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A Haitian 'ecodistrict:' conceptual design for integrated, basic infrastructure for the commune of Léogâne

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Abstract

Background: The island nation of Haiti poses an ongoing challenge to the international development community. Political instability and lack of basic public services, combined with weak technical and financial capacity, collectively undermine both philanthropy and international investment. Haiti's tragic vulnerability to natural disasters (earthquakes and hurricanes) and the public health crises that ensue have only compounded its level of destitution. These complex, interconnected circumstances doom single-threaded solutions.

Methods: The problems call instead for integrative responses, answers that cut across sectors and address multiple problems simultaneously. This proposal for critical services development in the Haitian commune of Léogâne seeks to reduce much of its poverty, malnourishment, pollution, health problems, flooding, deforestation, topsoil erosion and loss of biodiversity.

Results: The territory's long degraded ecosystem services, once regenerated through reforestation and riverbank stabilization, will boost agricultural production. More significantly, they will help provision targeted new energy, water and waste management systems designed together with synergistic exchanges in mind.

Conclusions: Across these sectors shared resource and energy flows will improve efficiencies, lower costs and reduce environmental impacts.

Keywords: Haiti, Earthquake reconstruction, Léogâne

Background

Set against decades of political volatility and economic stagnation, Haiti's marginal investments in critical infrastructural services have left its people struggling today with growing population pressures and increased needs in a context of dwindling resources. Haiti was already the poorest country in the Western hemisphere, with an unemployment rate as high as 70%, (Adelman 2011) when its capital was devastated by a magnitude 7.0 earthquake on January 12th of 2010. The tragedy was compounded by non-existent building codes and shoddy construction: somewhere between 230,000 to 316,000 Haitians lost their lives beneath collapsing structures, with hundreds of thousands more injured (O'Connor 2012). Port-au-Prince, which houses major government and administration offices, was devastated. With so many of the nation's public servants buried in imploding buildings, basic services were disabled for the long months that followed. Globally, well-meaning nongovernmental organizations (NGOs) rushed to offer services and to rally a hobbled people. But Haiti, already a nation with the highest number of NGOs per capita, was overwhelmed by what became a disorganized aid effort. Miscommunications and the lack of coordination that ensued only added to the chaos (Klarreich & Polman 2012). The government worked with international organizations to clear rubble and restore necessary services, while trying to rebuild internal capacity with limited funds. In October 2010, the unthinkable happened again, when a cholera outbreak swept through regions lacking energy, sanitation and secure potable water. As of May, 2013, the epidemic had claimed more than 8,000 lives (Cholera in Haiti).

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Ambitious plans to "Build Back Better," (disaster recovery plans undertaken by the Clinton Foundation, along with many others) have unfortunately stagnated. At this writing, three years following the quake, the Haitian people find themselves with only spotty improvements, increased need, and declining opportunities (Sontag 2012).

Current context

At the epicenter of the earthquake, the commune of Léogâne (population then, 130,000) sustained severe losses, with an estimated 93% of its buildings damaged (Eberhard et al. 2010) (Figure 1). While rubble has been substantially cleared, the few services that existed remain un-restored. Critical infrastructure needs to be comprehensively rebuilt. This poses an opportunity to consider progressive paradigms for utilities' integration and management.

Official waste collection in Léogâne is non-existent. Most refuse is piled and periodically set on fire, a form of 'local management (University of Notre Dame 2011a).' Plastics, along with other household debris, are thrown askance and washed downstream, clogging drainage channels and canals. The town lacks sanitary systems for human and animal waste, and waterways are overrun with organic material, creating serious health hazards (Archibold 2012).

The existing electrical grid (servicing only a small portion of the community) has not functioned since the earthquake. While the government has promoted a plan to connect Léogâne to the national grid, nothing has transpired to date (University of Notre Dame 2011b). In July 2012, Electricité d'Haïti (EDH) and the Ministry for Public Works partnered with Korea International Cooperation Agency (KOICA) to install a small microgrid serving 20,000 Léogâne residents, powered by diesel generators (Haiti - Energy 2012). The system is still not yet fully functional. Clinics, organizations and families with resources are left to run private generators with expensive, imported fuel. Few have been able to purchase solar panels. Throughout Haiti, lack of affordable energy limits employment, buying-power, access to education, opportunities,

Figure 1 Haiti overview.

and investment capacity (Barjon 2011a). For a nation largely comprised of remote rural poor, a distributed energy plan realized with local natural resources could greatly improve the standard of living for much of Haiti's population (OECD 2006a).

The water distribution in Léogâne is similarly problematic. During the 2008 hurricane season, the underground water supply system serving the town center was damaged and, without funding for repair, it has not functioned since (Piasecki 2013). Much of the population still struggles to access potable water. Those with means utilize private wells, while those without utilize shallow hand-dug wells, walk to a public water station or buy water in costly plastic pouches or other containers which are subsequently discarded. While the local water authority, DINEPA, has plans for restoring supply pipelines to the center, service to peripheral and rural areas will be limited to water kiosks (Rebuilding Léogâne Planning Workshop 2011a). The drainage system had been in a similar state of disrepair, but has recently been repaired through international aid. Much of the system, however, lies below sea level. Its drainage cannot be discerned, nor are the parties involved sharing operational plans (Piasecki 2013). Without transparency and local involvement progress is limited.

Transportation services are minimal and crude. Léogâne's limited roadway system is in severely deteriorated condition (University of Notre Dame 2011c). Market activities choke the town's central streets, limiting vehicle volume and speed (Shepard 2010). Roadbeds, rutted with puddles, have become vectors for mosquito nesting and water-borne illnesses. (Léogâne is a known center for mosquitos carrying lymphatic filariasis, which causes Elephantiasis.) Rural roadways are unpaved and intermittently overwhelmed by deluges, increasing the extent of erosion. To manage flooding, open drainage ditches flank roadways, posing significant hazards to unwary drivers. The lack of safe roadways also limits deployment of heavy equipment.

Large areas across Haiti have experienced severe environmental degradation. Overall, only 2% of the country remains forested (Library of Congress –Federal Research Division 2006). Both upland trees and coastal mangroves in this energy-impoverished landscape have been widely harvested for charcoal, the primary cooking fuel. Severe deforestation is also endemic in and around Léogâne, along the coastal areas and into its surrounding hills and mountains. No longer stabilized by root systems, upland soil erodes during tropical downpours. It overwhelms rivers and streams, fanning out downstream as it washes into the ocean. Routine flooding takes out roadbeds and creates impassable conditions across the alluvial plain in and around the town center.

Tropical floods have decimated the once confining banks of the Momance and Rouyonne Rivers, severely damaging not only riparian habitat, but also the deltas and estuaries. While natural causes exist for coastal habitat degradation (including the earthquake's seismic uplift that drained tidal marsh, exposed sub-tidal sea grass causing loss of coral reef and mangrove habitat), (Koehler & Mann 2011) anthropogenic impacts compound the damage through the massive influx of river sedimentation and the harvesting of mangroves for fuel (Rebuilding Léogâne Planning Workshop 2011b). Sited within the Caribbean's well-trafficked "Hurricane Alley," Léogâne's developed land area, along with its once bio-rich estuaries and coastal coral reefs, has become especially vulnerable to rising sea levels. Earthquake damage, coupled with environmental degradation, has triggered negative feedback loops, limiting local economic recovery. Practical opportunities for combined solutions to these interconnected problems have driven the integrative design of this proposed ecodistrict. (Ecodistricts are an urban planning term for sustainable development in a larger region where the ecological footprint is considered in planning and resources are used judiciously (Metzger and Olsson 2013)).

New paradigms for utilities in developing nations

Sixty percent of global energy growth in the next few decades will take place in developing nations, where about two billion people are living without access to electricity (Holm & McIntosh 2008). Many emerging economies, while constrained by other substantial barriers to progress, enjoy a potential window of opportunity to bypass petroleum-dependent technologies for next generation systems. Through implementation of largely renewable energy-driven solutions upfront, these nations may accelerate the technology application in holistic ways. For example, smart-grid and distributed micro-grid networks, compared to centralized systems, reduce losses while better matching load with demand (Gregory 2011a). By investing in renewable energy sources, developing economies may draw roadmaps for a lower carbon, global energy transition. This opportune, but non-traditional pathway, however, places significant burden of risk on energy policy decision-makers. Leapfrogging fossil fuel technologies will also entail considerable support and international cooperation from both governmental and private investment communities (Holm 2005). Globally, carbon-based energy systems have enjoyed inter-governmental protection, subsidy policies, and economies of scale achieved through investment in conventional generation and transmission (Holm & McIntosh 2008).

GEMi and a vision for Haiti

Project objectives and strategies for this ecodistrict design build upon, and are aligned with, the precepts of the Global Energy Model (GEM). The Global Energy Model Institute, a new nongovernmental initiative that bears its name (GEM Institute or GEMi), was formed to address many of these challenges (Global Energy Model Institute 2012). Its broad objective is to solve global energy poverty through the progressive application of clean, reliable power systems, based on proven technologies. GEM is the organizing framework for multi-sector investment and development with energy at its hub. Haiti is its initial pilot. A premise for its universal application is the nature of complex, cross-sectoral interactions around, and dependencies upon, energy. While GEM is technologically agnostic, it is biased towards solutions that serve the triple bottom line. The energy model itself is an integrated information management system that captures innovations and best practices and allows for successive refinement across different locales (Under development by Daniel C. Gregory of Positive Energies, LLC).

For Léogâne, it was assumed that many of GEMi's basic operating principles and implementation processes would be applied as givens. These include the reliance on stakeholder-driven development, development of Haitian professional and administrative capacity, and the utilization, wherever possible, of a local work-force. GEMi's mission also entails enabling and locally sustaining an expanding power system infrastructure through its planned education and training programs (Gregory 2010).

Haiti lacks a national grid beyond the one that currently serves Port-au-Prince and immediate environs. One of the visions for Haiti elaborated upon through GEMi involves the development of a national grid based significantly on existing hydropower that will be upgraded and enhanced (Brown 2011). For locales off the planned primarily North–south grid, a decentralized generation system is envisioned, with eventual grid connectivity. (Lemons, 2012). With Haiti's island context, renewable energy generation options are ultimately more cost-effective and viable due to the logistical and economic complications of foreign fossil fuel delivery and supply.

GEMi's reliance on diversified and networked renewable resources reduces dependence on imported fuel, limits carbon emissions and provides system diversification and resiliency. Currently, Haiti's energy is largely sourced from foreign fossil fuel hydropower; however, the existing dams are undergoing upgrades to increase the grid's base-load capacity. Refurbishing the dams risks extending negative impacts to the remaining intact ecological services contributed by the river. Sedimentation from unmanaged upland erosion must be constantly removed to maintain capacity. Moreover, methane, a highly potent greenhouse gas, is also emitted by untended decaying biological matter. Other options pose technical challenges. Both wind power and solar energy production fluctuate. Neither alone is sufficiently reliable, and each would require some measure of storage to be able to release energy on-demand. New multi-pronged or hybrid systems such as blended renewables, coupled with storage and backed up by diesel-fueled generation are envisioned to address the breadth of the challenge.

Methods

Holistic design for synergies across sectors: Léogâne as model for rural utilities

Plans for Léogâne's redevelopment include environmental remediation and optimization of material and resource flows across the energy, water, agricultural and transportation sectors. Investment in one sector, per the plan, creates the stability needed to initialize another; this is integral to the final outcome and can't be undertaken successfully unless the supporting sectors are in place. The new paradigms for the plan rely upon the cascading of energy, water or residual resources extracted from nature across these sectors. Through colocation and coupling of complementary components, the program will capitalize on designed-in exchanges among multiple system elements. For instance, floodwater control may also be used to generate energy, irrigate crops and improve water quality. Agricultural and municipal solid waste can provide energy and heat for industrial processes while returning beneficial soil amendments. The vision entails closing loops to create a self-sufficient, holistic system, one that captures synergies, creates economic efficiencies, and eliminates waste. Promoting synergies between economic gains and social infrastructure helps to amplify benefits, ensuring that real gains are made in all sectors for the poorest and most vulnerable people (OECD 2006b). The design also promotes colocation of complementary entities such as industry, hospitals, clinics and schools, allowing these entities to take advantage of infrastructural outputs and/or contribute inputs. Overall, the plan reduces reliance upon most 'first world' carbon-intensive systems, substituting for the most part technologies that can, after training, be constructed and managed by local labor. In addition to new jobs, the scheme also entails alternative employment opportunities for agriculture, agroforestry, and aquaculture industries envisioned for the commune, along with other forms of local enterprise.

Léogâne is an ideal locus for reconstruction as its landscape mirrors that of much of Haiti, with its steep rural mountains, rivers and streams, and its populous alluvial plains. Successes in Léogâne could be used as templates for integrated development across rural Haiti where conditions are similar. Interventions in Léogâne were therefore designed along just such a typical corridor running from the mountainous uplands in the South, through the more populous alluvial plain and down to the coast on the North. The area is bounded on either side by the Momance River and the Rouyonne River, both of which have large seasonal variations.

Local efforts to guide reconstruction along this mountain-to-coast transect will help to inform placement of the system's modular elements. Working components will be sited at locations with specific relationships to both natural resources and existing settlements (Figure 2). For

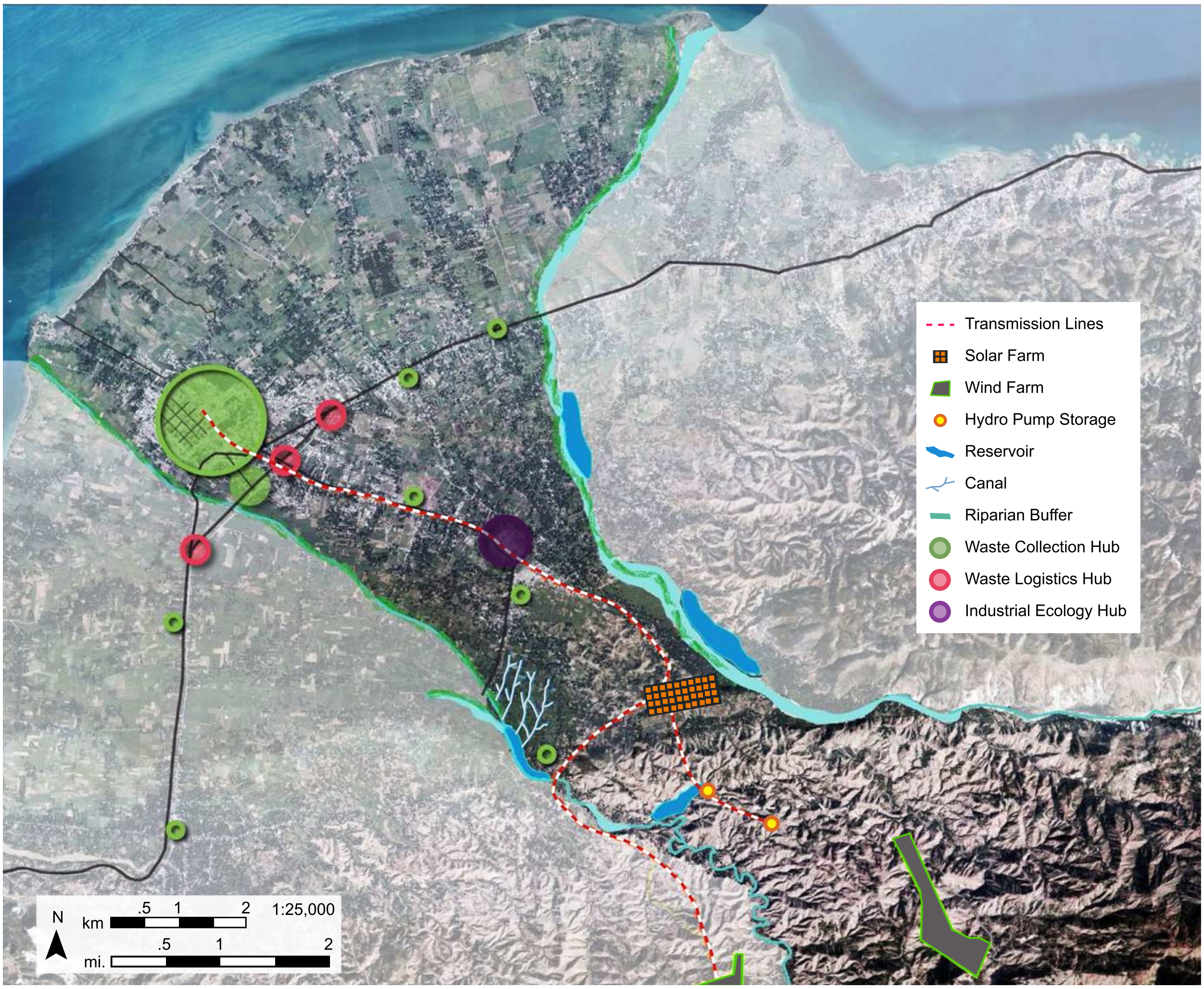

Figure 2 Integration of critical infrastructure overview.

example, the upland placement of wind turbines captures higher wind speeds. Photovoltaic arrays, interspersed with agriculture, occupy the middle range and power the pumping of water from a nearby receiving reservoir to a holding reservoir above for the pumped-hydro-storage generation system. Within this region too, biomass salvaged from agriculture will be used to supplement energy generation. All along this corridor, riparian resources will be stabilized for flood control, infrastructure protection, and for improved water quality for farming and aquaculture.

A base load generated by a pumped-hydro storage system (PHS) will power the industrial, civic and commercial sector. Explained below, the PHS is a generation system networked for reliability and redundancy. The distribution of electrical services also relies on an integrated delivery mechanism: a set of service points or "nodes" (Figure 3). This approach standardizes and maximizes the reach of new services. In the town center, for example, nodes serve neighborhoods, public plazas, the markets and other civic functions. Nodal locations will be linked by a newly paved road network. These stations will also serve as outlets for clean drinking water and as drop-off locales for waste collection. Here, cellphones may be recharged, as well as auxiliary LED lamps. Organic and solid waste dropped off at these service points (incentivized through rebates) will be carted to a nearby waste processing (biodigestion) plant site for augmentation of the power-supply. Economies obtained from colocation and simultaneous construction of these services will make the best use of limited resources until more are at-hand to finally extend services to individual dwellings. The nodal service points create an integrated web of services linking new and existing infrastructure. A few are designed to incorporate auxiliary community services such as "electronic cafes." A number of "nodes as community-hubs" are also planned for the town square, on school campuses, clinics and at the hospital.

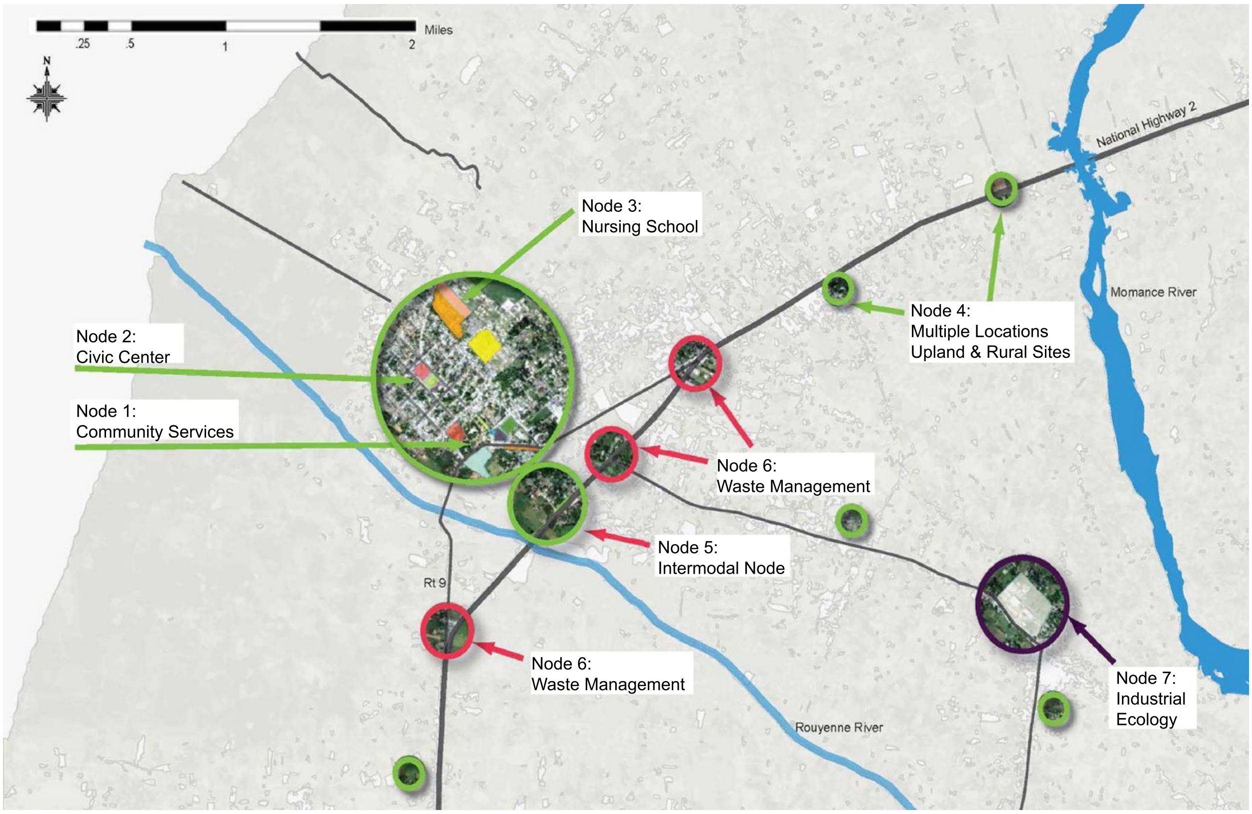

Figure 3 Downtown infrastructural nodes.

Proposal components

Generation of renewable energy

Léogâne's renewable power system (with diesel back-up) will have its base load generated by PHS, powered by distributed wind and solar PV farms of 10 MW and 8.6 MW respectively. Electricity produced by these renewables will pump a quantity of water from the lower to the upper reservoir, where it is stored until released on demand (Figure 4). Passed through turbines, it generates the base-load for the microgrid. The PHS effectively acts as the storage battery and load-leveling device for the overall system (one of GEMi co-founder Daniel C. Gregory's many primary organizing concepts). Léogâne's PHS system is sized at a 10 MW, with a 180-meter head. The upper and lower reservoirs each have a water storage volume of 157,000 m^3. The closed-loop flow of PHS water through surface-mounted pipes will not interfere with local riverine ecology; however, these must be placed in stabilized areas. For 8–10 hours during the day, electricity will reliably feed local micro-grids serving key industrial, commercial and residential locations, as well as some outlying areas. This type of system, which minimizes transmission losses, could serve much of Haiti where mountainous regions and streams are adjacent to urbanized areas.

For system resiliency, the PHS system is reliant on multiple, complementary sources with intermittent energy supply. While Haiti's North and West Departments enjoy dependable wind velocities, Léogâne's flatlands do not reliably produce sufficient wind speeds. Placement of wind farms at higher inland elevations in the commune will better take advantage of seasonal and diurnal on- and off-shore breeze. One or more solar farms comprised of commercially available PV panels will provide electricity to the PHS during the 11–13 hours of daylight. Excess power, not needed for water pumping, will augment the microgrid. Floating PV arrays are placed spanning across each of the PHS water reservoirs, comprising part of the generation system. Floating on pontoons, these arrays shade the water, reducing evaporation. The water in turn lowers the arrays' temperatures, improving their efficiency. The arrangement also avoids unnecessary displacement of agricultural land.

Placed on opposite hilltops at elevations of 600+ meters, a total of eighty-six 100 kW wind turbines will complement the solar farm as primary feed for the pumped-storage system. These medium size turbines, selected in part for easier transport on primitive roads, are supported by lattice towers that provide greater stability in this earthquake- and hurricane-prone region.

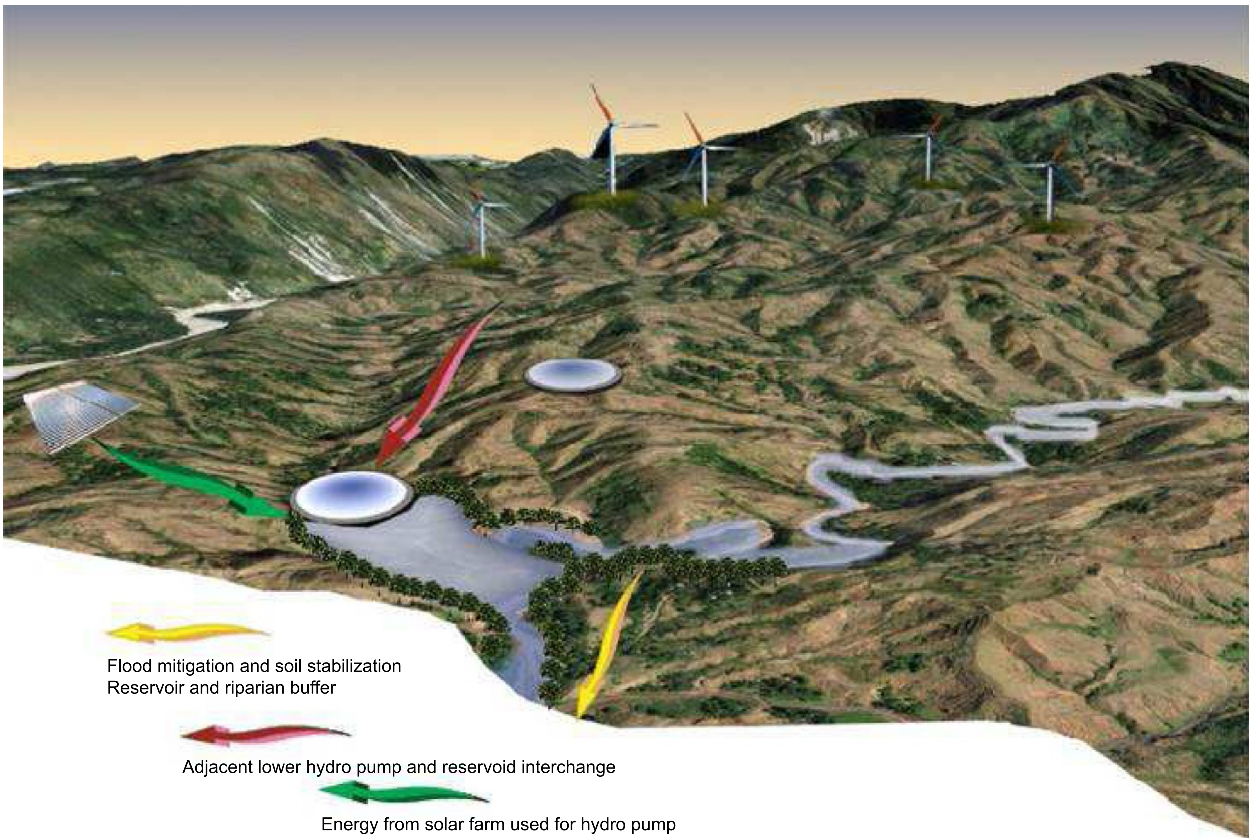

Figure 4 **Energy system co-location benefits.**

The GEM model assumes a long-term phased approach to 24/7 power. The electrical consumption planned per household is calculated initially as quite minimal; it covers basic energy services, allowing for night illumination, and the operation of small pumps for drinking water, radio and other small appliances including cell phone charging. Community nodes and hubs are more energy intense and require power sufficient for small refrigerators, laptop computers, basic medical equipment, and some income producing productive uses. In all, it is estimated that basic household services, along with commercial, community activities (schools and clinics) could be provided for on average just 50 kilowatt-hours per person per year, (Dilip Ahuja et al. 2008) for an annual project total of 5,000 MW hours.

Telecommunications upgrades

Even before the 2010 earthquake, Haiti's telecommunications infrastructure was generally underdeveloped (fixed line penetration at the lowest in Latin America and the Caribbean). However, the country's internet connectivity is comparatively robust as most Haitian internet service providers connect to the internet via satellite and are not reliant on undersea fiber optic cables. Also, despite the national poverty level, mobile phone coverage has grown rapidly. For that reason, the community nodes will provide capacity for cell-phone recharging and servicing as well as internet cafes.

Ecological restoration and enhancement

That valuable natural resources lie within its boundaries is a condition hardly unique to Léogâne. Just as elsewhere across Haiti, these ecosystem services represent one of its greatest assets. These, unfortunately, have been subject to degradation. Therefore, environmental stabilization and resource regeneration are necessary preconditions to the development of energy systems, agricultural improvements, industry and economic development. Stormwater management, flood control, soil stabilization and reforestation are critical prerequisites to the installation of the energy corridor. A program of river stabilization (repair of eroding banks and other flood control measures constructed with local materials) will alleviate hazardous deluges that occur during tropical downpours. New reservoirs located upland will store stormwater for irrigation. Riparian buffering, described below, will help reinvigorate damaged marginal areas, while the introduction of new agriculture, agroforestry, aquaculture practices, and the new rural settlements supporting them, will stabilize the topography and restore hydrological systems.

The delta Restoration of the imperiled coral reefs and mangroves, along with flood mitigation and bank restoration, is imperative to re-provisioning ecosystem services. Mangrove restoration must take place first so as to protect fragile corals implants that act as filtering systems, trapping debris and silt, balancing nutrient loads. Mangroves protect coastal zones from the impacts of major weather events. Reforestation and riverbank reconstruction will further reduce outflows of sediments and must be advanced with the delta restoration. Secondly, coral reefs, which take decades to build, have a vital interconnected role and must be quickly cultivated to also serve as storm surge barriers, while they rebuild local biodiversity. A promising artificial platform system called the "Reef Ball"™ is recommended for reef regeneration (The Reef Ball Foundation-Designed Artificial Reefs). It consists of a perforated concrete form with plugs of healthy new coral fragment inserts placed on the ocean floor in suitable habitat which can be economically utilized to speed the repopulation process. Mangroves can be planted in biodegradable baskets using a range of salt-tolerant and saline resistant species based on local conditions.

Riparian buffers The riparian corridors along the Momance and Rouyonne were former oases of ecological diversity. Stripped of native vegetation, the eroded riverbank must be rebuilt to confine river flow. The middle zone, bordering the mountainous highlands and the alluvial plain, is ill-equipped to manage flooding, resulting in soil loss from agricultural lands and damage to human settlements. Riparian restoration within a demarcated corridor between 50 to 300 feet wide will recreate vegetated and forest buffer strips and patches that armor the riverbank to absorb floodwaters and slow erosion. Through pollutant removal and temperature moderation downstream, marine biodiversity and water quality will be restored. These new riverine habitat corridors will also aid in species migration across adjacent developed landscapes. During initial restoration, land holdings must be restructured along these rivers, including no-trespassing conservation zones and a less stringent long-term management system developed with local input.

Reforestation and agroforestry In addition to the soil retention and ecosystem services returned through restored riparian buffers, trees and plantings are reintegrated using 'agro-forestry' models. Proposed intercropping of trees with food plants will foster stewardship while increasing land productivity through crop-shading and nutrient exchanges. Fruit production, timber from jatropha trees, vertiver grasses and coir industries can be integrated with adjacent irrigation channels to boost agricultural productivity and local enterprise. The integration of agroforestry is both economically and ecologically vital for regeneration (Collier 2009). Local inhabitants must be able to benefit while enabling ecological services to flourish.

Upland reservoirs New reservoirs will be constructed at higher elevations in the energy corridor for flood mitigation and water storage. Independent of the pumped-hydro storage system, these reservoirs (875 m^3 and 220 m^3 capacity for the Momance and Rouyonne Rivers respectively), will divert floodwaters. Freshwater drawn from this impounded source will be also used for local crop irrigation. Micro-turbines placed within these channels will provide power to local farmers in rural areas not serviced by the micro-grid. New 100-foot riparian buffers within this upland zone, containing an estimated 380,000 trees, shrubs and grasses combined with riprap from concrete debris, will stabilize the soil.

Other integrated services

Transportation As part of the integrated services development, improvements to roadbeds and associated stormwater drainage are vital to support the installation and upkeep of new infrastructure and spur economic development. Concrete pavers such as ones currently used in Léogâne are recommended for surfacing main and side street roads and plazas in the city center, as these are pervious to water and easy to repair. For resurfacing peripheral roads, application of lime-based soil stabilizers renders a more reliable pavement with low environmental impact at low cost. Such improvements can serve heavier traffic, including small vehicles moving collected waste to a new 'eco-industrial park' (defined below).

One of the major service points also serves as a multimodal transportation center: a dedicated hub located on one of Haiti's main highways just a short walk from the civic center. The station will accommodate buses, motorcycles, personal motor vehicles, and bicycles and has a small, attached market. It will be linked by new sidewalks, with pick-up and drop-off areas to improve pedestrian safety. Attached to the waiting area and public restrooms is a biodigester (see below) stationed to also receive large deposits of agro-waste delivered along the main road from outlying areas for transfer to the eco-industrial park.

Waste management Waste is an unrealized resource, its management central to local economic revitalization. It creates employment, fosters community involvement and promotes environmental stewardship. Proper refuse management reduces water supply contamination as well. A comprehensive proposal for Léogâne's waste diversion was developed that separates plastics, organics, metal and wood for recycling. It includes a new on-site processing facility, along with storage, transport, and connections to the large scaled biodigester and related generation facility (see An Eco-Industrial Park for Léogâne below). A mechanism to incentivize citizens to deliver sorted materials to the collection and pick-up points will be overseen by a new collection administration system. An educational campaign inculcating the benefits of resource conservation will also be vital for implementation.

Waste-to-biogas Seventy-five percent of Haiti's total waste stream is organic, comprised of crop residuals and other biomass, along with food and other domestic waste (Booth et al. 2010). It constitutes a largely untapped resource. The plan calls for a distributed biogas production system made up of strategically placed and variously scaled biodigesters (small for a cluster of dwellings, to larger community-scaled units). These biodigesters rely on slow anaerobic digestion that yields methane from organic human and animal waste mixed with agro-residuals. This is converted into useful biogas and a residual soil amendment byproduct. Benefits include production of a new fuel source for cooking or for additional electricity generation; improved sanitation and public health; greenhouse gas reduction, and increased farm yields, along with job creation.

An eco-industrial park for Léogâne Léogâne sits in an agricultural region long renowned for sugarcane production, Haiti's second largest cash crop after coffee. Yet in recent years, production and profits have faltered and Haiti has become a net importer of sugar from South America (Nienaber 2010). Léogâne now has one of the lowest yields for sugar cane in the Western hemisphere, with a range of 8 to 40 MT per hectare, compared to 85 MT in other parts of Haiti or Latin America (Barjon 2011b). Revival of the sugarcane industry (along with restoration of local food production) is essential for Haiti's overall recovery. Better management of existing resources and development of new markets would restore production to historic levels. A resurgent cane industry will restore much-needed jobs, as two-thirds of the Haitian work force and 25% of GDP production has remained in agriculture (Eberhard et al. 2010).

Léogâne's sugarcane production can be increased through more efficient management of existing resources as well as repair and expansion to the local processing facility, the Darbonne Sugar Mill. Additional resource efficiency can be gained through biodigestion of bagasse, the fibrous byproduct of cane processing. The biogas extraction method has a higher energy capacity than simple bagasse combustion, which is a source of pollution. The process also co-produces a high quality fertilizer. Such an integrated resource management approach makes use of unrecognized assets, while reducing reliance on expensive fossil fuel fertilizers and potentially boosting agricultural yields (Piasecki 2013). Extensions to the Darbonne Mill property would effectively turn it into an eco-industrial park. Colocation of an industrial-scaled biodigester at the sugar mill would provide secondary or stand-by biogas cogeneration in Léogâne. The bagasse/biodigester upgrade can be coupled with Léogâne's collected organic waste, delivered and stored on-site. This new co-generation system would have a capacity of 31.1 MW (Brown & Ward 2012). Plastic waste would also be processed as a complementary use in this eco-industrial park, recycled into lightweight compressed bricks for local use.

Discussion

Challenges and next steps

This proposal was built around the regulation of distributed renewable energy with the pumped-hydro storage as its lynchpin. To operate effectively, local environmental conditions must be stabilized. In addition construction must be staged to maximize resources. There are technological challenges as well. Pipelines must be protected from corrosion. The PHS water being exchanged requires filtration. The upland reservoirs will also need a measure of protection against sediment accumulation, a serious consequence of deforestation.

Successful ecological restoration will be contingent on temporary or permanent land acquisition. Stable administration and governance are essential for the necessary adjustments to land ownership and/or the creation of easements, complex social and financial transactions for Haiti. For fair distribution of services, placement of infrastructure assets cannot be done piecemeal, but rather systematically and according to a codified system such as GEM. Implementation of GEM's uniformity and modularity will require local, departmental and national cooperation.

A sophisticated understanding of local values and culture will be critical to program delivery. Particularly in Haiti, success or failure will depend upon the quality of local engagement as well as a commitment to local employment. The plan envisions an extensive stakeholder engagement process, which develops infrastructure based on input of local inhabitants, while conveying information about consumer responsibilities and costs. Long-term maintenance of these systems will demand skilled administrative and enforcement personnel. Therefore, a central strategy of GEMi, which will be necessary to implement this proposal, is to help train a workforce for the systems. Creating general awareness of the link between natural resources and infrastructure services is critical. This, along with technical training are GEMi cornerstones, not just for sustainable infrastructure, but ultimately sector-wide to balance short-term needs for water, food and shelter with investment in long-term. Given Haiti's history of electricity "piracy," it is also imperative to maintain the security of infrastructural components. The logistics of installing, maintaining and protecting expensive alternative energy infrastructure demand ongoing staff and security presence.

Creating and maintaining local political will and the capacity to coordinate with national ministries and other resources constitute the primary challenges to the plan's implementation. In-depth meetings with local leaders at all levels of governance and direct engagement with community members will be essential. Education will also be pivotal for acceptance of the paradigm shift involved in cross-sector integration. In many ways, Haitians are ready for this transition, given the failure of many infrastructure investments to date. A related challenge will also be first world buy-in to new infrastructural regimes implied by the integrated and autonomous ecodistrict—one designed with context sensitivity, with local input and for local self-reliance.

Financing will be an obstacle for integrated infrastructure systems, as it requires coordination of resources and personnel from across what are traditionally 'siloed' ministries. Funds sourced from the international community are also needed for the initial outlays, while the program embeds plans for self-sufficiency after initial support is withdrawn. Estimations of lifecycle costs and comparisons between conventional fossil fuel (coal or gas) and the proposed alternative energy systems are not meaningful here since all fuel sources must be imported by this island nation. While currently, PetroCaribe provides a very generous rate to Haiti that allows for a 25 year payback period with 2% interest, (Jacome 2011), the Government of Haiti lacks sufficient credit to ensure a competitive fuel supply for the long-term. Costs for solar PV farms installed in Haiti would likely incur a 30 to 40% premium over U.S. costs due to charges for shipping, tariffs (Gregory 2011b) and transport to hard-to-access locations. Installation of a smart-grid energy network is more competitive for Haiti (as other emerging economies that lack existing energy infrastructure) and would provide a significant leap forward for this energy-impoverished nation. Biomass digesters are also likely to be cost effective given the tandem social and economic benefits of also providing a solid waste management system over and above a supplementary energy system. The cost benefits for natural systems regeneration are significant. The outlay for upland ecological restoration is likely to be more than offset by eliminating future loss of life and property from seasonal and hurricane flooding. The natural systems afford a measure of resilience where none currently exists.

Conclusions

Substandard infrastructure must be redressed in the recovery from major disasters and in the development of sustainable models (Kijewski-Correa et al. 2012). Numerous opportunities exist throughout the island of Haiti and elsewhere for replication of a "whole systems," integrated infrastructural approach. Most of the proposed technologies and strategies are adaptable to areas with available natural resources. In Haiti, where simply meeting the daily needs of the population is an extraordinary challenge, the creation of relatively low cost, integrated, self-reinforcing and resilient solutions can hopefully launch long-term self-reliance and economic development. Elsewhere, Small Island Developing States (SIDS) might utilize similar concepts, adapting them to local geography, meteorology and ecology as a pathway to sustainability. SIDS additionally face enormous stresses from climate instability. Therefore they can be at the forefront in adopting renewable technologies for both climate mitigation and adaptation purposes.

Vulnerability stems from inadequate knowledge as well as deficient resources to apply that information (Kijewski-Correa & Taflanidis 2011). This proposal builds capacity and resiliency through applied practical knowledge of resources, their interdependencies, and by optimizing their reciprocities. Various components of this proposal may find more universal application. Sector integration is both common sense and necessary in areas with limited resources for development. The restoration of ecosystem services, renewable power systems designed around the energy/water/waste nexus, and the use of modular and economic nodal service points, provide a powerful grounding strategy useful in many developing and even developed areas. Though yet untested, it represents a logical, and perhaps revolutionary next step towards sustainability from which the developed world too may draw lessons.

Abbreviations

EDH: Electricité d'Haïti; GEM: Global Energy Model; GEMi: Global Energy Model Institute; KOICA: Korea International Cooperation Agency; NGO: Nongovernmental Organization.

Competing interests

Miriam Ward was employed by the Global Energy Model Institute from January 2012 to November 2012.

Authors' contributions

HB led both the study and design development with the assistance of MW. Both authors read and approved the final manuscript.

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