Economic and environmental impacts from industrial symbiosis exchanges: Guayama, Puerto Rico

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Abstract: Industrial symbiosis (IS) engages traditionally separate industries in a collective approach to competitive advantage involving the physical exchange of material, energy, water, and/or by-products. Although IS has been advocated as a business-friendly approach to environmental problems, there are few analyses of the financial and other business-related consequences for the individual participants in the exchanges. In this article, the nascent system of IS exchanges in Guayama, Puerto Rico, is explored from the environmental, business, and regulatory perspectives of the individual participants and the community. A coal-fired power plant built, owned, and operated by the AES Corporation is critical from the resource flow perspective with regard to uptake of water and sale of energy products. The article presents estimates of the economic and environmental costs and benefits for the symbiosis participants, concluding that there are substantial business reasons to engage in symbiosis, although the benefits fall unevenly on participating firms.

Key words: industrial symbiosis, cogeneration, by-product exchange, eco-industrial parks, environmental economics, business case for sustainability

I. INTRODUCTION TO INDUSTRIAL SYMBIOSIS

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 has the potential to redefine industrial organization by pushing firms to think beyond their boundaries. IS neither advocates nor eschews process level changes – rather, given the inputs and outputs of a process, IS intends to match input needs with outputs available, following the principle that one company's by-product can become another company's feedstock, thus reducing resource use at the system level.

Current IS 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 industrial symbiosis literature has documented various examples of IS [for a literature review, see 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 the economics and financing at the level of the eco-industrial park [4,5,6]. 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, USA. Several authors state that cost 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. The analysis presented here contributes to the ongoing discussion with detailed estimates of economic and environmental costs and benefits for a series of actual and potential exchanges in one municipality; and identifies the drivers for these exchanges where possible.

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 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.

The term "industrial symbiosis" was coined in the small municipality 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 by-products that become feed stocks in other processes. Estimated resource savings for the exchanges in Kalundborg are listed in Table 1. Results from Kalundborg estimate $15M collective annual savings have been achieved, primarily on resources, from a total investment of

$90M [8]. Total savings through 2002 are estimated at $200M, but detailed analysis to support this conclusion has not been performed [9]. The achievement of high levels of environmental and economic efficiency has also led to other collective benefits involving personnel, equipment, and information sharing. The Kalundborg symbiosis has evolved over the last forty years as a series of bi-lateral contractual arrangements between firms [10].

Figure 1: Industrial ecosystem at Kalundborg, Denmark: participants and flows.

Source: [11]

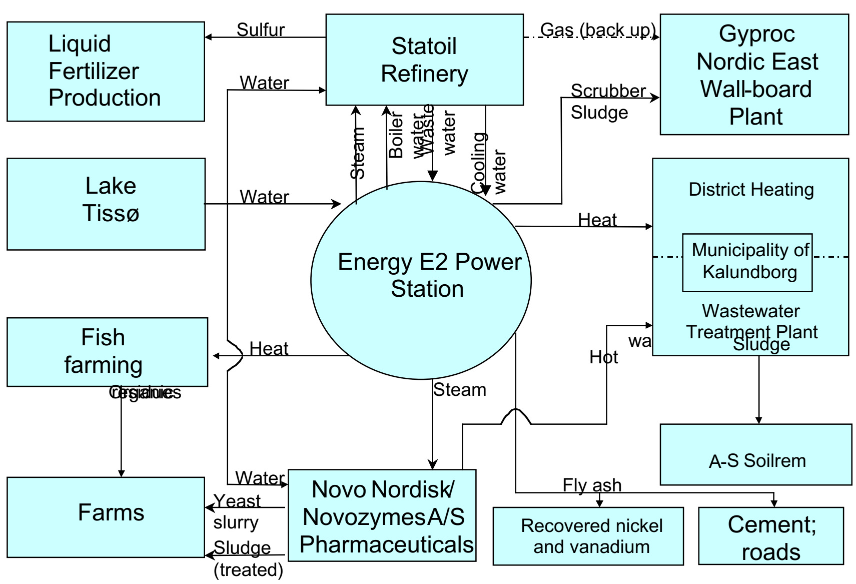


Table 1: Estimated resource savings at Kalundborg [8]

Ground water savings	2.1 million m^3 per year
Surface water savings	1.2 million m^3 per year
Oil savings	20,000 tons per year
Natural gypsum	200,000 tpy

II. CONTEXT AND SITING OF AES POWER PLANT, GUAYAMA

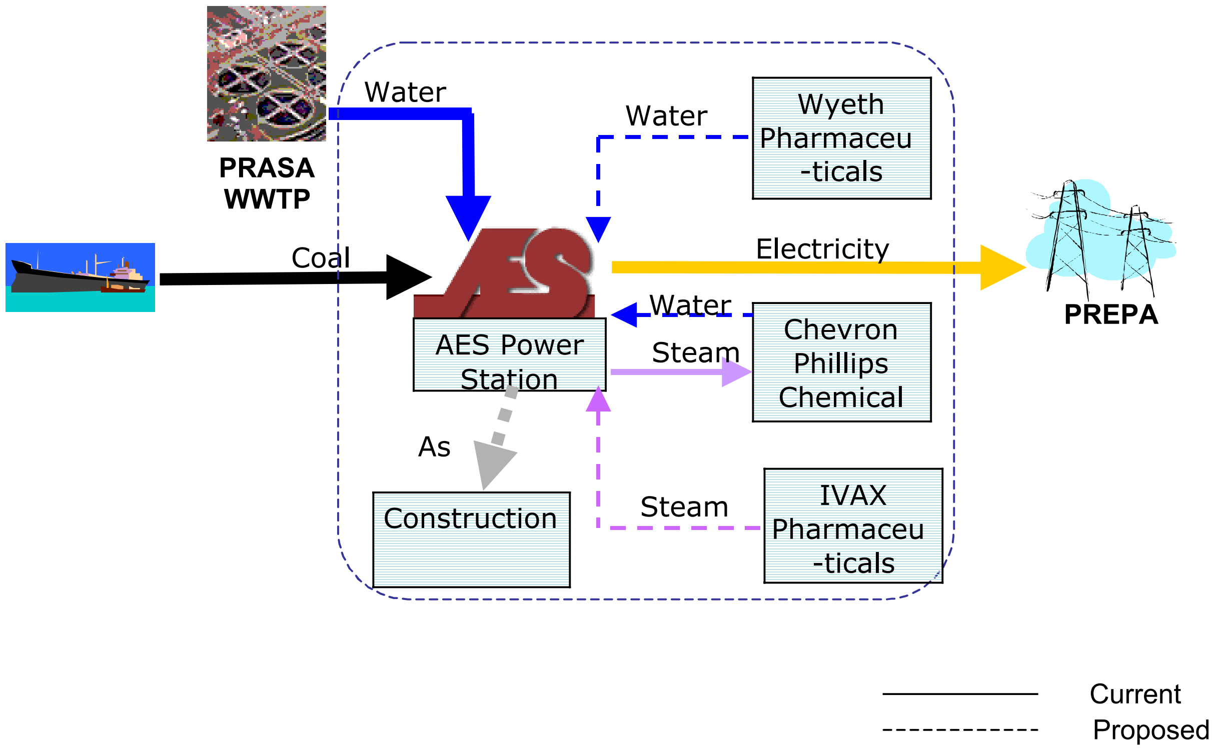
An evolving network of inter-firm exchanges in Guayama, Puerto Rico provides a tractable illustration from which to analyze the environmental and economic case for IS. Puerto Rico is a commonwealth of the United States, thus sharing many of its laws and business practices. The municipality of Guayama, on the southeastern coast of Puerto Rico, measures 169 km^2, 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-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).[i] 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 waste water treatment plant (WWTP) for cooling, and providing steam to the oil refinery. Additional steam and wastewater exchanges are under negotiation between neighboring pharmaceutical plants, the refinery, and the power plant. Beneficial reuse of the coal ash in construction is being explored. Using the construct of Kalundborg as a guide, an analysis of existing and potential exchanges in Guayama is presented 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.

Figure 2: Schematic of existing and proposed exchanges in Guayama, Puerto Rico.

Source: Adapted from [12]



Since 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 US energy restructuring and increasing need for power generation, PREPA opened this area in the 1990s to proposals from independent power generators. In 1978, a federal law was passed in the US to encourage the use of renewable, non-polluting 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, beverage quality CO_2, and desalinated water are common co-generation 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 [13]. A steam host was identified at only 2 of the 5 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 [14],[ii] and elsewhere in the US [16]. The criterion of a sufficient water supply was further interpreted in AES's environmental impact statement as requiring the "eliminat[ion of] the use of sea water and minimizing the use of potable water"

[17]. The water supply criterion was satisfied by collocating with a wastewater treatment plant (WWTP) for reclaimed wastewater input. Of the five sites evaluated, sufficient wastewater was identified only at Guayama.

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 Flood plain	7
Access to transmission grid	6
Highway access	5

Source: [17]

III. STEAM EXCHANGE

In the "model" system of Kalundborg, the Asnaes power plant provides steam to two large industrial neighbors: Novo Nordisk, a pharmaceutical manufacturer, and to Statoil, a petrochemical refinery. For these two recipients, the decision to contract for steam from Asnaes was made when they were faced with the prospect of upgrading and renovating their respective boilers; it was cheaper to buy the steam from Asnaes [18]. For the power plant, the steam exchange was an economic opportunity to use its waste heat. The exchange required an initial infrastructure investment for two miles of steam pipeline to connect the 3 participants that paid for itself in 2 years [18].

For AES in Puerto Rico, finding a steam host was essentially a "cost of doing business" 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. This analysis is not intended to be a complete life cycle comparison of the two steam generation methods (AES cogeneration via coal combustion, and Chevron Phillips generation via number 6 fuel oil combustion); a full analysis would include environmental impacts from upstream extraction and transportation of fuel oil and of increased inputs to AES Guayama (coal, limestone, lime, water, etc). The authors recognize the possibility (however counterintuitive) that a complete life cycle assessment of the two options could produce a different outcome [19].

<u>Net emissions from steam exchange: calculation</u>

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%) number 6 residual fuel oil [20]. Two of the four boilers were to be replaced by steam from AES Guayama [21]. 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 provide up to that amount to Chevron Phillips at any time: 105,000 pounds per hour (kpph) of high pressure process steam and 80 kpph of low pressure process steam.[iii]

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 5 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 [24]; and the EPA Air Pollutant Emissions Factors for generic industrial boilers of a size suitable to produce the same amount of steam [25]. Specific boiler information (such as size, costs, and steam output) was not available directly from Chevron Phillips. The 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 produce the contracted amount of steam. Results of both calculations are presented in table 3.[iv]

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 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 change from oil to coal.[v]

Table 3: Comparison of estimated emissions from steam production by Chevron Phillips and AES Guayama.

	Chevron Phillips Industrial Boilers Emissions			AES Guayama Emissions		
Emissions species	1. EIS emissions rates calculation (tpy)	2. EPA Emissions Factors calculation (tpy)	3. Average of 2 methods (tpy)	4. Emissions from steam contracted by Chevron Phillips (tpy)	**5. Net emissions** from steam production by AES Guayama (tpy) Column 4 minus col. 3)	**6. Net percent increase (decrease**) in emissions from steam production by AES Guayama
SO_2	1592	2381	1987	9	**(1978)**	**(99.5)**
NO_x	224	275	250	39	**(211)**	**(84.4)**
PM_{10}	105	153	129	6	**(123)**	**(95.3)**
CO	20	29	25	40	**15**	**60.0**
CO_2	159,000	143,000	151,000	202,000	**51,000**	**33.8**

Economic Impact of steam exchange: Chevron Phillips, AES Guayama

In this section the economics of the steam exchange is examined for each party. 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, the other producing 105 kpph at 700 psi) would require on the order of 11.7 million gallons per year of Number 6 residual oil according to the Council of Industrial Boiler Owner's (CIBO) research [26], and assuming (as with the emissions calculation) the boilers run 6775 hours per year, AES Guayama's expected average capacity level. The cost associated with industrial boilers is approximately $1/gallon of fuel delivered and fired [26]. 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# steam delivered. Economic results for Chevron Phillips are summarized in Table 4.

Table 4: Chevron Phillips estimated cost to produce steam and estimated steam cost.

Chevron Phillips costs to produce process steam	
Approximate cost for fuel oil, delivered and fired ($/yr)	11,700,000
Estimated steam cost ($/k#)	9.35

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% * .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 [26] and interviews, 25% is added for operations, maintenance and overhead; the overhead rate will vary with each plant's cost accounting calculations. In addition, if the $5M infrastructure cost is paid off over the twenty-five 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 below) [27]. This cost would be recuperated for any steam price exceeding $2.75/k#, although this calculation does not incorporate the profit AES requires. The difference between the costs of production ($2.75/k# for AES and $9.35/k# for Chevron Phillips) creates an estimated $8.27M economic surplus; 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.

Table 5: AES Guayama estimated cost to produce steam.

AES Guayama costs 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#)	**2.75**

* numbers do not add due to rounding to 3 significant digits

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 Number 6 fuel oil. Receipt of steam from

AES Guayama obviated 2 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-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 Phillip's cost to produce steam of $9.35/k# and AES's cost of $2.75/k#; and the community and local environment win because the symbiotic relationship substantially reduces net air emissions of SO_2, NO_x, and PM_{10}. One draw back is the substantial increase in CO_2 associated with global climate change.

IV. RECLAIMED WATER EXCHANGES

The electricity industry accounts for 39% of all freshwater withdrawals in the US, 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 and permits due to lack of available fresh water, 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 [28], China [29], and Israel [30]. There are two dimensions along which power generators can reduce their fresh water use: reduce the total volume needed by recirculating cooling water instead of passing once through; and replace fresh water with reclaimed water. Environmental concessions such as using reclaimed water for cooling, and recirculating cooling water are becoming part of the "cost of doing business" for new power plants [15, 31]. Increasingly stringent regulations of the U.S. Federal Clean Water Act also discourage once-through cooling for power plants to protect the aquatic species affected by the heated water discharge [31].

Two different motivators for water exchanges in Guayama are discussed in the following sections: the resource limitation gave rise to the siting condition for WWTP input for cooling water; and economics drove the industrial facility exchange negotiations.

Resource driven water exchange: PRASA WWTP, AES Guayama

Concern about groundwater availability has been identified as the initial driver of the Danish symbiosis [32]. The oil refinery, power plant, and pharmaceutical plant share surface water from a nearby lake in response to this condition; and the refinery and power plant share cooling water to reduce thermal pollution from water discharge to the fjord. Similar drivers exist for conserving water in Puerto Rico where water resources have been identified as a top environmental concern by the director of the EPA's Caribbean Division, Region II [33]. 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 [33]; and the groundwater has been contaminated by industrial discharges and overdrawn by agriculture and industry, resulting in salt water encroachment into the coastal aquifer [34].

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 boiler makeup and about 4MGD cooling water. Water used for boiler makeup must meet higher quality standards than 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 4MGD of extraction and discharge are avoided.

Economics driven potential water exchanges

Wyeth Pharmaceuticals, a finishing and tableting plant just north of AES Guayama across PR Route 3, is a third party in discussion with AES Guayama regarding a potential wastewater exchange. Wyeth currently discharges approximately 0.27MGD 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 [35]. 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 by-product exchanges have in the US [36]. 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; pipes already run from 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 fresh water 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 to $314,000 per year, depending on AES's use of wastewater.

Table 6. Economic impact of proposed Wyeth-AES Guayama water exchange.

Wyeth savings	
Amount of water exchanged	7.7 MG/mo * 12 mo/yr = 92.4 MG/y
Avoided cost, PRASA discharge fee	92.4 MG/yr * $0.002/G = $184,800/y
AES Guayama savings	
Avoided cost, cooling water use	92.4 MG/yr * $0.0.0002/G = $18,480/y
Avoided cost, boiler makeup use	92.4 MG/yr * $.001/G = $92,400/y

Source: [35]

<u>Environmental impact of Wyeth-AES Guayama water exchange</u>

Wyeth's discharged water ends up at AES Guayama, regardless 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 fresh water 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.

Preconditions for exchange

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]. In interviews with Wyeth, Wyeth is watching AES Guayama's financial situation while performing the necessary testing to prepare for the exchange [35].

V. POTENTIAL RESOURCE EXCHANGE: Ash

Generic power generation via conventional coal combustion creates by-products referred to as coal combustion products, or CCPs. CCPs include: fly ash, bottom ash, flue gas desulphurization (FGD) by-products, and boiler slag. Roughly one third of all US utility fly & bottom ash, which constitutes the majority of by-products, is reused, or about 24.4 million short tons per year [37]. A utility's CCP disposal cost may be as high as 1-3% of its annual budget [38]. The economic incentive for the generator to identify a marketable reuse for ash is clear: for those CCPs finding markets, revenues average $2/ton [39] as opposed to $10-15/ton disposal costs.

The reuses of ash found in Kalundborg are among the most common: in concrete, cement, and as backfill. Ash reuse has obvious environmental benefits: most directly, 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 CO_2 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 [40].

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 desulphurization (FGD) by-products are created downstream from the combustion chamber by the reaction of SO_2 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 FGD by-product is sold to a wallboard manufacturer as a substitute for mined gypsum. In the US, the majority of FGD sludge is managed onsite in waste piles. [37 p.48] The circulating fluidized bed (CFB) coal combustion technology in use in Guayama produces ash with a composition unlike traditional coal combustion plants. CFB plants do not produce separate high-sulfur by-products: CFB technology burns limestone together with the fuel in the combustion chamber, where the majority of the SO_2 is captured. As a result, the CFB fly 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 [41, 42, 43].

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 included cement, soil stabilization, and ash rock for highway fill [17]. AES Guayama is currently pursuing the application of the ash slurry as fill material for high voltage underground transmission lines [22].

The components of the CFB ash closely resemble the contents of Portland cement and its raw materials [44], thus the ash may be suitable for use as a raw material for cement.[vi] 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 sulfur-containing compound gypsum [44]. Two cement kilns in Puerto Rico within 50 miles of Guayama produce an estimated 1500 tpy cement.[vii] If the AES ash were suitable as an additive at a rate of 6% of inputs (common for high carbon ash [40] and for gypsum [44]) 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.

VI. 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 reduced environmental impact: for example, a 99.5% reduction in SO_2 emissions due to steam generation for Chevron Phillips is achieved, and AES avoids 4 MGD extraction of scarce fresh water through the use of treated effluent from the wastewater treatment plant.

Do these public benefits of cleaner air and water come at high cost to the private sector? 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 waste water is not only available, but also is considerably less expensive, some $1.2 million per year, than the cost of purchasing fresh water. In both instances, private benefits are achieved simultaneously with public ones. Regulatory conditions, however, influenced both water and steam opportunities. With respect to steam, AES became a steam supplier to meet the qualifying facility requirement under PURPA. 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 the business case for industrial symbiosis. Although AES does not appear to be the largest financial gainer (beneficiary) from the by-product exchanges, in part because it incurs set-up costs to receive waste water 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.

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 (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 they are 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. Coal combustion products are not regulated wastes.

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. In this way, government action could initiate symbiosis which, in turn, could inspire additional private trades. The IS literature shows that a single exchange is often the first step and that, as in Kalundborg or in the case of Chaparral Steel in Texas, "trades beget trades" [46].

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[i] Many of these facilities have changed hands repeatedly; they are referred to in this article by the owner at the time of writing.

[ii] Environmental concessions such as using wastewater for cooling have been identified as part of the "cost of doing business" for new power plants [15]. A proposed CoGentrix plant sited for Mayagüez, Puerto Rico, also in the mid-1990's, illustrates the political importance of reclaimed water use for new power plants. The CoGentrix proposal and the AES proposal shared a number

of features. Both proposed to burn coal, and provide steam, in the case of CoGentrix to the tuna manufacturers of Mayagüez. The projects faced very similar community opposition: concerns over air quality; union concerns over privatization of energy generation. However, the CoGentrix facility proposed using sea water for once through cooling, and discharging the warmed water to the bay, whereas the AES facility was designed to use reclaimed wastewater for cooling, and to recirculate it. All other factors are not equal, for example the timing of the permits. Still, the CoGentrix cooling water design was viewed as the weak link in the proposal: the Environmental Quality Board (EQB) granted then revoked a water quality permit, and the Planning Board refused a permit on the basis of adverse impacts on water quality in the bay and potential deterioration and destruction of the area's ecosystem. [14]

[iii] As of November, 2003, the Chevron Phillips facility is in full production with a new product line, and reduced process steam needs owing to changes in product lines: an average of 60kpph of high pressure and 50kpph of low pressure process steam [22]. 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 2 boilers to AES steam production is valid. Reinhardt [23] further discusses the challenges associated with choosing the relevant starting point for assessing relative improvements such as this.

[iv] One short ton = 2,000 pounds.

[v] The increase in CO2 emissions is inherent in the chemistry of the fuels. Based on EPA AP-42 Emission Factors for coal and fuel oil, and CIBO estimates for fuel input for steam production, 1000 pounds of steam generated by burning Number 6 fuel oil will generate 195 pounds of CO_2 versus 332 pounds generated from coal [25, 26].

[vi] The contents of Portland cement and its raw materials include CaO, SiO2, Al2O3, Fe2O3, MgO. [44]

[vii] Annualized production from July/Aug 2002 [45].