Resource sharing among co-located firms—referenced in the industrial ecology literature as “industrial symbiosis”—engages traditionally separate industries in a collective approach to business and environmental management involving the physical exchanges of materials, energy, water, and byproducts. While industrial symbiosis is seen hypothetically as a win-win situation, there are few analyses of the economic and environmental consequences for the individual participants in multi-faceted exchanges. In this article, the nascent industrial symbiosis network in Guayama, Puerto Rico, is explored from environmental, economic, and regulatory perspectives of the individual participants and the community. A coal-fired power plant, owned and operated by the AES Corporation, draws five million gallons per day of process water from nearby sources thus avoiding freshwater withdrawals and, through steam sales, significantly reduces emissions from a nearby refinery. This article quantifies economic and environmental costs and benefits for the symbiosis participants, concluding that there are substantial benefits to engaging in symbiosis, although these benefits fall unevenly on participating organizations. Policy intervention can be a viable means of motivating more regular occurrences of resource exchanges among groups of firms.

I. Introduction

A cooperative approach to business-environment issues is a key aspect of sustainable development (1). Resource sharing among firms offers the potential to increase stability of operations, especially in supply-constrained areas, by ensuring access to critical inputs such as water, energy, and raw materials. Industrial symbiosis (IS), a sub-field of industrial ecology, is principally concerned with the cyclical flow of resources through networks of businesses as a means of cooperatively approaching ecologically sustainable industrial activity. Industrial symbiosis, then, has the potential to redefine industrial organization by pushing companies to think beyond individual firm boundaries to a broader systems level.

Research-To-Date. Current industrial symbiosis research is evolving along several frontiers: from engineering and modeling of resource flows among entities in place-based industrial ecosystems, to analysis of the business and planning dimensions of those systems. Existing literature has documented various examples of industrial symbiosis (for a literature review, see ref 2). Quantification has been primarily of a technical nature: for example, Nemerow (3) includes mass flow analyses and calculations for various material exchanges in industrial complexes but little economic or financial analysis. Some sources look particularly at economics and financing at the level of the eco-industrial park (4–6). Kincaid and Overcash (7) report economic and environmental savings for a series of potential exchanges between industries in a six-county region in North Carolina. Several authors state that cost or pollution reduction is a major factor in the exchanges, but the specific environmental and economic benefits of particular exchanges are not presented.

Lowe (5) specifically identifies the need for data on investments and required (financial) return from industrial symbiosis projects. While some parts of symbiotic exchange such as co-generation and water cascading have been thoroughly studied and linked to industrial ecology, these generally tackle analysis of a single resource only (8, 9). This paper contributes to the literature with detailed analysis of economic and environmental costs and benefits for a series of actual and potential exchanges in one municipality in Puerto Rico; identifies the drivers for these exchanges where possible; and suggests policy interventions, based on current practice, that could motivate more groups of firms to engage in symbiotic activities.

The most frequently cited instance of industrial symbiosis is in the small city of Kalundborg, Denmark, where a well-developed model of dense firm interactions was encountered. The primary partners in Kalundborg, including an oil refinery, power station, gypsum board facility, and a pharmaceutical company, share surface water, wastewater, steam, and fuel, and also exchange a variety of byproducts that become feedstocks in other processes. Estimated resource savings for the exchanges in Kalundborg are listed in Table 1. Additional estimates from Kalundborg suggest that $15M collective annual savings have been achieved, primarily on resources, from a total investment of $90M (10). Total savings through 2002 are estimated at $200M, but detailed analysis to support this conclusion has not been performed (11). The achievement of high levels of environmental and economic efficiency has also led to other collective benefits involving personnel, equipment, and information sharing. The critical lesson from the Kalundborg symbiosis concerns the evolution of exchanges within a network—the Kalundborg case was not centrally planned and did not unfold all at once but evolved over the last forty years as a series of bilateral contractual arrangements between firms (12).

Quantifying Benefits. Much analysis has centered on environmental costs with less attention to benefits. The environmental benefits of industrial symbiosis are quantified by measuring the changes in consumption of natural resources, and in emissions to air and water, through increased cycling of materials and energy. The economic

<table>
<thead>
<tr>
<th>TABLE 1. Estimated Resource Savings at Kalundborg*</th>
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<tbody>
<tr>
<td>groundwater savings 2.1 million m³/y</td>
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<tr>
<td>surface water savings 1.2 million m³/y</td>
</tr>
<tr>
<td>oil savings 20,000 tons/y</td>
</tr>
<tr>
<td>natural gypsum 200,000 tpy</td>
</tr>
</tbody>
</table>

* Source: ref 10.
benefits of IS are quantified by determining the extent to which companies cycling byproducts can capture revenue streams or avoid disposal costs; those businesses receiving byproducts gain advantage by avoiding transport fees or obtaining inputs at a discount. In some cases, less tangible benefits are obtained from working cooperatively with neighbors, such as improving reputation and facilitating the permitting process.

II. Context for Analysis: AES Power Plant, Guayama

An evolving network of interfirm exchanges in Guayama, Puerto Rico provides a tractable illustration from which to analyze the environmental and economic case for IS. Puerto Rico is a commonwealth of the United States, thus sharing laws and business practices. The municipality of Guayama, on the southeastern coast of Puerto Rico, measures 169 km², and has a population of approximately 42,000. Before 1940, Guayama was primarily an agricultural economy with some light manufacturing. After a period of light industrialization in the 1940s and 1950s, the current industrial profile began developing.

In 1966, Phillips Petroleum opened a petrochemical refinery, which today is owned by a partnership between Phillips and Chevron. In the 1980s a number of pharmaceutical companies opened manufacturing plants in the Jobos Barrio (neighborhood): Baxter (1981), Wyeth (1985), IPR Astra Zeneca (1987), IVAX (pre-1994). There are also light manufacturing businesses in the industrial zone: Lata Ball (aluminum can manufacturing); Alpha Caribe (plastic bottle manufacturing); PR International (heavy machinery repair); and Colgate Palmolive (oral care and detergents manufacturing). In November 2002, AES Corporation brought online a 454 MW coal-fired power plant with atmospheric circulating fluidized bed (ACFB) technology.

Guayama hosts many of the same industries as Kalundborg: a fossil fuel power generation plant, pharmaceutical plants, an oil refinery, and various light manufacturers. Current exchanges in Guayama include the new AES coal-fired power plant using reclaimed water from a public wastewater treatment plant (WWTP) for cooling, and providing steam to the oil refinery (Figure 1). Additional steam and wastewater exchanges are under negotiation between neighboring pharmaceutical plants, the refinery, and the power plant. Beneficial reuse of the coal ash has begun as a means of stabilizing some liquid wastes. An analysis follows of existing and potential exchanges in Guayama with the power plant and refinery as critical participants. Costs and benefits to each company are explored as well as regulatory, political, and other relevant factors.

From its founding in 1941 until the 1990s, the Puerto Rico Electric Power Authority (PREPA or AEE by its Spanish acronym) built and owned essentially all of the power generation and distribution facilities on the island. PREPA has maintained control of electricity distribution; however, in the face of United States energy restructuring and increasing need for power generation, in the 1990s PREPA opened this area to proposals from independent power generators. In 1978, a federal law was passed in the United States to encourage the use of renewable, nonpolluting methods of power generation. The Public Utilities Regulatory Policies Act (PURPA) requires a public utility (such as PREPA) to purchase electricity from small producers, and from independent producers that maintain qualifying status, if the price of the electricity is below the utility’s own marginal costs of production. For an independent generator to maintain “qualifying facility” (QF) status, the facility must use at least 5% of its energy output for products other than electricity: steam and desalinated water are common cogeneration products. When PREPA opened to proposals from independent generators, it required that all proposed facilities qualify as co-generators under PURPA. In the 1990s, two independent projects were approved as QFs: AES Guayama, and EcoElectrica, a natural gas combined cycle plant in the southwestern part of the island producing electricity and two million gallons per day of desalinated water.

The siting decision for AES Guayama, as described in its environmental impact statement, was based on a number of factors (listed in Table 2), each weighted on a scale of 1–10 with 10 being the most important. Of the 4 factors weighted as “10s,” two embody the resource-sharing concepts of industrial symbiosis: “proximity to steam user,” and “sufficient water supply.” Both of these criteria proved challenging to meet. The availability of industrial hosts with sizable steam and/or process heat requirements, critical for AES to achieve QF status, has been anticipated to be a limiting factor for co-generation in general (14). A steam host was identified at only two of the five sites screened: the Chevron Phillips refinery in Guayama, and Sun Oil de Puerto Rico in Yabucoa. The lack of a suitable water supply has prevented the siting
and permitting of new power plants in Puerto Rico, including a somewhat comparable plant in the western city of Mayaguez (15), and elsewhere in the United States (16). The criterion of a sufficient water supply was further interpreted in AES’s environmental impact statement as requiring the “elimination of the use of seawater and minimizing the use of potable water” (17). The water supply criterion was satisfied by locating with a wastewater treatment plant (WWTP) for reclaimed wastewater input. Of the five sites evaluated, sufficient wastewater was identified only at Guayama.

III. Quantifying Steam, Water, and Other Exchanges

Steam. For AES in Puerto Rico, finding a steam host was a necessity owing to PREPA’s requirement for PURPA QF status. AES Guayama sited next to a Chevron Phillips refinery and built the pipeline infrastructure necessary to provide steam to Chevron Phillips. In this section, the costs and benefits of the steam host agreement are analyzed from an environmental perspective in terms of net air emissions, and from the economic perspective of both AES Guayama and Chevron Phillips, independent of tax considerations. In considering AES cogeneration via coal combustion, and Chevron Phillips generation via no. 6 fuel oil combustion, off-site environmental impacts such as upstream extraction and transportation of both fuel oil and increased inputs to AES Guayama (coal, limestone, lime, water, etc.) are not inventoried (18).

Net Emissions from Steam Exchange: Calculation. In the mid-1990s when AES was seeking a steam host, the Chevron Phillips (then just Phillips) petrochemical refinery was producing aromatic hydrocarbons (paraxylene, cyclohexane, and orthoxylene) and gasoline. Process steam was generated on-site with four industrial boilers burning high-sulfur (2.5%) no. 6 residual fuel oil (19). Two of the four boilers were to be replaced by steam from AES Guayama (20). In 2001, the Chevron Phillips refinery began an extensive reengineering process. Although the actual amounts of steam purchased have varied and will continue to do so—especially with reengineering—this calculation is based on the amount originally contracted because AES Guayama is currently committed to providing up to that amount to Chevron Phillips at any time: 105 thousand pounds per hour (kph) of high-pressure process steam and 80 kph of low-pressure process steam. As of early 2004, the Chevron Phillips facility is producing a new product line with reduced process steam needs owing to changes in product lines: an average of 60 kph of high-pressure and 50 kph of low-pressure process steam (21). Post-reengineering without the steam exchange, two boilers would still have been required to provide Chevron Phillips process steam; currently, all four boilers are offline. Thus, despite reengineering, the comparison of two boilers to AES steam production is valid. Reinhardt (22) further discusses the challenges associated with choosing the relevant starting point for assessing relative improvements such as this.

The net emissions impact calculation must account for both the decrease from decommissioning two industrial boilers at Chevron Phillips, and the corresponding increase in air emissions generated by AES Guayama to produce process steam for Chevron Phillips. Emissions of five pollutants (SO$_2$, NO$_x$, PM$_{10}$, CO, and CO$_2$) resulting from the boilers at Chevron Phillips were estimated using two sources: a report for the specific Chevron Phillips industrial boilers within the environmental filings for AES Guayama (23); and the EPA Air Pollutant Emissions Factors for generic industrial boilers of a size suitable to produce the same amount of steam (24). Specific boiler information (such as size, costs, and steam output) was not available directly from Chevron Phillips. The weight in short tons per year (tpy) emitted of each compound was calculated from the emission rates by assuming that the boilers operated the same number of hours per year as AES to provide the contracted amount of steam. Results of both calculations are presented in Table 3.

The corresponding increase in air emissions generated by AES Guayama to produce process steam for Chevron Phillips was estimated based on heat balance information provided by AES Guayama. The fractional portion of emissions resulting from steam generation is shown in column number 4 of Table 3. The net impact is the additional AES Guayama emissions less avoided Chevron Phillips emissions, listed in the last column for SO$_2$, NO$_x$, PM$_{10}$, CO, and CO$_2$. Data indicate a substantial reduction in the emissions of SO$_2$, NO$_x$, and PM$_{10}$: the net reduction of 1978 tpy of SO$_2$ emissions is almost 11 times the total SO$_2$ emissions from the AES Guayama plant as a whole. Both CO and CO$_2$ emissions increased based on the inherent chemistry of switching from oil to coal. On the basis of EPA AP-42 emission factors for coal and fuel oil, and industry estimates for fuel input for steam production, 1000 pounds of steam generated by burning no. 6 fuel oil will generate 195 pounds of CO$_2$ versus 332 pounds generated from coal (24, 25).

With respect to the economic impact of the steam exchange on both Chevron Phillips and AES, the actual steam price negotiated by AES Guayama and Chevron Phillips is not public information, so the various costs involved (Chevron Phillips’ avoided costs from the industrial boilers and AES’s costs for producing the process steam) are estimated, as are the revenues, based on interviews and appropriate engineering literature.

For Chevron Phillips to produce 185 kpph of process steam from 2 industrial boilers (1 boiler producing 80 kpph at 200 psi and the other producing 105 kpph at 700 psi) would require on the order of 11.7 million gallons per year of no. 6 residual oil according to the Council of Industrial Boiler Owner’s (CIBO) research (25), and assuming (as with the emissions calculation) the boilers run 6773 h per year, AES Guayama’s expected average capacity level. The cost associated with industrial boilers is approximately $1/gallon of fuel delivered and fired (25). Thus, we may estimate Chevron Phillips’ avoided costs at approximately $11.7M, and Chevron Phillips will have a net economic gain from the steam host relationship at any steam price less than $9.35/k lb. stream delivered. Economic results for Chevron Phillips are summarized in Table 4.

For AES Guayama, the costs involved in providing the contracted amount of steam include the fixed, one-time, up-front $5M to build the steam lines to Chevron Phillips, and the variable costs associated with the increased inputs to the AES Guayama boilers. AES Guayama’s material inputs are scaled up by 7.3% to produce 210 kpph process steam at the QF amount. Chevron Phillips contracts for 63.8% of that capacity, thus we attribute 7.3% x 0.638 = 4.7% of material input costs at full process steam to the Chevron Phillips contract, estimated at $2.72M per year for variable expenses. Based on CIBO calculations (25) and interviews, 25% is added for operations, maintenance, and overhead; the overhead

| TABLE 2. Site Screening Criteria Used by AES, with Assigned Weighting Factors (on a Scale of 1−10, with 10 Being Most Important)* |
|---|---|
| proximity to steam user | 10 |
| water supply | 10 |
| proximity to port | 10 |
| conditions that minimize environmental impact | 10 |
| heavy industrial zoning | 9 |
| far from residential areas and communities | 7 |
| land outside of Zone 1 floodplain | 7 |
| access to transmission grid | 6 |
| highway access | 5 |

* Source: ref 19.
TABLE 3. Comparison of Estimated Emissions from Steam Production by Chevron Phillips and AES Guayama

<table>
<thead>
<tr>
<th>Species</th>
<th>Emissions (tpy)</th>
<th>1. EIS rates calculation</th>
<th>2. EPA factors calculation</th>
<th>3. Average of 2 methods (tpy)</th>
<th>4. Emissions from steam contracted by Chevron Phillips (tpy)</th>
<th>5. Net emissions from steam production by AES Guayama (tpy) (Column 4 — Column 3)</th>
<th>6. Net percent increase (decrease) in emissions from steam production by AES Guayama</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO2</td>
<td>1592</td>
<td>6775</td>
<td>2381</td>
<td>1967</td>
<td>9</td>
<td>(1978)</td>
<td>(99.5)</td>
</tr>
<tr>
<td>NOx</td>
<td>224</td>
<td>6775</td>
<td>275</td>
<td>250</td>
<td>39</td>
<td>(211)</td>
<td>(84.4)</td>
</tr>
<tr>
<td>PM10</td>
<td>105</td>
<td>6775</td>
<td>153</td>
<td>129</td>
<td>6</td>
<td>(123)</td>
<td>(95.3)</td>
</tr>
<tr>
<td>CO</td>
<td>20</td>
<td>6775</td>
<td>29</td>
<td>25</td>
<td>40</td>
<td>15</td>
<td>60.0</td>
</tr>
<tr>
<td>CO2</td>
<td>159,000</td>
<td>6775</td>
<td>143,000</td>
<td>151,000</td>
<td>202,000</td>
<td>51,000</td>
<td>33.8</td>
</tr>
</tbody>
</table>

TABLE 4. Chevron Phillips Estimated Cost to Produce Process Steam and Estimated Steam Cost

- approximate cost for fuel oil, delivered and fired ($/yr) = 11,700,000
- estimated steam cost ($/k lb.) = 2.75

TABLE 5. AES Guayama Estimated Cost to Provide Process Steam to Chevron Phillips

- cost for infrastructure ($/yr) = 43,700
- variable costs, estimate ($/yr) = 2,720,000
- estimated overhead, O&M ($/yr) = 750,000
- total cost to provide process steam ($/yr) = 3,440,000
- estimated steam cost ($/k lb.) = 2.75

* Numbers do not add due to rounding to 3 significant digits.

rate will vary with each plant’s cost accounting calculations. In addition, if the $5M infrastructure cost is paid off over the 25-year life of the contract at 9.5%, the rate for a recent AES Guayama debt offering, there is an additional $43,700/year charge, for a total materials, overhead, and infrastructure cost of approximately $3.42M (see Table 5) (26). This cost would be recouped for any steam price exceeding $2.75/k lb., although this calculation does not incorporate the profit AES requires. The difference between the costs of production ($2.75/k lb. for AES and $9.35/k lb. for Chevron Phillips) creates an estimated $2.87M economic surplus (based on 185 kph of steam x 6775 h); its distribution will depend on the price negotiated between AES and Chevron Phillips, and on the actual costs to each of the companies for the production of steam.

Summary. Steam Exchange. Prior to entering a steam-host agreement with AES, Chevron Phillips generated its own process steam with four industrial boilers burning high-sulfur no. 6 fuel oil. Receipt of steam from AES Guayama obviated two industrial boilers at Chevron Phillips, and AES Guayama gained QF status to generate electricity in addition to the process steam. As described above, this is a win-win situation: Chevron Phillips wins because the steam from AES Guayama is cheaper than what it was generating onsite; AES Guayama wins because it gains QF status as well as some (we assume) profit from selling steam to Chevron Phillips, based on the differential of Chevron Phillips’s cost to produce steam of $9.35/k lb. and AES’s cost of $2.75/k lb.; and the community and local environment win because the symbiotic relationship substantially reduces net air emissions of SO2, NOx, and PM10. One drawback is the substantial increase in CO2 associated with global climate change.

Reclaimed Water Exchanges. There are two dimensions along which power generators can reduce their freshwater use: reduce the total volume needed by recirculating cooling water instead of passing once through; and replace freshwater with reclaimed water. Environmental concessions, such as using reclaimed water for cooling and recirculating cooling water, are becoming more common for new power plants. Increasingly stringent regulations of the U.S. Clean Water Act discourage once-through cooling for power plants to protect the aquatic species affected by the heated water discharge (27). Two different motivators for water exchanges in Guayama are discussed: the resource limitation that gave rise to the siting of the AES power station near a wastewater treatment plant; and the economically driven opportunity for potential savings for nearby industrial facilities.

Resource Driven Water Exchange: PRASA WWTP, AES Guayama. Water resources have been identified as a top environmental concern in Puerto Rico by the director of the EPA’s Caribbean Division, Region II (28). Along the south coast, where Guayama is located, water resources have been a concern since the mid-20th century, and current supplies show signs of deterioration. The surface water system suffers from inefficient infrastructure and poor water quality (28); and the groundwater has been contaminated by industrial discharges and overdrawn by agriculture and industry, resulting in saltwater encroachment into the coastal aquifer (29).

As a result of the water resource limitations, the siting criteria for AES (see Table 2) included proximity to a reclaimed water source. The Guayama wastewater treatment plant (WWTP) performs secondary treatment on approximately 5 million gallons per day (MGD) of municipal sewage; prior to the AES Guayama exchange, the effluent was discharged to the Caribbean Sea. AES uses water for two distinct purposes: approximately 1 MGD for boiler makeup and about 4 MGD for cooling water. Water used for boiler makeup must meet higher quality standards than that used for cooling water. The only water emitted by AES is in the form of vapor from the cooling towers. With the exchange in place, the WWTP reroutes its discharge to AES Guayama for use as cooling water, and approximately 4 MGD of extraction and discharge are avoided.

Economics-Driven Potential Water Exchanges. Wyeth Pharmaceuticals, a finishing and tableting plant just north of AES Guayama, is a third party in discussion with AES Guayama regarding a potential wastewater exchange. Wyeth currently discharges approximately 0.27 MGD of treated wastewater to the Guayama WWTP. Wyeth’s wastewater treatment and disposal has an approximate cost of $0.001/G for treatment and $0.002/G for disposal (30). By sending its treated wastewater directly to AES Guayama, Wyeth would avoid the $0.002/G discharge fee charged by PRASA. The facility also becomes eligible for “zero discharge” status, which may qualify the facility for additional flexibility in its relationships with regulators, as other byproduct exchanges have in the United States (31). Treatment is still required to the same level of quality for any water leaving Wyeth’s premises; tests are being conducted to determine whether any changes in treatment will be necessary for the exchange, although none are anticipated. Minimal additional infrastructure would be required since pipes already run from AES Guayama to Wyeth Pharmaceuticals.
Wyeth and AES to a central point at their shared boundary for discharge to PRASA.

The economic impact on AES Guayama of this exchange will not be known until the use for this wastewater is determined. If the wastewater is suitable for boiler makeup, it will replace freshwater AES Guayama currently purchases from PREPA at a cost of $1/kg; otherwise, it will replace a portion of the lower-value cooling water currently purchased from the Guayama WWTP at a cost of $0.20/kg. The net economic benefits of the ongoing exchange are listed in Table 6. Wyeth and AES Guayama each would benefit economically through avoided costs without significant additional expense; Wyeth’s savings would be substantially larger. AES Guayama is currently negotiating with two other industrial neighbors regarding potential reuse of their wastewater; flows could add up to 0.86 MGD or 17% of AES’s input needs, for a potential range of savings of $63,000–$314,000 per year, depending on AES’s use of wastewater.

Environmental Impact of Wyeth-AES Guayama Water Exchange. Wyeth’s discharged water ends up at AES Guayama, regardless of whether it comes directly from Wyeth, or via the Guayama WWTP; there is no change in final disposal. The net impact of this industrial wastewater exchange on freshwater extraction is not known until the use of the Wyeth water is determined: if the Wyeth discharge is clean enough to be used for boiler makeup, then it replaces fresh surface water AES currently purchases from PREPA. If it is suitable instead only for cooling water, then it circumvents the PRASA WWTP (reducing the amount purchased from PRASA) and does not affect extraction directly. Wyeth’s criteria for water exchange with AES Guayama are the same as the AES Guayama criteria for a steam host: “The potential users should possess economic stability and long-term permanence” (17).

Potential Resource Exchange: Ash. Generic power generation via conventional coal combustion creates byproducts referred to as coal combustion products, or CCPs. Coal combustion products include: fly ash, bottom ash, flue gas desulfurization (FGD) byproducts, and boiler slag. Roughly one-third of all U.S. utility fly and bottom ash, which constitutes the majority of byproducts, is reused, or about 24.4 million short tons per year (32). Disposal for a utility’s coal combustion products may be as high as 1–3% of its annual budget (33). The economic incentive for the generator to identify a marketable reuse for ash is clear: for those coal combustion products finding markets, revenues average $2/ton (34) as opposed to $10–15/ton disposal costs.

The most obvious environmental benefit of ash reuse is that its own disposal is avoided. It also displaces the use of other materials such as sand when it is reused—thus reducing extraction and, in some cases, transportation for the replaced material. As a concrete additive (its largest use), ash displaces cement thereby reducing the CO₂ emissions associated with the cement manufacture. As a raw material for cement manufacture, ash displaces the extraction of materials such as limestone and sand, and may displace some fuels as well (35).

At a coal combustion plant, bottom ash is created within the combustion chamber, and fly ash is collected after the combustion chamber. In traditional coal combustion plants, flue gas desulfurization (FGD) byproducts are created downstream from the combustion chamber by the reaction of SO₂ in the waste gases with lime injected into the scrubber. The scrubber’s output is primarily calcium sulfate, a precursor to artificial gypsum. In Kalundborg, this flue gas desulfurization byproduct is sold to a wallboard manufacturer as a substitute for mined gypsum. In the United States, the majority of flue gas desulfurization sludge is managed onsite in waste piles (32, p 48). The circulating fluidized bed (CFB) coal combustion technology in use in Guayama produces ash with a composition unlike that of traditional coal combustion plants. These plants do not produce separate high-sulfur byproducts: this circulating fluidized bed coal combustion burns limestone together with the fuel in the combustion chamber, where the majority of the SO₂ is captured. As a result, the circulating fluidized bed fly ash and bottom ash are substantially higher in sulfates and lime (unreacted CaO) than traditional ash. Feedlot stabilization, agricultural soil amendment, and coal mine reclamation have been identified as suitable applications for CFB ash (36–38).

AES Guayama’s annual ash production is about 220,000 tpy. AES Guayama faces an annual cost of ash disposal of about $3M, consistent with trade literature citing $10–15/ton disposal fees. This is their single largest operating expense, thus AES has a strong financial incentive to address disposal. In addition, AES Guayama is committed to off-island disposal of its ash; the ash can only stay in Puerto Rico for beneficial reuses. Initial plans for reuse investigated cement, soil stabilization, and ash rock for highway fill (17). AES Guayama has pursued the application of the ash slurry as fill material for high-voltage underground transmission lines (21) and late in 2004 began using some ash to stabilize liquid waste prior to landfiling (39).

The components of the CFB ash closely resemble the contents of Portland cement and its raw materials including CaO, SiO₂, Al₂O₃, Fe₂O₃, and MgO (40), thus the ash may be suitable for use as a raw material for cement. The high lime content of the ash matches the primary input to cement: limestone. The carbon content provides an additional fuel source. The high sulfur content is the primary drawback for use in the kiln. However, common additives to cement finishing mills (post-kiln) include the sulfurt-containing compound gypsum (40). Two cement kilns in Puerto Rico within 50 miles of Guayama produce an estimated 1500 tpy cement (41). If the AES ash were suitable as an additive at a rate of 6% of inputs (common for high-carbon ash (35) and for gypsum (40)) then approximately two-thirds of the ash could find beneficial reuse, at an avoided disposal cost for AES of $1.85M/year and potential revenue of $296,000/year.

IV. Discussion of Results

The economic and environmental impacts of existing and proposed materials, water, and energy exchanges among firms in Guayama, Puerto Rico have been presented. There is clear evidence of substantial public environmental benefit: for example, a 99.5% reduction in SO₂ emissions due to steam generation for Chevron Phillips is achieved, and AES avoids extracting 4 million gallons per day of scarce freshwater through the use of treated effluent from the wastewater treatment plant.

Economically, the analysis presented here suggests that the biggest financial winner is Chevron Phillips. By not having to operate its old boilers to produce steam, the company gains significantly through reduced operating costs, and,
based on those savings, negotiated an acceptable contract with AES for steam purchase. For AES, treated wastewater is not only available, but also is considerably less expensive than the cost of purchasing freshwater by some $1.2 million per year. In both instances, private benefits are achieved simultaneously with public ones.

Regulatory conditions, however, influenced both water and steam opportunities. With respect to water, recognizing southeast Puerto Rico as a dry area, the use of treated wastewater at AES was included as a condition in the siting agreement. This leads to another key finding concerning industrial symbiosis. Although AES does not appear to be the largest financial gainer (beneficiary) from the byproduct exchanges, in part because it incurs setup costs to receive wastewater and sell steam, AES gains in another critical way. It is reasonable to assume, having examined the history of this and other projects in Puerto Rico, that AES would not have achieved society’s “license to operate” without its willingness to engage in symbiotic activities. This can be taken literally as the necessary permits and figuratively as permission in a democratic society to carry out vital functions such as provision of energy and water in a broadly acceptable way.

From the two required exchanges of water and steam, it is evident that integration of industrial symbiosis criteria into the siting process is one way to protect natural resources such as water and air. A reasonable future policy direction, already begun in some areas, would be to require water reuse for new power plants and some type of combined heat and power generation. The electricity industry accounts for 39% of all freshwater withdrawals in the United States, second only to agriculture (16). To conserve this resource, power plants are facing increasingly stringent requirements on water use; some states and municipalities have denied siting permits due to lack of available freshwater; and the EPA has proposed regulations that could limit the amount of water used by power plants (16). Examples from the current literature of the pursuit of water reuse opportunities motivated by limited water resources come from such diverse geographic areas as Australia (42), China (43), and Israel (44).

Additional voluntary exchanges are under consideration to achieve private benefit or reduce private costs with respect to water and coal plant ash. Various industrial neighbors to AES are negotiating to send wastewater directly to the power plant; these wastewater exchanges do not displace extraction or disposal (assuming they are used for cooling water makeup, the most likely scenario) and the same wastewater would have arrived at AES via the WWTP in either case. Rather, additional wastewater exchanges are economically driven for the partners to avoid the cost of discharge to PRASA. Ash disposal is AES Guayama’s largest operating expense; thus the company is highly motivated to find alternative beneficial uses of the ash, but such an on-island opportunity must not violate the tangible and intangible aspects of its license to operate.

The industrial symbiosis literature can be interpreted to show that a single exchange is often the first step and that, as in Kalundborg, Denmark or in the case of Chaparral Steel in Texas, “trades beget trades.” (45) This pattern looks to be repeated in Guayama based on several requests, particularly for exchange of chemicals, now being evaluated by nearby firms. In essence, successful initiation of trading within colocated firms appears to bring a shift in thinking—a change in the dominant trajectory of firm individualism—creating a willingness to consider further trading. Given the nature of environmental and economic benefits identified in the case of Guayama with respect to air, water, and byproducts, it is reasonable to infer that those benefits, none of which are very unconventional, can be found in many other comparable situations.

The organizational hurdles may lack of information across firms, perception of high transactions costs across firms, insufficient trust or communication across firms, or lack of a regulatory push. Key, then, is catalyzing the early exchanges so that firms will be open to the potential benefits of additional ones when economically and environmentally desirable. The role of the private sector is critical in furthering industrial symbiosis (2). Yet, as in the case of Guayama, regional government action to foster wastewater reuse or national government action to encourage co-generation in PURPA, can also be powerful catalysts. Through selected policy interventions such as those described to reward wastewater reuse or additional use of waste heat, government action could advance symbiosis which, in turn, could bring additional public and private benefits in its wake.

Literature Cited

(11) Christensen, J. Presentation at Yale Industrial Symbiosis Research Symposium, January 9, 2004; New Haven, CT.
(19) Berrios, A. Former Director, Air Quality Program, Puerto Rico Environmental Quality Board; Interview March 22, 2003.