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Towards A Circular Energy Economy: Cross-Sector Successes in Brazil and India

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Abstract

A new paradigm for energy production is one that emulates the closed-loop circular systems of natural ecosystems. At once holistic, economical, and equitable, energy production based upon reciprocities with other sectors (e.g. telecommunications, water, sanitation, and waste management) can leverage synergies and provide multiple co-benefits. With avoidance of fossil fuels, less pollution, and reduced throughput of matter and energy, such a circular energy economy offers a model for critical electricity provision for the next 2 billion people in emerging economies—both those moving to cities and particularly those who remain in rural poverty. Three exemplary cases, one in India and two in Brazil, reveal the efficacy of renewable power created through cooperative, cross-sector initiatives that also yield economic and social benefits. The first, methane recovery in Belo Horizonte, Brazil, illustrates the potential for closed-loop use of an otherwise wasted energy source in rapidly urbanizing settlements. In the second case, Omnigrid Micropower Company leveraged affordable electricity for some of India's poorest rural citizens by combining the electricity demand from the telecommunications sector to support the economical construction of small- to mid-size solar power plants. Lastly, Brazil and Paraguay's Itaipu Binacional, developer of the world's largest generator of renewable power, addressed the pollution of its reservoir from agricultural waste by establishing a rural waste-to-energy program that electrified 2,200 households. Moving beyond conventional, mono-sectoral approaches to energy delivery, these alternative, circular strategies for power production are solving energy poverty. As blended, multi-functional systems, they have also fostered job creation, allowing for economic growth while suppressing carbon emissions.

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

Defining the Circular Economy

The notion of a "circular economy" is modeled on self-sustaining ecosystems and grounded in their complex, self-organizing, and circular flows of energy and matter. By cascading (passing along) waste energy and processing waste nutrients for reuse in the cycle, such a closed-loop, complex system reduces new resource inputs while eliminating waste, pollution, and emission outputs.[1] Optimized by design this way, a human-engineered system of goods and services may be considered restorative or regenerative. The circular economy stands in contrast to the extractive, once-through, or linear economy upon which our open-ended economic system — and industrialized consumption of resources — has been predicated. Derived in principle from the discipline of industrial ecology — industrial strategies for resource efficiency, dematerialization, and waste prevention — a circular economy lowers the externalized risks and costs associated with waste and energy leakage.[2] Increasingly, through governmental initiatives and corporate social responsibility programs, these strategies are being embedded in corporate culture, benefiting business and yielding improved social and environmental benefits.

The concept of a circular economy has been gaining momentum since its introduction in the late 1970s. Most recently attributable in part to theoretical influences such as "cradle-to-cradle"[3] and the proactive work of the Ellen MacArthur Foundation,[4] it has gained traction through implementation in China, where it is centrally promoted as a key strategy.[5] In Europe, policymakers have issued a comprehensive European Circular Economy Package.[6] As a replacement for the dominant economic modes of the industrialized world, the circular economy is espoused by environmentalists and increasingly by decision-makers as a crucial means of steering human society in general, and the business sector in particular, toward operating within the ecological limits of the planet. In contrast to our growth-oriented, waste-producing, business-as-usual means, a circular economy may not only safeguard the integrity of ecosystem services essential for humanity's survival but also help rebuild natural capital.

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[1] Geissdoerfer, Martin, Savaget, Paulo, Bocken Nancy M.P and Hultink, Erik Jan, "The Circular Economy – A new sustainability paradigm," *Journal of Cleaner Production* 143 (2017) 757-768.
[2] Nakajima, Nina, "A vision of industrial ecology: state-of-the-art practices for a circular and service-based economy," *Bulletin of Science Technology Society,* 20, no.1 (2000):154-169.
[3] McDonough, William, and Braungart, Michael, *Cradle to Cradle: Remaking the Way We Make Things*, first ed. New York: (North Point Press 2000).
[4] Ellen MacArthur Foundation (EMF), 2013b. *Towards the Circular Economy,* vols. 1 &2, Isle of Wight: (EMF 2013).
[5] Liu, Qian, Hui-ming Li, Xiao-li Zuo, Fei-fei Zhang, and Lei Wang. "A survey and analysis on public awareness and performance for promoting circular economy in China: A case study from Tianjin." *Journal of Cleaner Production* 17, no. 2 (2009): 265-270.
[6] European Commission. "Towards a circular economy: A zero waste programme for Europe." Brussels, COM (2014) final.
http://www.eukn.eu/fileadmin/Files/News/2014/towards_a_circular_economy.pdf

Integrated Infrastructural Services as a Mode of the Circular Economy

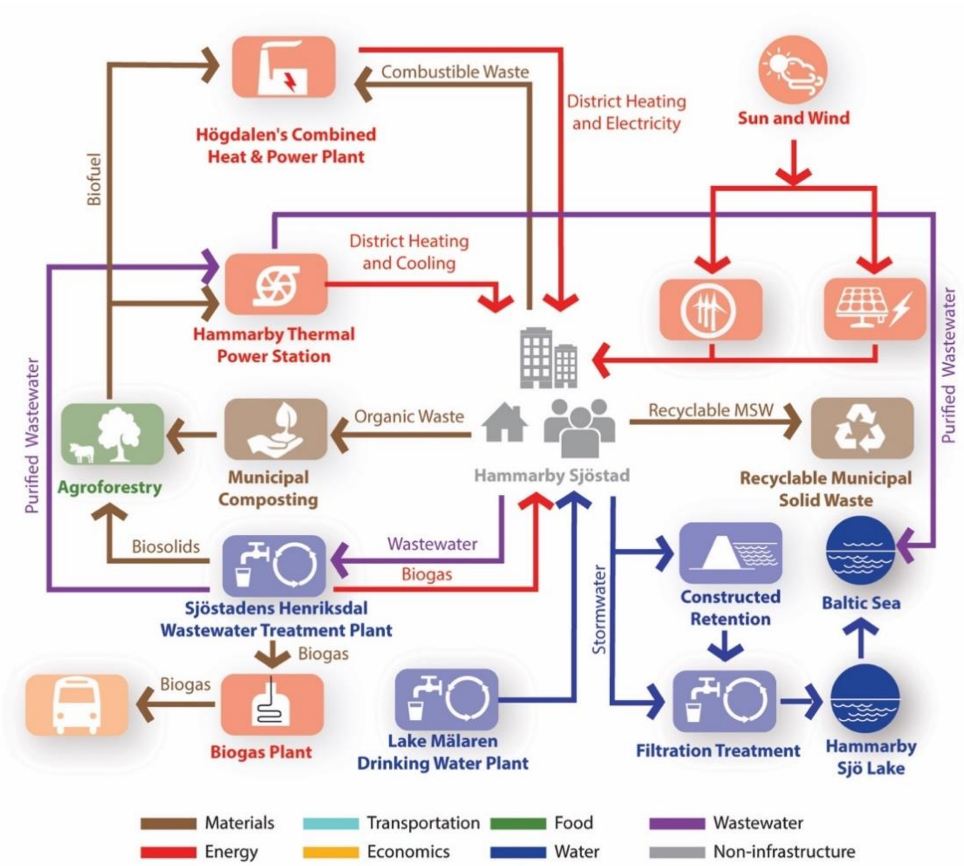
Assuming that the transition towards a global circular economy has just begun, a track record of its successes built on economic returns on investment for the business community will be imperative for motivating such a paradigm shift. As society's political, economic, and environmental actors foresee the circular economy as a crucial pathway for decoupling finite resource consumption (and concomitant negative externalities) from economic growth, how, we might ask, would we apply the circular economy's high-level operating principles to the critical *infrastructural services* that underpin economic growth — the resource- and energy-intensive provision of energy, sanitation, water, waste management, communications, transport, etc.? Would a circular economy approach to planning and operating these assets deliver more sustainable and resilient services? How might we recover waste to support renewable energy production? How might critical systems be reconceived collectively as more interconnected to reduce dependency on non-renewable resources and energy? The following successful precedents, along with the case studies that follow begin to suggest some answers to these questions.

Modelled according to the tenets of industrial ecology, with facilities clustered facilities to capitalize on the efficiencies, the first eco-industrial park in Kalundborg, Denmark exemplifies such beneficial energy and material flows. Developed around a central coal-fired power plant, waste steam and hot water feeds an oil refinery and pharmaceutical company while warming greenhouses, a fish farm, and nearby homes. Kalundborg also recovers fly ash from its stacks to substitute for virgin gypsum in its sheetrock manufacturing plant. These are some of 22 separate exchanges in the park (as of 2011). The eco-industrial park's initial $60 million investment has returned $15 million in annual savings and eliminated 64,000 tons of CO2 while reducing air, water and soil pollution.[7]

In a newly completed neighborhood of Stockholm called Hammarby Sjöstad, officials used a similarly circular archetype which linked its infrastructural services to reduce metabolic urban flows.[8] In this "Hammarby Model" (Fig. 1), connections were fostered across heat and power, sewage, and waste handling utilities. Waste heat recovered from the sewage treatment plant is combined with heat issued from a local woodchip-fired Combined Heat and Power (CHP) plant to provide new district heating. Methane gas from wastewater is processed into cooking and vehicular fuel while the residual sludge is reused to fertilize the forest.[9]

[7] Domenech, Teresa and Davies, Michael. "Structure and Morphology of Industrial Symbiosis Networks: The Case of Kalundborg," *Procedia Social and Behavioral Sciences* 10 (2011): 79–89.
[8] Iveroth, Sofie Pandis, Anne-Lorène Vernay, Karel F. Mulder, and Nils Brandt. "Implications of systems integration at the urban level: the case of Hammarby Sjöstad, Stockholm." *Journal of Cleaner Production* 48 (2013): 220-231.
[9] Iveroth, Sofie P. "The Potential of the Infrastructural System of Hammarby Sjöstad in Stockholm,Sweden." Energy Policy 59 (2013): 716-726.

Figure 1: The "Hammarby Model," integrated urban systems for Hammarby Sjöstad, Sweden. Redrawn by Logman Arja from the original by Lena Wettrén, Bumling AB.



Source: Hillary Brown and Logman Arja. (Reprinted courtesy of The MIT Press from *Infrastructural Ecologies: Alternative Development Models for Emerging Economies,* by Hillary Brown and Byron Stigge).

As unique industrialized world examples, these closed-loop, circular arrangements among infrastructural — often including some commercial — assets demonstrate how to leverage multiple synergies from networked energy, water, and waste services to bolster both economic and environmental performance. The exceptionality of Hammarby Sjöstad reminds us that the uptake of these models for infrastructural development has been slow. Instead, industrial era models mostly hold sway. The convention for developed nations' "legacy systems" has been to disaggregate water, waste, energy etc. into *separate sectors*, physically and jurisdictionally, isolating them as single purpose and linear instead of multivalent and closed-loop.

Therefore, one opportunity for humanity would be to foster the embrace of circular planning in the provision of new and extended infrastructural services in both the rural and urban *developing world* where growth of and demand for infrastructural services are rapidly escalating. The following three case studies demonstrate how new actors, employing innovative and relational thinking, are positioned to unlock the value of the circular energy economy, one that can support economic growth while avoiding resource depletion and ecosystem degradation**.**

Resource Loop-Closings and Beyond: Belo Horizonte, Brazil

Typically located near urban areas, landfill sites are the most visible indicator of today's linear, once-through economy. Conventionally filled with municipal solid waste (MSW) — a mix of inorganic and organic material (46 percent global average)[10] — these sites release harmful methane into the atmosphere. Landfill gas alone leads to the worldwide release of between 19.99 million and 59.99 million metric tons (approximately 22 million to 66 million tons) of methane annually.[11] Recovering and utilizing gas from the decomposing organic matter in sanitary landfills for energy generation represents a closed-loop bio-cycle and is a considered a transitional, carbon-neutral energy solution. Understanding and replicating this approach is extremely relevant for low income countries that can only spend a fraction of their solid waste management budgets on waste disposal, with most MSW going simply to waste collection and not to appropriate treatment.[12]

Background to the initiative

The local government of Belo Horizonte established and operated its first sanitary landfill in a highly urbanized region northwest of the city in 1972. The site, which occupied 114 hectares (282 acres), received some 4,200 tons of MSW daily until its closure in 2007. It was just the prior year that Belo Horizonte had established its Municipal Committee on Climate Change and Eco-Efficiency. Under this umbrella, it was undertaking major projects for GHG mitigation, including solar hot water heating and a rapid-transit bus program.[13]

An early adapter (1993) of Integrated Solid Waste Management (ISWM), a comprehensive waste reduction, collection, composting, recycling, and disposal system, the city's waste scavengers — sweepers, pickers, collectors, packers, and sellers — had formally partnered with the municipal administration. Together they created an effective urban waste management

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[10] Walker, Dale, "Urban Biocycles," Ellen MacArthur Foundation, 28 March 2017, 1-34 at 13, https://www.ellenmacarthurfoundation.org/publications/urban-biocyles (Accessed 20 July, 2017.)
[11] A. Robinson, G. Sewell, N. Damdaran, E. David, and N. Kalas-Adams, "Landfills in Developing Countries and Global Warming," in *Proceedings Sardinia 2003, Ninth International Waste Manage- ment and Landfill Symposium*, Cagliari, Italy, CISA, Environmental Sanitary Engineering Centre, October 6–10, 2003, 2.
[12] ICLEI-IRENA Case Study, 2013, Belo Horizonte, Brazil, Waste to energy for more effective landfill site management: https://www.irena.org/Publications/RE_Policy_Cities_CaseStudies/IRENA%20cities%20case%203%20Belo%20Horizonte.pdf (accessed 20 July, 2017).
[13] World Wildlife Fund, "Belo Horizonte Sustainability," http://wwf.panda.org/what_we_do/footprint/cities/urban_solutions/themes/governance/?228952.

system that professionalized their positions, systematized their processes, and improved working conditions (Fig. 2).[14] Creating a circular recovery system of solid waste byproduct was the next step.

Figure 2: A member of the waste picker cooperative, Belo Horizonte, Brazil.

Source: Courtesy of Sonia Dias.

Previously the biggest single source of GHG emissions in Belo Horizonte (2014 population 2.5 million), the landfill site was transformed in 2007 into a Municipal Waste Treatment Center, the Centro de Tratamento de Residuos Sólidos (CTRS). When the landfill shut down, it held 17.4 million m^3 (22.75 million yd^3) of waste that had accumulated since 1972 and covered a land area of 65 ha (161 acres) (Fig. 3). While an initial goal had been to address odor at the landfill, which

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[14] Ana Paula Bortoleto and Keisuke Hanaki, "Analysis of Waste Prevention Policies Applied at the Solid Waste Management in Belo Horizonte, Brazil," International Solid Waste Association, 1–8 at 4, http://www.iswa.org/uploads/tx_iswaknowledgebase/543801_Paper.pdf. Accessed on: 15, July 2017.

continued to be a problem, the city also moved to add another option to its renewable energy choices.

Figure 3: Aerial view of the Centro de Tratamento de Residuos Sólidos in Belo Horizonte, Brazil.

Source: Google Imagery copyright 2017.

Closing the Bio-cycle Loop

Whereas in most of Brazil landfill sites had open biomethane drainage systems where gas is wasted by simply flaring it, Belo Horizonte contracted with the bid-winning Asja Ambiente Italia SpA (Asja) Company in 2007 to recover and treat the gas for use in electricity generation. By 2010, the site operated a 4.5 MW capacity energy plant.[15] This was in part thanks to an innovative funding and financing mechanism: the sale of carbon reduction credits under the Clean Development Mechanism (CDM). Under this program, established in 2006, developed nations — those that have made emission-reduction commitments under the Kyoto Protocol — can help finance emission-reducing project implementation in developing countries. This is accomplished through their purchase of Certified Emission Reduction Credits (CERs) from these emerging nations, thereby helping to finance such projects. Here, as is typical in this significant program, Asja was required to

[15] ICLEI-IRENA, Ibid

comply with specific requirements of the CER credits. At the site, Asja today operates the Biogas Processing and Utilization Center. Its gas production process involves purification to remove sulfuric gasses and decrease water volume. Once combusted in General Electric gas engines, it generates enough grid energy to support electricity consumption of approximately 30,000-35,000 people.

Between 2009 and 2010, it reduced the city's GHG emission by 237,473 tCO^2e/y, which by 2016 had fallen to 91,475 tCO^2e as the continued extraction depletes the methane accumulation.[16]

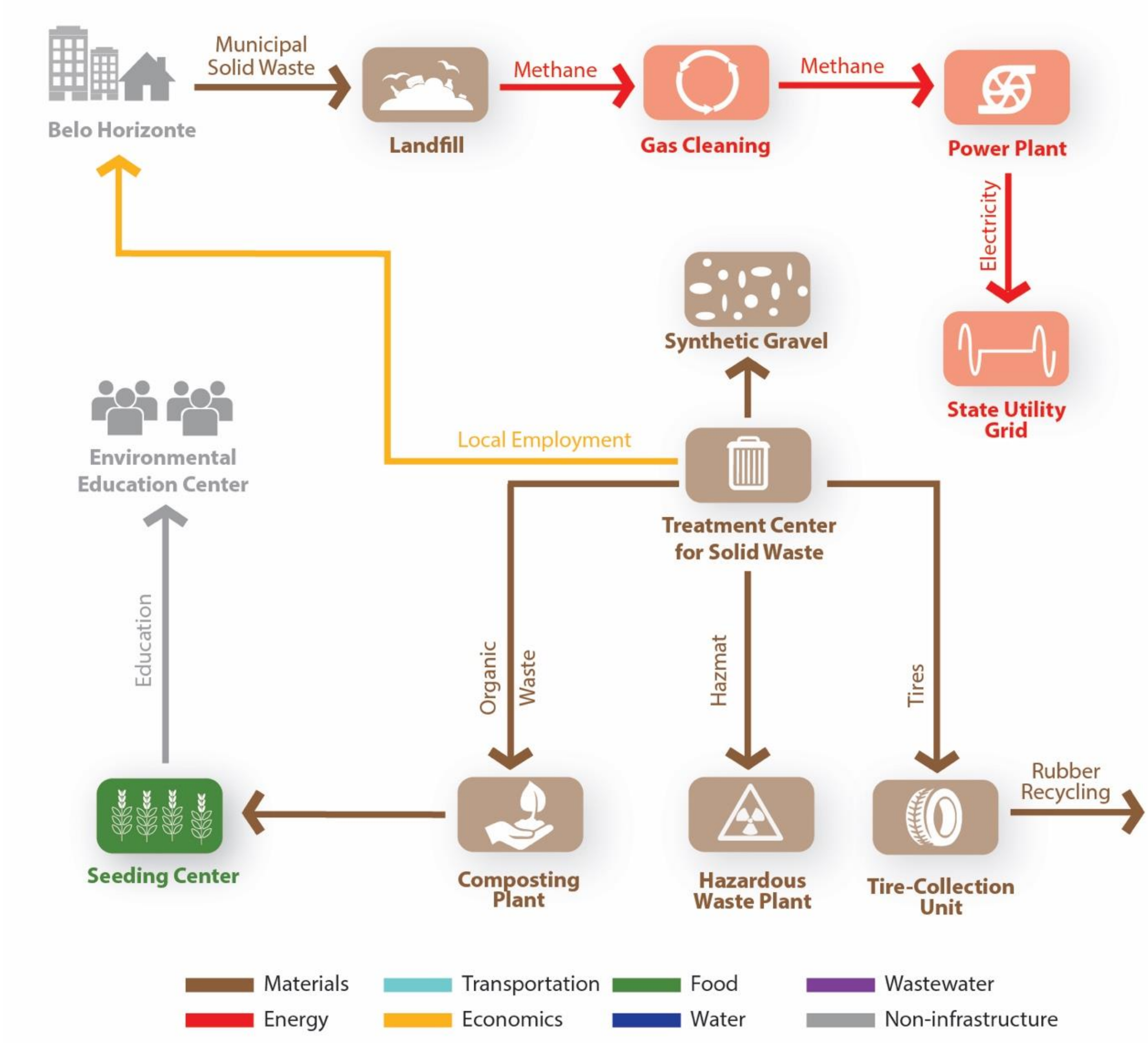
Expanding the Circular System

Today, under the jurisdiction of its Department of Urban Cleaning (Superintendência de Limpeza Urbana (SLU)), Belo Horizonte has expanded the complex web of its circular economy at the site, embracing recovery and regenerative processes from complementary sectors. The CTRS operates several co-located facilities (Fig.4). These include the following enterprises:

1) a composting plant, which processes selected organic waste collected from markets for the schools' vegetable gardens, parks, and squares of the city
2) a recycling facility for construction waste, which yields synthetic gravel used for roadway paving
3) a "seedling station," which grows plants used to support the environmental restoration of the landfill site
4) a hazardous medical waste plant
5) a plant that recovers tire rubber for offsite recycling
6) an environmental center offering tours to as many as 144,000 students annually to learn about the circular economy.[17]

[16] Ibid.
[17] Ibid.

Figure 4: Landfill gas to energy and solid waste management, Belo Horizonte, Brazil.



Source: Hillary Brown and Logman Arja. (Reprinted courtesy of The MIT Press from *Infrastructural Ecologies: Alternative Development Models for Emerging Economies,* by Hillary Brown and Byron Stigge).

In recognition of its co-located and integrated solutions to waste management, mitigation of the environmental impacts of the landfill, and reductions of GHG emissions, Belo Horizonte receives 6 percent of the value of the electricity sold. This is in addition to what the municipality receives as revenue from the sale of approximately 1.3 million CERs sold in the international market during its ten-year CDM crediting period.[18]

The program falls within the Brazilian government's initiative to increase the production of electricity from renewable sources and reduce the country's greenhouse gas

[18] World Wildlife Fund, "Belo Horizonte Sustainability," http://wwf.panda.org/what_we_do /footprint/cities/urban_solutions/themes/governance/?228952.

emissions by between 36.1 and 38.9 percent from projected amounts by 2020.[19] By harvesting its myriad waste sources and integrating them in this fashion, this public/private entrepreneurship has not only made major strides towards this goal, but it has also gained profitable returns. As other emerging economies see their consumption and thus their waste production mount and begin to shift from open dumps to sanitary landfills, they should seriously consider adopting this comprehensive and integrated solid waste management and energy production model. They too could at once cascade their resources, turning waste to energy and recovering both biological and technical nutrients while providing educational programs that advance the circular economy in their metropolitan area.

Omnigrid's Solar Asset-Sharing Strategy: An Enabling Framework for Value Creation

Another aspect of the circular energy economy illustrated in the following case study is the optimization of asset usage through sharing. We are mostly familiar with how peer-to-peer sharing (e.g. Uber, Zipcar, Airbnb) is revolutionizing the transport and hospitality sectors by extending the deployment of a particular asset. Similarly, the combined use of a single infrastructure facility through co-location means fewer resources consumed and less waste produced.[20] Omnigrid Micropower Company's achievement in India sets it apart from other power providers. It serves two very different kinds of clients via a single solar power plant, a shared-use arrangement that makes the business model financially viable – selling electricity to the rural poor – without necessitating government subsidies.

Background to the innovation

The potential of such an eco-innovative and effective approach is enormous. There are approximately 237 million citizens in India who lack access to reliable electricity.[21] Consequently, economic development is stalled for those beyond the reach of the electric grid. Some are already technically "wired" but still receive quite an irregular power supply. While ownership and management of India's electrical distribution networks is shared between both public and private distribution companies (DISCOMs), the latter, which typically serve large urbanized areas, can neither spare the power nor afford the cost of extending transmission and distribution lines to remote locales. Nonetheless, because sunlight is a key resource in India – greater than 60 percent of the country receives annual average global insolation of 5kWh/m2/day[22] — the government has embraced the strategy

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[19] General Electric Website, "GE's Landfill Gas Technology Powers New Brazil Landfill Gas-to-Energy Project," Press Release, October 31, 2011, http://www.genewsroom.com/Press-Releases/GEs-Landfill-Gas-Technology-Powers-New-Brazil-Landfill-Gas-to-Energy-Project-220762
[20] Arup 22
[21] World Energy Outlook, WEO Database, 2015, http://www.worldenergyoutlook.org/weo2015/ Accessed on: 16 July, 2017.
[22] T. V. Ramachandra, T.V., Jain, R. & Krishnadas, G., Hotspots of solar potential in India, *Renewable and Sustainable Energy Reviews.* 15 (3178–3186), 2011.

of serving its rural populations with distributed, renewable solar power.[23]

Despite the ubiquity of solar energy and regulatory support of rural power provision, the remote installation of photovoltaic power plants has been traditionally perceived as financially risky. This is due to the low density of customers as well as the higher cost of distributed vs. grid-served electricity. Additionally, rural communities have experienced faulty or substandard products and overall often unreliable services despite the higher cost they pay.[24] Therefore the installers themselves are concerned about both the inclination and the ability of indigent rural populations to pay, guaranteeing a reasonable return.

Despite these deterrents, Omnigrid Micropower Co., Pvt., Ltd. (OMC) saw a unique opportunity for solar-powered generation in Uttar Pradesh, one of India's most populous (200 million) and poorest states. The company envisioned a business model that capitalized on the large energy demand of the dynamic telecommunications industry. With India's base of in excess of a billion subscribers,[25] a near majority of India's 400,000 off-grid cell phone tower base stations were running on diesel generators as recently as 2013. These generators are costly from both an operational and maintenance perspective; they also pollute the air and contribute significantly to India's carbon footprint. Beginning in 2012, tower operators were mandated by the government to transition 50 percent of their power system to renewables by 2015.[26]

Circular thinking fosters a sharing economy

Founded in 2011, OMC is a Gurgaon, India-based Renewable Energy Service Company (RESCO) which 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 electricity to cellular towers with micro-solar power plants, typically producing less than 50kW.[27] Despite the aforementioned drawbacks to powering off-grid populations, OMC recognized the market potential for providing solar-powered electricity in Uttar Pradesh. They realized that the renewable powering of remote cell phone towers under a long-term supply contract would comprise an "anchor" demand, thereby

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23 GNSED. Renewable energy-based rural electrification: The mini-grid experience from India. New Delhi: Prepared by The Energy and Resources Institute (TERI) for the Global Network on Energy for Sustainable Development (GNESD), pp.1-31.

24 Liu, C., Renewable energy, once a dream, lights up some of India's slums, *ClimateWire*. December 20, 2013, http://www.eenews.net/stories/1059992166. Accessed on: 11 July, 2017.

25 Rai, S., India just crossed the 1 billion mobile subscribers milestone and the excitement's just beginning, *Forbes,* https://www.forbes.com/sites/saritharai/2016/01/06/india-just- crossed-1-billion-mobile-subscribers-milestone-and-the-excitements-just- beginning/#73753be17db0 Accessed on: 18 July, 2017.

26 Tweed, K., Why cellular towers in developing nations are making the move to solar power, *Scientific America* January 15, 2013, http://www.scientificamerican.com/article/cellular-towers-moving-to-solar-power/. Accessed on: 17 July, 2017.

27 Krishna, R.J., Renewable energy powers up rural India, July 29, 2015. *The Wall Street Journal.* https://www.wsj.com/articles/renewable-energy-powers-up-rural-india- 1438193488. Accessed on 19 July, 2017.

guaranteeing a revenue stream that could subsidize the service to nearby rural communities. Based on this combined service arrangement, OMC could piggy-back the delivery of electricity to adjacent villages via microgrids, making this otherwise dicey investment more "bankable" from the perspective of their partnering financial institutions.

Under this Community Power program, by 2013, OMC had constructed eleven 9 to 18kW micro solar power plants, costing about 50 lakh (US$75,385) each.[28] This stands in contrast to the high capital costs of a coal-fired plant and its long construction timeline—typically 5 to 7 years versus 3 months for the implementation of an OMC solar plant. Additionally, according to one estimate, powering a single mobile base station with an OMC PV-power plant reduces carbon emissions between 40 and 50 metric tons annually while eliminating the energy losses typical of long-distance power transmission.[29]

Augmenting a low resource-consuming, high efficiency energy economy

Another significant feature of the program capitalizes on a closed-loop bio-cycle: these power plants may be supplemented by biogas-generated electricity, utilizing biomethane produced by local anaerobic biodigesters which feed on agricultural, animal, and human waste. The micro power plants can also readily be supplemented by wind energy. The power plants can even be equipped with battery banks and/or diesel-fired backup generators to guard against low solar insolation levels during monsoon seasons (see Fig. 5).[30]

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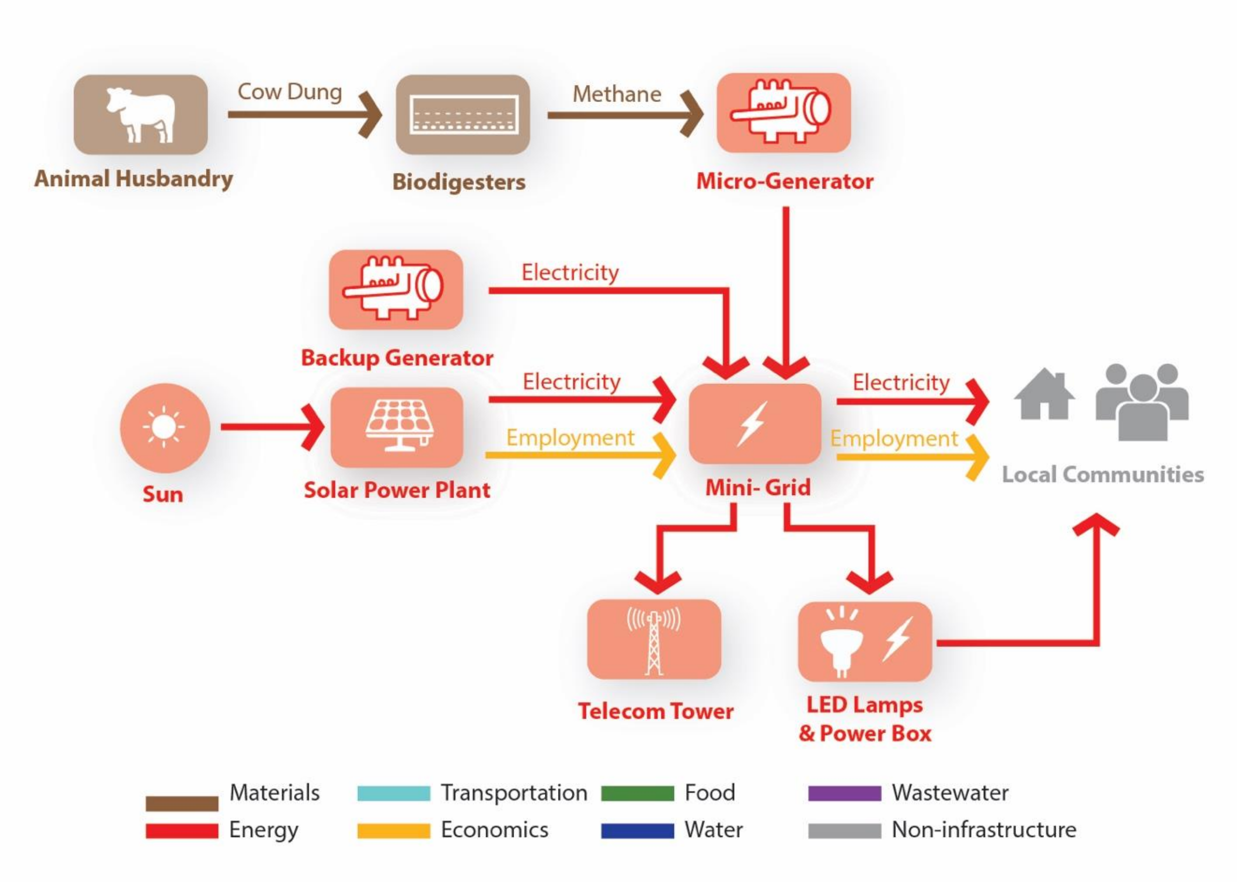
[28] Ibid.
[29] Tweed, Ibid.
[30] Almqvist, P., Cutting the cord for a better energy future," *The Solutions Journal* 4(2) June 2013, http://www.thesolutionsjournal.org/node/22511?page=31%2C0%2C0%2nC0%2C. Accessed on: 17 July, 2017.

Figure 5: Diagram of OMC power plant and microgrid, Uttar Pradesh, India.



Source: Hillary Brown and Logman Arja. (Reprinted courtesy of The MIT Press from *Infrastructural Ecologies: Alternative Development Models for Emerging Economies,* by Hillary Brown and Byron Stigge).

Another aspect of the circular energy economy is its innovative use of advanced technology, saving energy and resources. Supplied through local distributors, villagers are using affordable and technically appropriate microgrid-adapted power equipment. These include portable and rechargeable LED (low-emitting diode) lanterns that completely eliminate the need for household wiring. Based on a prepayment business model, these lanterns costs about 100 rupees ($1.50) each month, versus 180 ($2.70) for kerosene. The lanterns are collected each morning by "light wallahs," recharged, and returned to customers later the same day (see Fig. 6). To further support elimination of wiring, for 350 rupees ($5.45) a month customers can lease a *bijli* box (PowerBox), a battery capable of powering two lanterns, a fan or T.V., and a cellphone charger.[31] Since 2012, mini-refrigerators and high-efficiency irrigation pumps have further diversified OMC electrical services.

[31] Dubey, A., Microgrids lift villages out of dark age, *Nikkei Asian Review*. April 1, 2015. http://www.omcpower.com/blog/p/nikkei-asian-review-microgrids-lift-villages-dark- age. Accessed on: 19 May, 2017.

Critical to OMC's inventive and circular thinking is understanding the needs and limitations of their remote rural customers.

Figure 6: OMC's light wallahs carrying recharged lanterns, Uttar Pradesh, India.

Source: Courtesy of OMC Power. Photo Credit: Pär Almqvist.

The game-changing nature of the Bharti/OMC partnership is based on linking 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 belief that indigent rural citizens may not gain electricity access economically. Where the cost recovery for comparable (non-renewable) power plants might take 7 or more years, OMC breaks even within a half year. A co-benefit of the program to the community is direct job creation: OMC employs between 10 and 15 rural workers per cell tower complex.[32]

Scaling up circular innovation

In 2014, the World Economic Forum named OMC Power a 2014 Technology Pioneer as the first renewable start-up company to create commercially

[32] Guay, J. Meet Uttah Pradesh, India's Next Distributed Solar Hotbed. Sierra Club blogs, Compass: Pointing the way to a clean energy future. 19 November, 2012. http://blogs.sierraclub.org/compass/2012/11/meet-uttar-pradesh-indias-next- distributed-solar-hotbed.html. Accessed on: 17 July, 2017

viable and sustainable grid-less rural power plants. OMC has gone on to enter further agreements with SunEdison (a global US-based renewable energy company) as well as the Rockefeller Foundation to scale up distributed power in rural India. The Foundation recognizes that energizing these millions of remote citizens can help unleash India's entrepreneurial potential.[33] Workers can enhance their incomes by working after dark, students study, and women prepare meals post-sundown, avoiding the cost and health damaging effects of kerosene. Such transformational accomplishments, effectuated by OMC's "disruptive innovation", are testimony to the power of relational and circular thinking.

Itaipu Binacional's Full Circle Solution: Rural Agro-energy and Hydropower Protection

The prospects for successful "circular infrastructure economies" are further validated in a third case study. Here, with intelligent caretaking of its assets and deliberate integration across economic sectors, an organization yielded results greater than sum of its parts. In solving one of its operational predicaments, this bi-national energy company created a collaborative platform that yielded "circular-by-design" services, new jobs, and new manufacturing.

Three years after its inaugural operation in 1991, the 8km (5 mile) wide Itaipu hydroelectric dam across the Paraná river bordering Paraguay and Brazil was recognized by the American Society of Civil Engineers as one of the seven modern "Wonders of the World."[34] Itaipu Binacional (IB) is the bi-national entity that successfully completed and operates this large generator of renewable power. With its 14 GW installed capacity, it supplies 17 percent of Brazil's energy demand and 75 percent of Paraguay's. It could be argued that its contentious and transgressive construction — which displaced nearly 60,000 occupants,[35] reduced biodiversity, degraded land and water, and eliminated of a national park — has been partially compensated by IB's community engagement activities over the last two decades that embrace sustainable development and promote rural energy access, environmental conservation, and local employment.

While today its name reflects its locale on the Paraná river watershed separating Brazil and Paraguay, many of the system's infrastructural assets belong to ANDE, Paraguay's public utility, and Eletrobrás, among the largest of Brazil's power utilities. It was funded, however, by the Brazilian government. In 2002, 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

33 OMC Power Press Release, March 8, 2016, The Rockefeller Foundation and OMC Power reach a U.S. $4.5 M deal to finance 100 minigrids in rural India, http://www.omcpower.com/blog/p/press-release-rockefeller-foundation-omc-ink-us4- 5m-deal. Accessed on: 19, July 2017.

34 Gregory T. Pope, "The Seven Wonders of the Modern World," *Popular Mechanics* 172, no. 12 (December 1995): 48–56.

35 Terminski, B., Development-induced displacement and resettlement: Theoretical frameworks and current challenges. *Development,* 10, pp. 101–134, 2013.

other renewable infrastructure, from small hydropower to biomass and wind turbines.[36] In December 2009, Brazil 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 industrial sectors, additional renewables, and improvements to agricultural and animal husbandry practices.

Precipitating concerns and Itaipu Binacional's response

The Paraná 3 watershed (8,000 km^2) which comprises the power plant reservoir's main area of influence is home to more than 35,000 local farms that produce mostly soy-beans and maize. It is also home to more than 1.5 million pigs, 30 million poultry, and the agro-industries based on these plant and animal production practices.[37] The combination of intense agriculture and meat production in this basin created problems at the Itaipu dam. The reservoir's water quality became degraded by deforestation, run-off from soil tilling, and the inflow of phosphorus from agricultural fertilizers and pesticides. The reservoir began to experience both premature filling with sediment and eutrophication, both threats to hydropower production.[38]

Recognizing the linkages between the reservoir's altered hydrology, the region's poverty, and the overall ecological impairments due to agriculture, IB enlarged its mission to embrace environmental and social stewardship in the watershed basin. It instigated the *Cultivando Agua Boa* (CAB) or Cultivating Good Water program: 63 initiatives including conservation of water, protection of farmland and forests, and reduction of agricultural land and water pollution. Strategies introduced included no-till farming; new rural sanitation and wastewater treatment; elimination of pesticides; and forest and stream restoration.[39] Through the CAB program, which emphasized civic society's participation in the farming settlements, IB built an exemplary, multidimensional framework for local stewardship. In 2015, IB received the Best Water Management Practices award from the United Nations *Water for Life* program.

Agro-energy closes the loop

Established by IB in 2009 in the Paraná river watershed, the Agroenergy Condominium for Family Agriculture Sanga Ajuricaba was a key outcome of a sustainability-oriented partnership between IB's Office of Renewable Energy, the

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36 Mathias, M.C. & Mathias, J.F., Biogas in Brazil: a governmental agenda. *Editorial Board Members*, 2015.

37 WWAP (United Nationals World Water Assessment Program), *Facing the challenges: case studies and indicators*, Paris: UNESCO, pp. 1–62, 8–9, 2015.

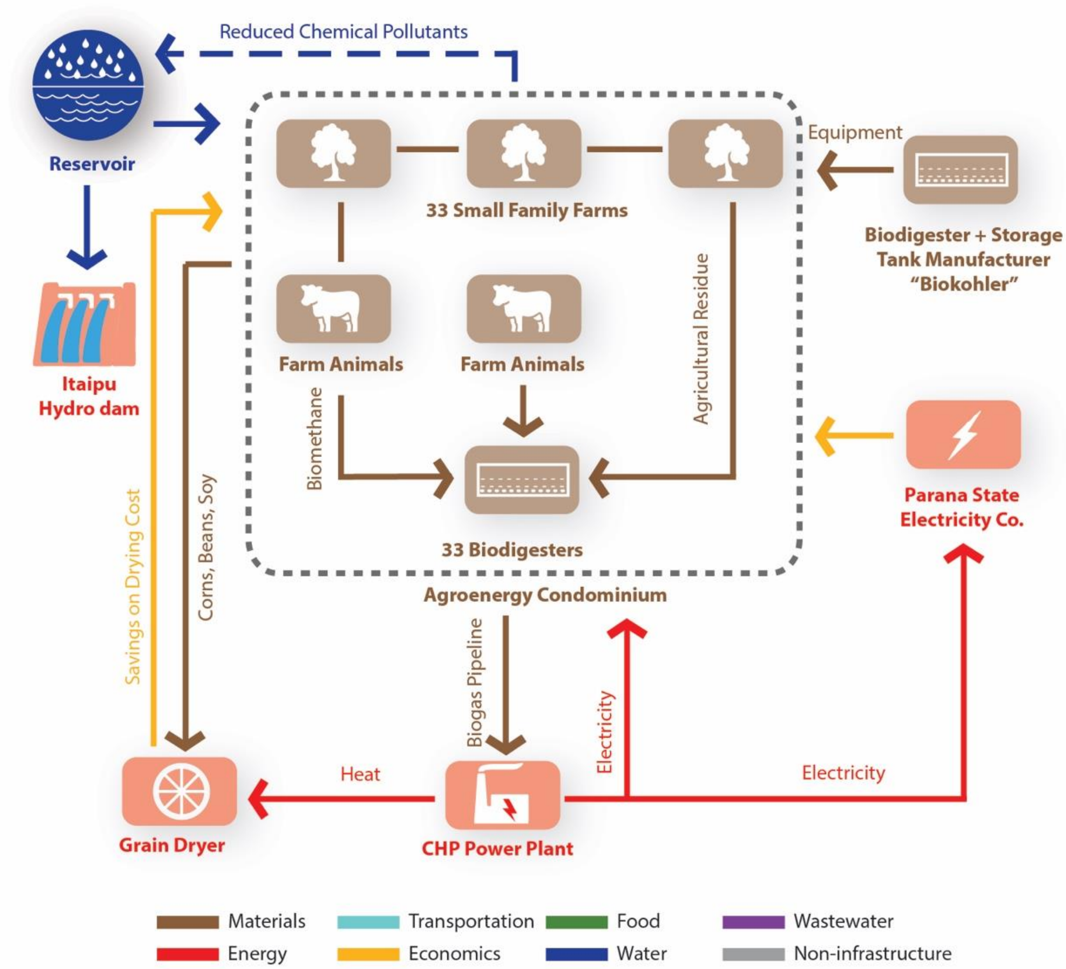
38 Coimbra-Araújo, C.H., Mariane, L., Júnior, C.B., Frigo, E.P., Frigo, M.S., Araújo, I.R. & Alves, H.J., Brazilian case study for biogas energy: Production of electric power, heat and automotive energy in condominiums of agroenergy. *Renewable and Sustainable Energy Reviews*, 40, pp. 826–39, 2014. https://doi.org/10.1016/j.rser.2014.07.024

39 WWAP ibid.

Institute of Technical Assistance and Rural Extension, the Paraná State Electricity Company, the International Center for Renewable Energies, and other entities. Consisting of 33 small-scale family farms, this cooperative became the focus of IB's effort to reduce pollution by supporting the production of biogas and biofertilizers from area waste. It also aimed to help eliminate energy poverty in the region.

IB's program installed individual anaerobic biodigesters at each farmstead that could process the corn production waste with manure from the farmers' herds (approximately 1,000 head of cattle and 3,000 swine). The farmers in the condominium collectively have produced 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. Sent through a 22 km (13.7 mile) pipeline to a central power plant, the biogas collectively generates electricity, heat, and – after upgrading – a biogas-based vehicular fuel.[40] Electricity generation of 445,000 kWh/year serves approximately 2,200 local households, with farmers receiving revenue from surplus sold back to the state's energy distributor. [41] Notably, the residual slurry is also an excellent organic fertilizer for the farms. Finally, a centralized grain dryer, which runs on the thermal energy produced by the power plant, dries products such as corn, beans, and soy beans, reducing farmers' drying costs by as much as 90 percent (Fig.7).

Figure 7: Diagram of Itaipu Binacionale's agroenergy condominium for family agriculture, Paraná River basin, Brazil.



Source: Hillary Brown and Logman Arja. (Reprinted courtesy of The MIT Press from *Infrastructural Ecologies: Alternative Development Models for Emerging Economies,* by Hillary Brown and Byron Stigge).

Given the fact that much of the nation's agricultural wastes accumulates across its territories — with 77 percent of Brazil's population still employed in farming as of 2015 — distributed power generation from waste biomass and manure, produced through anaerobic bio-digestion, is an obvious means to rural electrification. Circular logic therefore underscores how *agro-energy* eco-effectively transforms the environmental liabilities of Brazil's farming sector – the methane derived from animal manure and the watershed-polluting organic chemicals from fertilizer – into electricity and 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.[42]

The reciprocities between hydro dam water quality protection and rural energy access have also produced a range of co-benefits and employment. These include water quality improvement in 206 micro-basins; restoration of riverine buffer zones with 40 million trees; and the creation of two biological sanctuaries. The Condominium biogas initiative, with assistance from IB, has also fostered a small local industry, Bio-Kohler, which manufactures the fiberglass biodigesters, storage tanks, and cooking stoves designed for biogas use.[43]

At the same time, CAB has delivered educational services geared towards improved nutrition, organic farming practices, cultivation of medicinal plants, and the introduction of aquaculture. CAB has established five local waste cooperatives and 25 regional waste associations that improve the livelihoods of solid waste handlers.[44]

IB has scaled up its circular stewardship well beyond its own customer base. The Agroenergy Condominium model initiated in Paraná has been since introduced in Uruguay, especially in the State of San Jose, which produces the highest carbon emissions nationally due to its dairy-heavy agricultural economy. Led by Eletrobrás with funding from a group of the world's thirteen leading energy companies and with IB as the project consultant, 22 farms will be connected to a central micro-

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[42] WAAP, Ibid.

[43] Mario Osava, "Brazilian Hydroelectricity Giant Promotes Biogas," *Terramerica: Environment and Development*, September 2013, 2, http://www.ipsnews.net/2013/09/brazilian-hydroelectricity -giant-promotes-biogas/. Accessed on: 24, July 2017.

[44] Itaipu Binacional, Cultivating good water overview, available at: https://www.itaipu.gov.br/en/the-environment/cultivating-good-water. (Accessed 20 July 2017).

thermoelectric plant which will produce 764 m3 (1,020 cubic yards) of biogas daily, with an expected energy production of 1.53 MWh/day.[45]

Surmounting Barriers to Circular Thinking in the Infrastructure Sector

Certainly, circular thinking (infrastructure integration) is not the only pathway to reducing the global carbon footprint. As renewable technologies become increasingly cost-competitive with conventional generation, nations are already forging ahead, installing new distributed renewable installations at a meaningful pace. In fact, according to one report, in 2016, total global capacity increased by 9 percent over 2015, to nearly 2,017 GW globally.[46] Nonetheless, the three examples detailed above show that a complementary and multidimensional approach to decarbonization can result from circular thinking. These cases reveal how one system's waste or surplus can be useful to another, producing socio-economic co-benefits. Belo Horizonte extended its initial investment in landfill gas recovery into a diversified job-generating practice of waste recovery. In linking telecommunication infrastructure's demand to its solar power plant, Omnigrid Micropower was able to electrify rural communities and spur new employment. In resolving its own critical hydropower problems, Itaipu Binacional simultaneously promoted rural community agro-energy and economic development.

Given the wide diversity of actors in the infrastructure space — governments, multilateral financial institutions, nonprofits, and private enterprises — who is best posed to implement new models based on the principles of infrastructural ecology? The answer, to a great extent, is all of them. However, entrepreneurial thinking on behalf of OMC aside, government, as in the cases above, has a special lead role to play through policies, regulation, and incentives.

Governments at all levels are often most able to create progressive policies which coordinate the many entities involved in creating circular energy systems. Many low-latitude countries have abundant potential for renewable energy production, aside from hydroelectricity. National governments there can and should retire carbon-based subsidies. Eliminating or reducing importation of "cheap" gas or oil and gas would incentivize the use of indigenous energy sources, at the same time improving the balance of trade. Federal governments can establish joint water, energy, and agriculture commissions. In Nepal, for example, the national creation of the Biogas Support Program opened up opportunities for private biogas companies to scale up rapidly.[47] Governments can encourage pursuit of the Clean Development

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[45] Itaipu Binacional, *Biogas production model from Paraná will be replicated in Uruguay*, Press Release, 27 August, 2013, available at: https://www.itaipu.gov.br/en/press-office/ news/biogas-production-model-parana-will-be-replicated-uruguay. Accessed on: 21 July, 2017.

[46] REN21 Secretariat, UN Environment News Release, June 7 2017. http://www.ren21.net/wp-content/uploads/2017/06/Press-Release_ENGLISH.pdf Accessed on: March 2, 2018.

[47] United Nations Asian and Pacific Centre for Agricultural Engineering and Machinery (UNAP-CAEM), "Recent Development in Biogas Technology for Poverty Reduction and Sustainable Development" (Beijing: United Nations Economic and Social Commission for Asia and the Pacific [UNESCAP], 2007), 55, http://www.un-csam.org/publication/F-Biogas.PDF. Accessed on May 12, 2017.

Mechanism (CDM) as a supplementary revenue source to support infrastructural ecologies for energy production. National investment in coordinated geospatial mapping and databases can illuminate potential synergies across diverse sectors. Finally, at the national level, governments can incentivize infrastructure integration through their access to international development funds.[48]

At the state or local level, strong leadership can align objectives and activities and engage staff across ministries and departments in new approaches to cross-sector infrastructural development. Interagency collaboration can, however, be extraordinarily challenging. To that end, mayors or governors can set up separate authorities or commissions empowered to lead integrated resource planning for the inter-reliant sectors of water, energy, waste, sanitation, and agriculture, easing negotiations or resolving disputes. Such entities would assess a number of projects for potential complementarity and synergies, with an emphasis on piloting those with a potential to be widely replicated.

From a financial perspective, delivering a single, combined project instead of several diverse ones might reduce transaction and overhead costs. Merging capital budget lines from two or three agencies in order to capitalize a single project may create some bureaucratic complexity, but it is a great mechanism to raise sufficient funding to get a project off the ground. It also offers the prospect of aggregating user fees that would provide quicker return on investment. Local governments can also consider instruments such as expedited approvals or tax breaks to reward multi-sector project development by private or nongovernmental entities.[49]

Conclusions

Driven by private entrepreneurship or public leadership and coupled with the use of strategic policy levers that spur other combinations of investment, infrastructural ecology has the potential to help redress environmental degradation as well as the economic and political instability that plagues many emerging economies. On their road to low-carbon infrastructure, infrastructural service providers in emerging economies — both public and private gas and electrical utilities — can work closely together to find synergistic opportunities to build closed-loop, circular energy systems. They must be attentive to opportunities inherent in untapped or underused local resources. In particular, these can include waste streams from agriculture, sanitation, domestic cooking, and even municipal solid waste. Infrastructural services economically provided through circular assemblages can create sustainable energy access for remote and impoverished populations with multiple benefits.

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48 Brown, Hillary and Stigge, Byron. *Infrastructural Ecologies: Alternative Development Models for Emerging Economies,* (Cambridge, MA: MIT Press, 2017), 193-212.
49 Brown, Hillary and Stigge, Byron. *Infrastructural Ecologies: Alternative Development Models for Emerging Economies,* (Cambridge, MA: MIT Press, 2017). 175-192.