Efficiencies provided are for electricity only. CHP efficiencies, if applicable, would be much higher. Capacity factors provided for non-dispatchable technologies—wind and solar PV.

Source: Ricardo analysis from multiple sources.

Integrating Decentralized Energy Technologies

Hybrid Systems

Hybrid DE systems include any combination of two or more of the decentralized technologies mentioned in the previous section. By utilizing multiple technologies, the specific drawbacks of an individual technology (e.g., variability) can be mitigated while still realizing many of the benefits of decentralized energy. In this effort, hybrid DE systems often involve a combination of both fossil and renewable technologies such as solar, wind, and hydro. The electricity grid in any given country is, in fact, a hybrid system utilizing many different generation sources such as coal, hydro, and gas utilized on a large scale. Many hybrid DE systems are able to provide grid-quality power even when no grid connection exists.

As such, the design of DE systems should not be focused on the sole use of a single technology but on the deployment of the most appropriate mix of complementary technologies, so as to secure supply at the lowest possible cost while respecting the environment. An example of a technology mix is the deployment of small solar panels working alongside a battery bank and diesel generators. Wind-diesel hybrid systems are also quite popular. In both these cases, the primary source of power is the renewable generator with the diesel providing back-up for periods of low sunlight or wind. These types of systems would typically involve a higher capital cost, partially offset through lower diesel use and lower emissions.

The Micro-Grid Concept

A natural extension to hybrid DE systems is the micro-grid, which is simply a small version of a centralized transmission and distribution grid.[13] It involves two or more modular generators feeding directly into a low-voltage distribution system and supplying two or more loads. This setup creates a remote "island," which is self-sufficient without the need for a centralized grid connection. In some cases, the micro-grid may be coupled to the central grid for balancing or peaking purposes; however, this connection will not typically have the capacity to support the system's full demand and can be decoupled at any time to put the system back into island mode. In this way, the micro-grid would be seen by a grid operator as a single generator or load. Micro-grid systems present a viable alternative to distribution grid extension or reinforcement for isolated communities.

[13] For comparative purposes, the traditional centralized transmission and distribution grid could also be referred to as the "macro-grid."

Urban Electrification

One particular application of the connected micro-grid would be for currently underserved urban areas. In many cases, these represent densely populated areas of cities that, although near existing distribution networks, would likely require grid reinforcement at a minimum or possibly necessitate further centralized-plant capacity to be brought online. The population of these areas is typically unable to afford the costs for this additional infrastructure, requiring government subsidy, which explains why in many cases it hasn't been deployed. As such, much of the electrification in these areas is achieved either through small generators if the household or business can afford the costs, or often through electricity theft. Indeed, until only recently, power utilities were reluctant to acknowledge electricity theft and underreported T&D losses to hide its magnitude.

When considering the costs of theft and additional infrastructure required in providing electricity to these underserved areas, in addition to the local socioeconomic benefits mentioned earlier, DE micro-grids may potentially be a viable alternative. However, resource options for an inner city are typically limited; fossil fuels will come at high cost while wind, geothermal, and hydro sources are unavailable. Two potential DE options to be considered are biomass and solar PV. Biomass, using wastes in particular, is well suited to this type of environment as it solves two problems: providing electricity and providing an outlet for waste. Ideally, waste could be separated into two streams—solid municipal waste and wet organic waste. The solid waste could be directly incinerated to provide heat and hot water, while the wet waste could be converted through a process called anaerobic digestion (AD) into methane suitable for either cooking or additional power generation. As discussed in a case study in the next section, AD has already seen widespread deployment in China, reaching over 40 million homes.

However, while solving the two issues of electrification and waste disposal, biomass use may cause a third issue, that of increased local pollution. As such, adequate control systems must be utilized for any systems deployed in urban locations.

Information and Communication Technologies as an Enabler

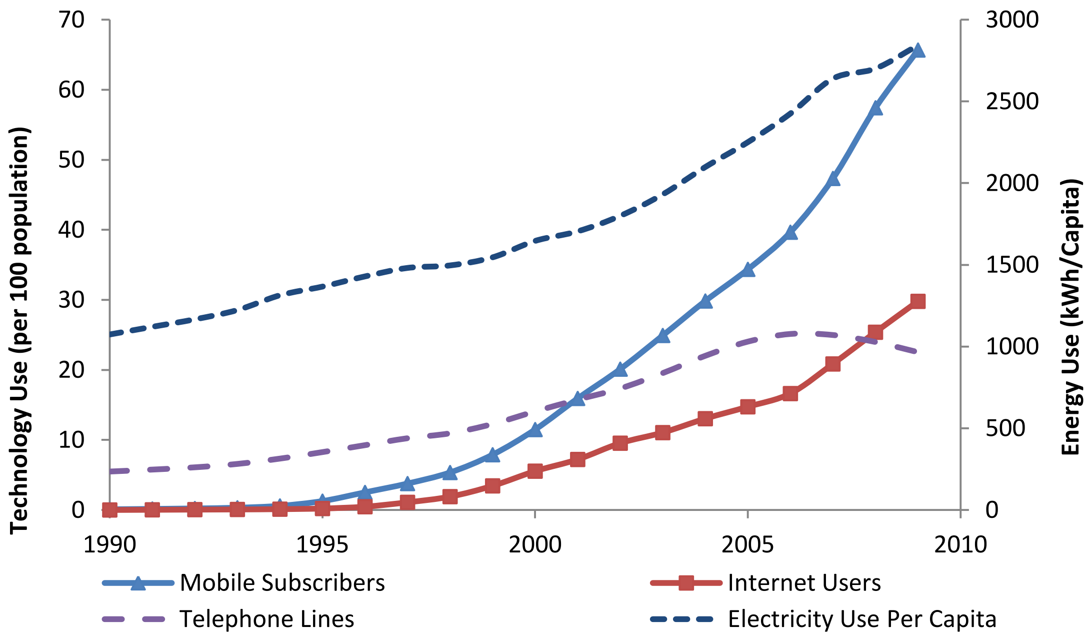
In order for the micro-grid to function, supply must be balanced with demand at a system level. In the past, this has been difficult due to the requirement for manual intervention and a lack of coordination between generators and loads. Historically, most micro-grids have been developed *ad hoc*, which has resulted in poor levels of performance. However, there is a growing trend toward convergence between the information and communication technologies (ICT) sector and the power sector that will act as a key enabler for micro-grids in developing countries. Two key trends are driving this convergence:

1. Communications networks are rapidly expanding, particularly in emerging markets.
2. Advances in smart-grid technology are reducing the cost of demand-side management hardware and software.

In many ways, these changes mimic the revolutionary changes that we have witnessed in the computing industry over the past 30 years. In the 1970s and early 1980s, most computing was performed using large and expensive mainframe (i.e., centralized) computers. However, technological progress allowed the same functions to be performed at smaller scales and at much lower costs, which opened the door to the personal (i.e., decentralized) computing market. Communications technology then advanced in the 1990s, to a point where personal computers could be connected and work cohesively with the centralized computing infrastructure, thereby creating the Internet. Similar trends will allow DE micro-grids to become an economical and sustainable option for emerging markets.

As shown in **Figure 4,** the number of mobile subscribers, and to a lesser extent, Internet users, has grown considerably faster than that of fixed phone lines or electricity demand in the Asia-Pacific over the past ten years. This trend illustrates two key points. First, that in many areas of the Asia-Pacific, power consumption (which is often used as a proxy for economic development) has developed relatively slowly. At about 2,800 kWh per person, demand is less than a third of that for OECD countries. Second, mobile and Internet communications have accelerated their growth over the period, with adequate access now available across most parts of the Asia-Pacific. This is largely due to the rapid decrease in costs for computers and mobile phones. Because integrated micro-grids require a sophisticated set of remote devices and communication networks, this necessary condition for deployment is largely in place. Sensors and control equipment can communicate using these wireless networks, allowing operators to balance electrical supply with demand in real time, either within the micro-grid itself or integrating it with the centralized grid.

Figure 4: Penetration of technology and electricity in the Asia-Pacific



Source: IEA and World Bank.

This convergence of two historically separate sectors is creating many new opportunities in the market. However, due to the relative inertia of power companies and many of their suppliers, the gap is largely being filled by Internet and computing companies.

For example, Google's first attempt at demand-side management came with the now-retired PowerMeter project. The company is now progressing with its Android@Home platform. This program basically creates an open-source platform for all home appliances to communicate with each other and could be a key enabler for the demand-side management of heating, lighting, and electronics. This is a key trend of the smart grid where end devices need increased processing power to use energy more efficiently; Google is hoping that appliance manufacturers will utilize the Android platform rather than designing their own.

Cisco has also adopted smart-grid technologies as a key part of their business model, offering a "complete communications fabric" of networking equipment and software to manage the data flow and network management systems for grid operators to monitor and control millions of devices in the field. This convergence is widespread, and many other technology companies including Intel, Microsoft, and IBM are developing products and services for the emerging smart-grid market.

Case Studies

Decentralized energy systems have been deployed with varying levels of success to electrify underserved communities in the poorer and/or rural parts of many countries. This section looks at three different examples of how regulators implemented DE systems to expand electricity coverage in their countries and what technologies and mechanisms they utilized.

Rural Electrification in the Philippines

In 2003 the Philippines' Department of Energy (DOE) launched the Rural Power Project (RPP) with a goal of electrifying 100% of its villages by 2008 and 90% of all households by 2017. This program would involve providing DE systems to over one million homes. Recognizing solar PV as a key technology to achieve this target, the DOE rolled out Project ACCESS in 2006 in partnership with the MIRANT Foundation and supported by the World Bank and Global Environment Facility (GEF). The project is targeting 76 remote villages across the provinces of Aklan, Iligan, Masbate, Northern Samar, and Palawan, with plans for another 400 villages.

Project ACCESS utilizes a Sustainable Solar Market Package (SSMP) approach. The SSMP recognizes that scale is necessary to overcome some of the commercial issues typically experienced when doing business in remote communities. The framework grants a private sector organization with the sole contractual right to provide PV services to a cluster of contiguous villages in order to create the required scale. Public sector and donor resources are used to fund shared public facilities while the assigned contractor also has an obligation to sell PV systems on a commercial basis to at least a quarter of the households in the community. Microfinance schemes and government subsidies are used to help offset the capital costs for a household. In order to ensure a sustainable operation, an SSMP package covers the supply and installation of PV systems along with a maintenance and repair contract, typically five years with an option to extend.

Under the RPP, the DOE is also promoting the creation of electrical micro-grids. The first such one was designed by PowerSource Philippines in 2005. The stand-alone micro-grid is part of PowerSource Community Energizer Platform (CET), which provides 1,300 households in the village of Rio Tuba with around-the-clock electricity powered by two 210-kW diesel generators. A 3 MW biomass gasifier power plant and associated plantation will be added to this community to supply the nickel mine and support future growth. PowerSource is embarking on another electrification project for 650 households on the island of Malapascua in the Cebu Province, which will hybridize generation between 150 kW of diesel generators, 200 kW of biomass power, and 80 kW–150 kW of wind capacity.

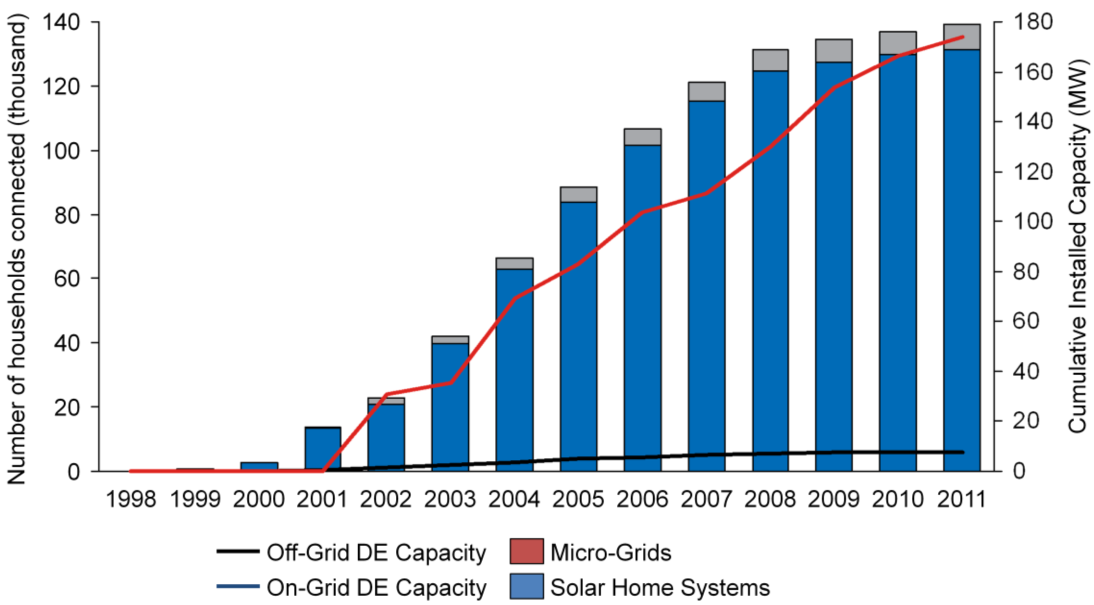
Biomass represents a good opportunity to electrify rural areas of the Philippines; residues from large sugarcane, rice, and coconut plantations could potentially fuel about 1 GW of sustainable power generation. Yet issues remain mainly on the logistics and financial structures available for these projects, where sizes normally exceed the 200 kW compared to the 2 kW–5 kW range of a typical solar deployment.

The RPP program has successfully involved stakeholders from both the public and private sectors to provide DE systems using a scalable business model. By the end of 2010, 2,100 public facilities and 8,300 households had been fitted with solar PV systems while an additional 1,300 customers were connected to the micro-grid in Rio Tuba. Though this process, jobs have been created at a local level, while the access to reliable electricity has provided additional social and economic benefits to the community. However, these programs remain heavily dependent on international aid for their development. The development of a local framework and financing structures needs to continue for these initiatives to be completely sustainable.

Building up the DE industry in Sri Lanka

For the past fifteen years, the government of Sri Lanka has run programs to electrify its poorer, rural communities. Starting with the Energy Services Delivery (ESD) program in 1997 and now continuing under the Renewable Energy for Rural Economic Development (RERED), these programs have resulted in electricity provision for over 135,000 off-grid households with an additional 175 MW of decentralized renewable energy connected to the grid (see **Figure 5**). Largely due to these initiatives, Sri Lanka progressed from an electrification rate of 67% in 2003 to over 85% by 2009.

Figure 5: Off-grid and on-grid DE systems deployed under Sri Lankan initiatives



Source: Renewable Energy for Rural Economic Development (RERED).

The program has been funded though a $115 million line of credit from the International Development Agency (IDA) of the World Bank and a $8 million grant from the Global Environment Facility (GEF). Loans for specific projects are dispersed through participating credit institutions (PCI), which conduct independent credit assessments to ensure that projects are economically sound and meet the required engineering and environmental criteria. This credit support has proved to be a key enabler for many of these electrification projects.

The RERED program covers both on-grid decentralized renewable generation and off-grid generation on an individual home or community-scale level. The village power projects are intended for regions where grid connection is not feasible and are built, owned, and operated by the communities themselves through special purpose electricity co-operative societies (ECS). To date, almost all of the village micro-grid projects have been created using micro-scale hydro. There are approximately 350 of these hydro installations compared to three village-level wind systems and ten village-level biomass systems. However, cost reductions and improved reliability are making these alternative technologies more feasible.

In a typical village power system, a small-scale (<50 kW) generator will provide power to 40–60 households, providing them with 75 W–150 W for up to 12 hours per day; this amount is enough to provide basic lighting, communications, and refrigeration services. Capital costs have been supported though grants and loans, with a cost-based generation tariff charged to each connected household. Operations and servicing training is provided to the ECS by the equipment supplier.

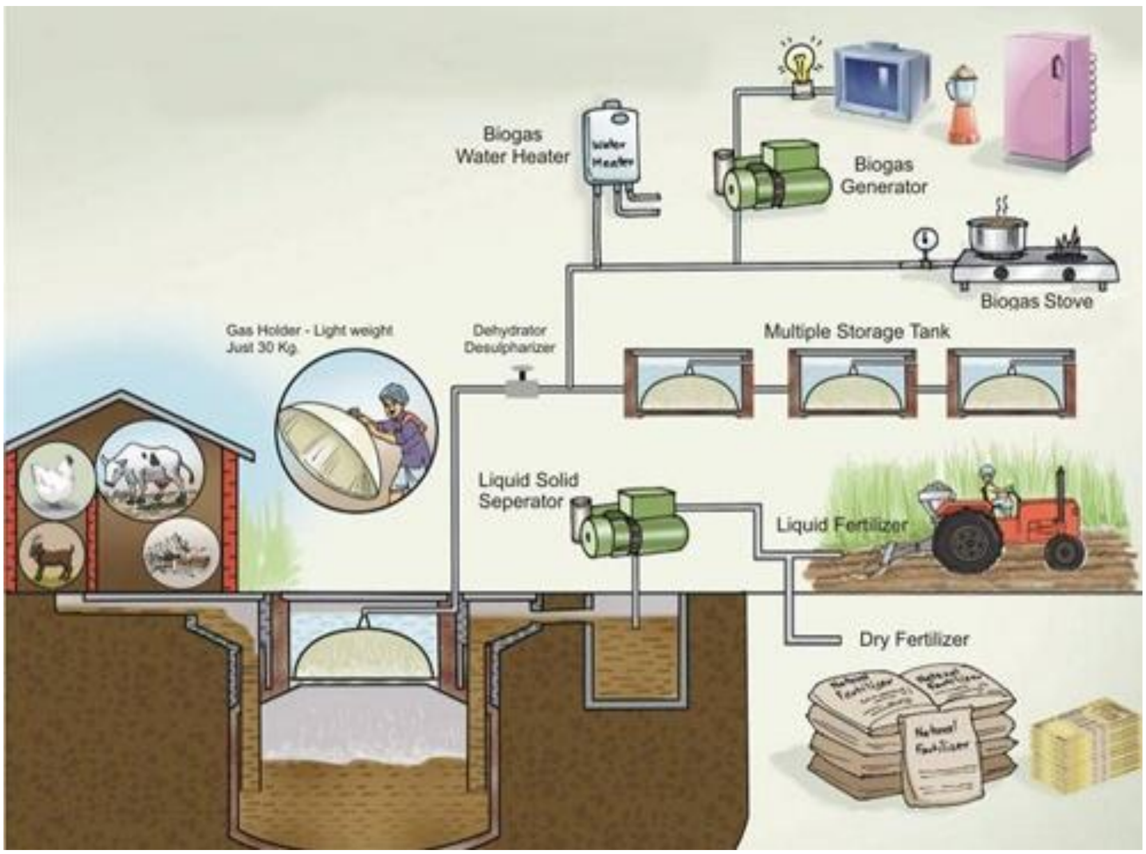
This private sector–led program has created a dynamic local industry for decentralized renewable energy. The steady stream of projects has created a self-supporting industry of developers, financiers, equipment suppliers, and consultants. The public-private partnership has also proved to be a viable method of leveraging international funds.

Biogas in China

Over the past 30 years, China has pursued an aggressive electrification program that has resulted in access to electricity for over 99% of the population. While this scheme has provided power for appliances and lighting, heating and cooking continued to be based primarily on simple biomass. During the late 1970s and early 1980s, China started to explore the potential of producing biogas in rural areas. Biogas is formed through the controlled decomposition or anaerobic digestion of organic waste materials such as food and manure. The methane-rich gas produced can be directly combusted for cooking, heating, or hot water; used to power a generator; or upgraded to form natural gas–quality biomethane.

As part of this program, China created the “China Dome” style of digester and deployed over six million units. A modern, medium-scale version of this type of plant is shown in **Figure 6** below. Smaller domestic installations are able to meet approximately 80% of the cooking needs of a family of four, while larger ones can be coupled with gas engines to produce electricity.

Figure 6: Rural fixed dome AD biogas plant



Source: Puxin Biogas.

This biogas initiative was expanded with the National Rural Biogas Construction Plan (2003–10) with the goal of reaching 20 million households by 2005 and 50 million households (20% of the total rural population) by 2010. To promote their deployment, a government subsidy of 1,000 yuan (c. $160) was provided for each digester unit installed.

Between 2005 and 2010, the central government alone invested 21.2 billion yuan (c. $3.4 billion) to increase the use of biogas in rural areas, which was further supplemented by provincial and local governments. Furthermore, approximately 23,000 medium- and large-scale installations have been built next to waste sources such as sewage treatment plants, industrial livestock farms, and alcohol distilleries. In its 12th Five Year Plan, China mentions that it will increase subsidies to household biogas users, although no numbers have been released.

The main driver for deploying this technology is to treat household and farming wastes. However, these projects are also economically efficient, as the plant is low-cost and able to replace use of inefficient and hazardous biomass cooking or expensive fossil fuels while producing a nutrient-rich fertilizer as a byproduct. Biogas digesters are also environmentally beneficial by reducing the methane emissions from compost by approximately two-thirds and saving about 2 tons of fuel wood.[14] The program in China has been supported through the use of training programs for local farmers, such as the National Biogas Professional Certification courses offered in Shanxi province. The Chinese Ministry of Agriculture also operates an international training and research center in Chengdu, Sichuan province.

The success of the decentralized biogas industry in China has been due to four key factors:

1. A strong government support program, backed by adequate subsidies
2. An economically viable solution, offering significant cost savings and health benefits
3. Private sector investment driven by the large and growing market
4. Training programs to allow users to maintain their systems

Key Insights for Policy and Regulation

Many countries in the Asia-Pacific are presently faced with a delicate balance of providing universal electricity coverage and keeping pace with growing electricity

[14] L. Kangmin and M.W. Ho, Biogas China, Institute of Science in Society, 2006.

demand while ensuring that power utilities can remain financially sustainable. As decisions made by leaders today will impact their nations for the next 30 years, it is crucial for them to periodically revisit their overall energy strategies in order to be able to respond to changing social, economic, and technology landscapes.

There is no doubt that decentralized energy systems, when used appropriately, could offer significant social, economic, and environmental benefits to the Asia-Pacific. However, in order to achieve the maximum potential of these systems, governments have to take into consideration the following three factors:

1. Power needs, system design, implementation, and deployment
2. Financing mechanisms
3. Regulatory frameworks and system remuneration

Design and implementation have become essential parts of the system. The progression is from obsolete centralized systems where the starting point was capacity building, to a situation where the system is developed as an enabler to help in local development. In this new business model, the system design should be driven by the future needs and economic growth of the area, taking into account the socioeconomic benefits, and where possible it should exploit local resources and sustain local employment. In addition, the design should take into consideration whether the system is to be implemented in a rural or urban area. In urban areas, we should look at the heat and power needs of the specific areas or buildings where the system is to be connected, as well as possible integration at a later stage into the grid, to make excess power available.

The key to success in a DE system lies in its ability to be self-sustainable. While there might be a financing hurdle involved in the initial capital cost, operating costs should be covered through the additional socioeconomic benefits that the system provides.

Securing financing for DE projects in poor areas in developing countries is not an easy task, and today most of the financing comes from international and multilateral government agencies and NGOs in the form of grants or soft loans. However, there is still a lack of incentives and financing mechanisms available for private developers to invest in many of these regions.

In recent years, the UN Framework Convention on Climate Change (UNFCCC) has brought together developed and developing nations alike to tackle the global issue of climate change. One of the agreements reached by the Kyoto Protocol convention set a framework for a mechanism called the Clean Development Mechanism (CDM), aiming to provide funding, through the sale of carbon credits, to projects that will decrease emissions in developing nations. However, as the value to investors in these projects is driven by the somewhat superficial price of carbon, there has been continued volatility in this finance channel; this has been further exacerbated by the current economic turmoil and the lack of a successor to the Kyoto Protocol, which ends in 2012. Furthermore, the CDM system has been plagued by a high level of bureaucracy and manipulation and the bankruptcy of several projects. All of these factors have depleted the amount of financing available through the CDM system and raised doubts regarding its future viability.

As such, the need to develop proper economic models remains in the hands of governments and financiers alike. Governments need to provide financiers with the required stability and predictability , and financiers in return, should promote long-term and low cost of capital funding for these types of projects.

Finally, governments need to ensure that their regulatory frameworks and remuneration policies do not create unnecessary barriers to the deployment of DE systems. Liberalization of electricity markets has been taking place, to varying degrees and levels of success over the past three decades. In many cases, this is a prerequisite for the proper functioning of an electricity market and is necessary to promote DE systems. A truly competitive power market not only involves competition among large, centralized generators, but also competition between centralized and decentralized systems. In many cases, the small scale of DE systems makes them unattractive to large incumbents tied to the legacy “bigger is better” mentality. Their rigid procedures are designed around creating economies of scale and generally make them inefficient at building smaller sites. New, smaller, and/or local players should be allowed to enter a market in order to create competition and promote DE systems. This is particularly relevant in state-run or monopoly markets.

However, market conditions must also allow for the entrance of smaller, local players. Grid connection fees and transaction costs are in many cases a fixed amount regardless of size, which favors the larger generators; ideally, these fees and costs should be proportionate to the amount of power supplied to the grid by a generator, to reflect their actual use. Many DE systems are designed to meet a specific load, and only excess generation would be supplied back to the grid. Access to the grid should be made nondiscriminatory, allowing grid-connected DE systems to compete fairly with centralized systems. This is often accomplished through the unbundling of electricity supply and distribution. Furthermore, the approval process for a new generating facility in many countries can be tedious and lengthy due to excessive bureaucracy. While this may be appropriate for larger sites, particularly around environmental assessments, it could detract from a key benefit of DE systems, namely the relatively short time to commission a new system.

Price subsidies and other market manipulation practiced by some governments have the effect of distorting competition in the national power generation industry. While some DE systems could be viable in a perfectly competitive market, any government intervention to artificially cap wholesale prices could make them uneconomical. If national electricity price limits are necessary for a market, they should be tiered to reflect the contributions of the various components of the supply side.

Conclusion

This paper has discussed the historic reasons why centralized power generation came to exist in developed economies, and became the conventional wisdom of the industry. We have suggested that these legacy solutions may not necessarily be the best way forward for expanding power systems in the Asia-Pacific. Decentralized energy systems offer many potential social, economic, and environmental benefits to poor and remote regions, and may potentially offer a lower overall cost than the alternative of extending the existing grid. As each circumstance is unique, there is no “one size fits all” solution available.

Therefore, a sound understanding of the technologies involved and their individual strengths and weaknesses is needed in order to identify an optimal solution for areas currently underserved by the existing power grid. DE technologies can work together in micro-grid systems and be integrated into existing centralized infrastructure. The feasibility of these systems has been improved though advances in communication and power technologies. To take advantage of these benefits, governments in the Asia-Pacific can take an active role in optimizing their power systems using DE technologies by using the financing and regulatory levers available to them.

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