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INFRASTRUCTURAL ECOLOGY AS A PLANNING PARADIGM: TWO CASE STUDIES

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ABSTRACT

Moving beyond conventional mono-sectoral planning and management of urban systems, 'infrastructural ecology' advances a multi-objective, holistic design approach. Planned integration across the sectors of energy, water, sanitation and waste allows for reciprocal exchanges across two or more systems, leveraging synergies and providing multiple co-benefits. By reducing overall throughput of matter, eliminating wastes and avoiding carbon-intensive technologies, this paradigm offers a model for critical services provision for the next 2 billion people in emerging economies – both those moving to cities and particularly those who remain in rural poverty. Two exemplary cases, one in India, another in Brazil, reveal the efficacy of renewable power produced by cooperative, cross-sector initiatives. The first, Omnigrid Micropower Co., Pvt., Ltd. (OMC) realized a workable bottom line for solar-powered generation that serves some of India's poorest, rural citizens when combined with the power demand from the telecommunications sector. OMC's remote small to mid-size solar power plants today serve nearby telecom tower base stations *and* deliver community energy needs through mini-grids and adapted power equipment that eliminates expensive wiring for household service. These installations not only electrify villages, they provide permanent jobs. In the second case, Itaipu Binacional, the entity behind the world's largest generator of renewable power, the 8-km (5-mi)-wide 14 GW Itaipu hydroelectric dam, had sustained degradation of water quality in its reservoir from the area's agricultural waste. It partnered with farmers to develop an Agroenergy Condominium that used distributed biodigesters to process the waste from local corn production and farmer's herds, producing biogas sufficient to energize 2,200 households while yielding high quality fertilizer. The Agroenergy Condominium and OMC's cross-sector solution are both examples of strategic investments addressing energy poverty, improving quality of life, and increasing economic productivity while keeping carbon contributions level.

Keywords: biogas, hydropower, infrastructure, microgrid, photovoltaics, solar energy, waste

1 INTRODUCTION

Over the last two decades, the post-industrial imperatives for energy efficiency, renewable energy, sanitary waste and resource management, clean air and water have become more deeply embedded in the mindsets of urban planners and government officials. Yet few fully understand and act upon the deep interrelationships among these sustainability concerns, their interdependencies and synergies. *Systems thinking* is an approach that enables us to understand the dynamics of interactions and exchange opportunities. It helps us solve for complexity. Using relational or systems thinking and ecologically-reflexive planning and design (modeling constructed systems on the behavior of natural ones), the different infrastructural services – energy, water, sanitation, waste – can be optimized as a large ecological whole.

The notion of 'infrastructural ecology' is an emerging, innovative field of speculation and research. It derives from the discipline of *industrial* ecology [1, 2], which remodels industrial systems along the lines of ecosystems, emulating the resource cycling that occurs in the natural environment. Industrial ecology practices may help actualize the synergistic potential between different enterprises' production processes through exchange of their residual by-products [3]. Reclaiming resource flows for potential reuse minimizes the consumption of

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virgin materials and reduces the practice of sinking wastes into the environment [4]. Similarly, *infrastructural* ecology applies just such a closed-loop paradigm to conventional public services. It promotes sharing of waste output from one system to support another. Benefits may include operational savings, reduced greenhouse gas emissions, and waste reduction, along with job creation and other community co-benefits, creating in effect, a 'virtuous cycle,' a chain of events favorably reinforcing themselves through a feedback loop. Analogous to the functioning of natural ecosystems, infrastructural ecology is in turn holistic and integrated, economical and equitable, and more adaptable and resilient to changing climate conditions.

As a planning framework, infrastructural ecology promotes physical and administrative integration across a combination of critical systems: energy, water, sanitation, local agriculture, transport or IT. Projects may be connected or combined whereby one system effectively 'hosts' a second, enabling its more efficient and cost-effective implementation. As one example, the SMART (Stormwater Management and Roadway Tunnel) system constructed in Kuala Lumpur, Malaysia reduces downtown vehicular congestion, while during monsoonal flooding, it diverts stormwater into part or all of the tunnel [5] – an elegant single solution solving two problems. Both Omni Micropower's installations in Uttar Pradesh, India and Itaipu International's in Ajuracaba, Brazil, are similarly planned for advantage by reciprocity.

2 OMNI MICROPOWER'S DISRUPTIVE INNOVATION POWERS RURAL VILLAGES

Approximately 237 million citizens in India lack access to reliable electricity [6]. For those beyond the reach of the grid, or those already technically 'wired' but receiving no supply, economic development has been forestalled. In India, ownership and management of electrical distribution networks are shared between both public and private distribution companies (DISCOMs). Companies serving large urban areas can neither spare the power nor support the cost of extending transmission and distribution lines to rural areas [7]. Therefore, the Government of India has prioritized powering the 70 plus percent of its rural area population with decentralized and renewable power [8]. Sunlight is abundant throughout most of India, with more than 60 percent of the country receiving annual average global insolation of 5 $kWh/m^2/day$ [9]. In India's states with large concentrations of rural poverty, like Uttar Pradesh, solar energy holds great promise.

However, even as the nation's regulatory framework supports rural electrification, solar power providers have largely regarded installation of photovoltaic power plants as fraught with financial risk. Given the low customer density in rural areas, private sector or NGO-funded solar mini-grids (decentralized power distribution infrastructure) are more expensive than grid-served urban electrification. Moreover, despite the real demand, many communities have experienced substandard photovoltaic products and unreliable services, leaving them less willing to pay [10]. The installers' concerns therefore turn on both the ability and inclination of poor rural residents to pay, thereby ensuring a steady revenue stream. Finally, the threat of the future arrival of a grid can also potentially undermine private sector or NGO investment.

Despite these drawbacks, Omnigrid Micropower Co., Pvt., Ltd. (OMC) saw a market potential for solar-powered generation in Uttar Pradesh (population 200 million), one of India's most populous and poorest states. In 2012, OMC developed an unusual business model that leveraged demand from the telecommunications industry. OMC contracted with cell phone tower owners to power their operations utilizing an OMC solar power plant. With a workable bottom line guaranteed for 10 years, they were then able to furnish off-grid citizens living nearby the power plant with affordable electricity.

2.1 A successful combinatory approach

The mobile phone industry in India has proven to be one of the most dynamic markets worldwide, with a base of more than one billion subscribers as of late 2015 [11]. As recently as 2013, nearly 40 percent of India's 400,000 off-grid cell phone tower base stations were running off diesel generators. Expensive to run, these generators require regular maintenance and produce air pollution and carbon emissions. Beginning in 2012, a government mandate required cell phone tower operators to transition half of their towers to renewable sources by 2015 [12]. According to an estimate by one source, powering a single mobile base station with an OMC power plant equates to an annual CO_2 emissions reduction of between 40 and 50 metric tons [13]. While renewably-powered base stations are not an inexpensive proposition, given the surge in cell phone use, the telecom industry has multiple incentives to wean the towers from fossil fuels.

Founded in 2011, the Gurgaon, India-based Renewable Energy Service Company (RESCO) Omnigrid Micropower finances, builds, maintains and operates solar and wind powered micro power plants. In 2012, OMC partnered with Bharti Infratel (India's leading telecom tower infrastructure service provider) to furnish cellular towers with micro power plants, typically less than 50kW, thereby supplanting their diesel generators [14]. OMC's breakthrough was recognizing that the needs of the remote cell phone tower constituted an anchor demand and guaranteed revenue stream. On that basis, it could piggy-back the provision of electricity to adjacent villages, making this otherwise risky investment more 'bankable,' i.e. engendering support from financial institutions.

By 2013, under its Community Power program, OMC had constructed eleven 9- to 18-kW micro solar power plants, costing about 50 lakh ($75,385) each, and sized so that their surplus power could be shared with local rural communities using microgrids [14]. This program was OMC's 'disruptive innovation,' one that amalgamated telecommunication sector requirements with the electrical demands of the poor. It is the cell phone tower's serving as an assured base demand, under a long-term supply contract, that helped offset the otherwise high development costs, making the village microgrid financially feasible.

Typically, the plants are located near the tower base station and are connected with power cables. Compared to the high capital costs of coal-fired plants and their long construction duration – typically five to seven years – photovoltaic-powered micropower plants radically lower the costs and reduce construction to about three months. They also eliminate the energy losses that accompany long distance power transmission. Additionally, these power plants may be supplemented by wind power or biogas-generated electricity, utilizing biogas obtained from local anaerobic biodigesters fed by animal, human and agricultural waste. The micro power plants can also be equipped with battery banks and diesel-fired backup generators to tide them across monsoonal seasons [15].

2.2 Serving diverse customer demand

OMC's rural electrification program also furnishes village householders with affordable microgrid-adapted power equipment, supplied through local agents. Overall, the business model relies upon pre-paid services for power used. OMC leases out portable lanterns already charged by the microgrid. These lamps take advantage of the unusual efficiency of LED lighting technology, thereby eliminating costly wiring for individual household service. The lanterns cost about 100 rupees ($1.50) each month, versus 180 ($2.70) for kerosene. Collected each morning by 'light wallahs,' they are recharged and returned to customers later the same day. A *bijli* box (PowerBox), or battery capable of powering two lanterns, a fan or T.V. and cellphone charger, can be leased for 350 rupees ($5.45) monthly [16] (Fig. 1). While the lanterns are affordable for all incomes, the *bijli* serves roughly the top 50 percent of income classes. Beginning in 2013, OMC began to diversify its product lines, leasing mini-refrigerators and high-efficiency irrigation pumps. Key to OMC Power's business strategy is understanding the desires of their rural customers.

The game-changing nature of the Bharti/OMC partnership is based on tying the telecom industry's needs to community power provision. It is significant that more than half of OMC's revenue stream comes from local residents, disproving the assumption that indigent rural citizens could not support an adequate revenue stream. The arrangement has been favorable for OMC as well: OMC breaks even within a half year, whereas full payback for comparable power plants might take 6 to 7 years. Moreover, Bharti Infratel has found that its rural cellphone customer base has surged [7]. Lastly, the communities enjoy the benefits of direct job creation: OMC employs between 10 and 15 workers per tower [17].

2.3 Scaling up innovation

OMC is the first power company to transform power provision in rural India into a scalable, sustainable and commercially practicable business. In 2014, the World Economic Forum recognized OMC Power as one of the most innovative technology start-ups, naming it the 2014 Technology Pioneer. By 2015, OMC had entered into an agreement with SunEdison, a global renewable energy company headquartered in the U.S., to establish off-grid solar power projects in 5,000 Indian villages, potentially the largest private sector undertaking in distributed

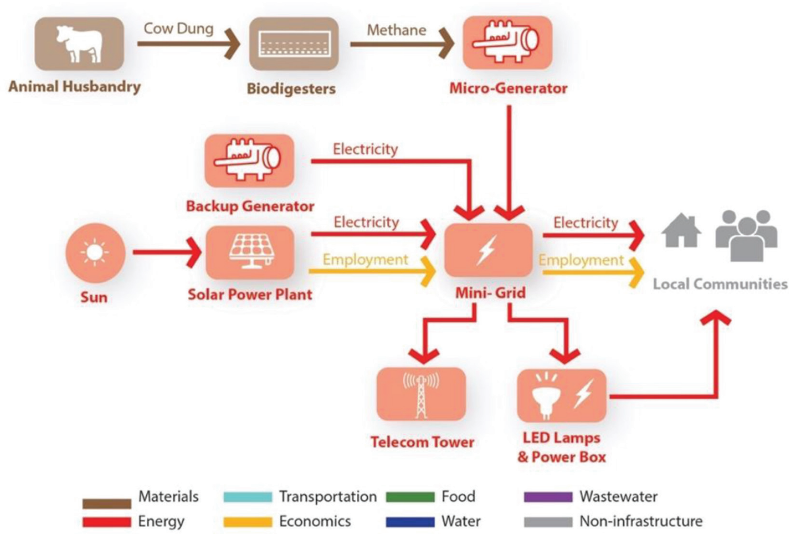

Figure 1: Diagram of OMC power plant and microgrid, Uttar Pradesh, India. (Reprinted courtesy of The MIT Press from *Infrastructural Ecologies: Alternative Development Models for Emerging Economies,* by Hillary Brown and Byron Stigge).

power for rural India [18]. In this endeavor, the partnership leverages the expertise of each organization, combining the technical know-how, local, and telecom knowledge of OMC with the project development and financing expertise of SunEdison.

In 2016, the Rockefeller Foundation and OMC Power completed a $4.5 million agreement that would finance the construction and retrofitting of 100 solar power plants in rural Uttar Pradesh, serving villages where power access is either currently unavailable or inadequately available. The Rockefeller Foundation recognizes that such access will liberate India's entrepreneurial potential, spur new businesses, and improve overall productivity [19].

Today, an artisanal textile shop in the small village of Meer Naga, once sporadically electrified, has secure lighting. Workers can double their incomes by working after dark; children can study; and women can cook after sundown, without the cost and polluting effects of kerosene [7]. Such life-altering opportunities, enabled through OMC's breakthrough vision, are testimony to the power of relational and holistic thinking.

3 AGRO-ENERGY IN THE AJURICABA RIVER BASIN OFFERS A CROSS SECTOR COLLABORATION

It might be said that failure to perceive relational dynamics – the interrelatedness between two otherwise distinct systems – is endemic to modernity's pervasive 'mechanistic' worldview. Perhaps this viewpoint is not yet pervasive in emerging economies, where relational thinking may be more endemic. As a start-up enterprise, Omnigrid Micropower astutely foresaw a critical economic and social advantage in linking telecommunication infrastructure's need to its solar power plant capability. A similar, relational viewpoint maybe attributed to the Itaipu Binacional (IB) company's recognition of the potential for rural community agroenergy to resolve its own critical hydropower problems.

The major operational stage of the 8-km (5 mile-) wide Itaipu hydroelectric dam on the Paraná river bordering Paraguay and Brazil was successfully completed by IB as a bi-national initiative in 1991. Three years later, it was lauded by the American Society of Civil Engineers as one of the seven modern Wonders of the World. Expanded in 2007, it remains the world's largest generator of renewable power, with an installed capacity of 14 GW. It furnishes as much as 75 percent of Paraguay's and 17% of Brazil's energy consumption [20].

Itaipu, which means 'the sounding stone' in the Guarani language, had a controversial beginning. As in other mega dam construction projects, its construction displaced 59,000 occupants along the Paraná River banks [21]. It also destroyed a national park, (including Guaíra Falls, a popular tourist site that was dynamited); and led to land and water degradation and loss of biodiversity. Given this history, IB's community engagement activities over the last two decades – embracing sustainable development and promoting rural energy access, environmental conservation, and employment – might be viewed as partial recompense for its earlier transgressions.

The name Itaipu Binacional reflects the dam's locale, as it reaps the benefit of the Paraná river watershed that separates Brazil and Paraguay. While the Brazilian government funded the full construction cost and the IB, the company, manages and operates the dam's hydropower plant, the remaining infrastructural assets belong to Eletrobrás, among the largest of Brazil's power utilities, and ANDE, Paraguay's public utility. Despite the fact that approximately 88 percent of Brazil's electricity is renewably sourced by hydroelectric generation, the nation established an incentive program to promote other renewable infrastructure in 2002, from small hydro, to biomass and wind power [22]. In December 2009, it set a target of reducing countrywide greenhouse gas emissions by between 36.1 and 38.9 percent below business-as-usual projections by 2020. This was to be achieved through a combination of efficiencies in the building and industry sector, additional renewables and improvements to agricultural and animal husbandry practices [23].

3.1 Degradation of the reservoir and Itaipu Binacional's response

The power plant reservoir's main area of influence, the Paraná 3 watershed (8,000 km^2), is the home of more than 35,000 local farms, with 43% of them covering up to 10 hectares (27.7 acres) and many of the rest up to 50 hectares (123.5 acres). The farms produce mostly soybeans and maize but the area also includes animal farming, with more than 1.5 million pigs, 30 million poultry, along with multiple agro-industries based on these plant and animal production practices [24]. The intensity of agriculture and meat production in this basin area began to have an impact at the head of the Itaipu dam. Deforestation, run-off from soil tilling, and the influx of phosphorus from fertilizers and pesticides collectively affected the water quality of Itaipu lake, the seventh largest reservoir in size in Brazil. Since the dam's completion (and now compounded by climate change), the reservoir experienced both premature filling with sediment and eutrophication, each a threat to hydropower production [25].

In 2003, recognizing the linkages between the dam's altered watershed hydrology, the region's poverty, and the environmental harms associated with both agriculture and energy production (namely the hydro dam's methane emissions), IB expanded its mission to include social and environmental stewardship in the basin. On Brazil's side of the basin, it initiated the *Cultivando Agua Boa* (*CAB)* or Cultivating Good Water program as a response. CAB targeted 63 initiatives including conservation of water, protection of farmland and forests, and the adoption of strategies to reduce land and water pollution by agriculture. These included the use of no-till farming, promotion of rural sanitation and wastewater treatment, reduced pesticide use, and forest and stream protection [24]. Through the CAB program, which was especially based upon civic society's participation in the farming settlements, IB built a model, multidimensional framework for local stewardship. In 2015, IB received the Best Water Management Practices award from the United Nations *Water for Life* program.

3.2 Agroenergy's ascendancy as an answer

Central to this sustainability framework, the Agroenergy Condominium for Family Agriculture Sanga Ajuricaba was established by IB in 2009 in the Paraná river watershed. It was the outcome of a partnership between IB's Office of Renewable Energy, the Institute of Technical Assistance and Rural Extension, the Paraná State Electricity Company, the International Center for Renewable Energies, and other entities. Located in the municipality of Marechal Candido Rondon-PR Brazil, the cooperative consisted of 33 small-scale family farms. These became the focus of IB's effort to reduce pollution by supporting the production of biogas and biofertilizers from area waste while fighting poverty in the region.

At each farm, IB installed individual anaerobic biodigesters to process the corn production waste with manure from the farmers' herds (approximately 1,000 head of cattle and 3,000 swine). With the participation of farmers, the condominium collectively generates 15,800 cubic meters (4.2 million gallons) of agricultural residue and manure annually – organic waste that yields 266,600 m^3 (348,699 cubic meters) of biogas. The biogas travels through a 22-km- (13.7 mile-) long pipeline to a central power plant where it generates electricity, heat, or, – after upgrading – a biogas-based vehicular fuel [26]. Overall, IB estimates the gas generates 445,000 kWh/year of electricity, sufficient energy to serve about 2,200 area households

[27]. The surplus is sold to the state's energy distributor, producing revenue for the farmers. The farmers also make use of the plant's grain dryer, which runs on the thermal energy produced by the power plant, to dry products such as corn, beans, and soy beans, reducing their drying costs by as much as 90 percent [25] (Fig. 2).

As of 2015, 77 percent of Brazil's population remains employed in farming. Given the fact that the nation's agricultural wastes can be found widely spread across much of the country's territories, distributed power generation from its waste biomass and manure, processed through anaerobic biodigestion, is a logical means of affording energy access to remote areas. Such *agroenergy* transmutes the environmental liabilities of Brazil's farming sector – principally the methane derived from animal manure and the watershed-polluting organic chemicals from fertilizer – into electricity and a bio-fertilizer. Both provide a useful source of additional income for rural settlements while helping to foster decentralized renewable generation and diversification of energy resources [24].

3.3 Related results

Under IB, the basic reciprocities between hydro dam water quality protection and rural energy access gave rise to a range of related benefits. Water quality and quantity was upgraded

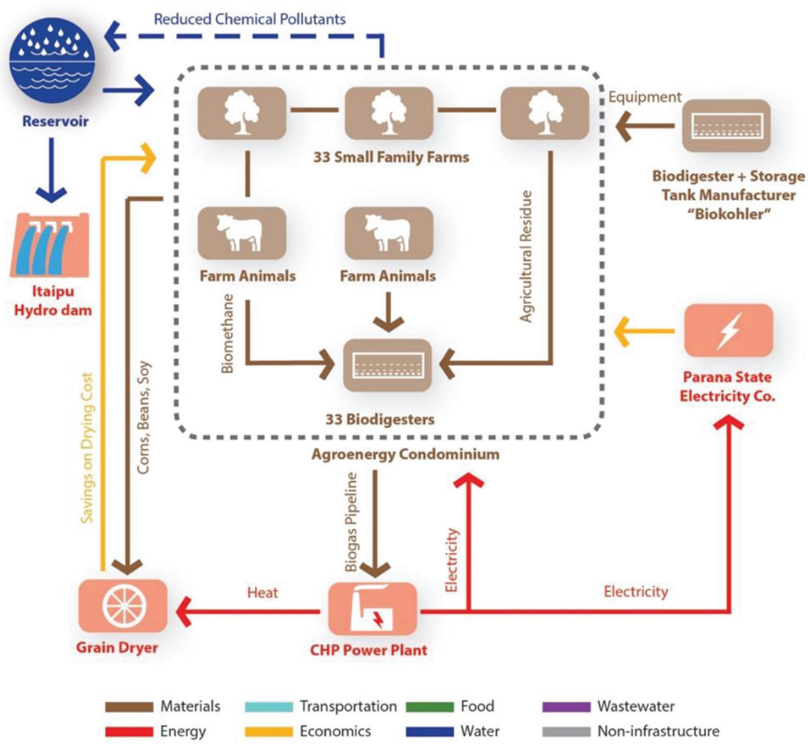

Figure 2: Diagram of Itaipu Binacional's Agroenergy Condominium. Reprinted courtesy of The MIT Press from *Infrastructural Ecologies: Alternative Development Models for Emerging Economies,* by Hillary Brown and Byron Stigge.

in 206 micro-basins; 1,321 km (821 miles) of riverine buffer zones were restored; 40 million trees were planted; and two biological sanctuaries and a 13-km (8-mile) biodiversity corridor were introduced. At the same time, CAB provided technical assistance to convert the industrial farming practices to organic agriculture, replacing chemical fertilizer with the waste slurry byproduct from biodigestion. CAB also promoted the cultivation of medicinal plants; nutritional education; and development of aquaculture in combination with agricultural practices. A related initiative included the establishment of 5 waste cooperatives and 25 waste associations regionally, improving the lives of the solid waste handlers [28].

3.4 Scaling up innovation

Itaipu Binacional's laudable stewardship vision extends well beyond its customer base. The model Agroenergy Condominium Sanga Ajuricaba program, developed in Paraná, is being introduced into Uruguay in the State of San Jose, near Montevideo, which has the highest percentage of carbon emissions from agriculture. This is in part because Uruguay is undergoing strong industrial development, particularly in its milk-production industry, which has significant environment impacts. The program is being led by Eletrobrás with funding from a group formed by the world's 13 leading energy companies, with IB acting as project consultant. Twenty-two farms will be connected to a central micro-thermoelectric plant, which will produce 764 m^3 (1,020 cubic yards) of biogas daily, with an expected energy production of 1.53 MWh/day [29].

4 CONCLUSION

From energy giant to visionary agent of sustainable development, Itaipu Binacional has played a transformative role in the region. The same could be said for OMC Power, whose rapidly scaling new business model is creating widespread new economic opportunities across Uttar Pradesh and beyond. These two companies share a commitment to working in the public interest. Each organization's mission has recognized both the power of context and the importance of corporate stewardship. The successes of each derive from an ability to operate within a network of reciprocal relationships. Each has endeavored to create a new entity, what might be called an 'energy commons,' as a vehicle for societal transformation.

As a planning paradigm, infrastructural ecology is based upon the understanding that our energy, water, waste systems, like ecosystems, are highly interconnected with each other in ways that are complex, but that present real synergistic opportunities. From an economic, social, and environmental standpoint, emerging economies today need to be able to think relationally; to appreciate potential linkages; and to leverage both innovative and time-honored technologies in a whole systems approach to development.

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