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OM Forum

Operations Management Challenges for Some "Cleantech" Firms

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A "cleantech" firm is one with an innovative technology and/or business model for serving an existing market with dramatically reduced environmental impact. This paper describes operations management (OM) challenges faced by five cleantech companies, and a few questions that these raise for OM and multidisciplinary research. It aims to fuel readers' motivation to identify and pursue others. The OM community has fundamental roles to play in the creation of an environmentally sustainable economy.

Key words: environment; energy; process innovation; supply chain management; capacity investment; bankruptcy; public policy
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1. Introduction

Environmental sustainability is achievable and affordable, but requires a reinvention of how we produce and deliver goods and services. This paper describes five "cleantech" companies that together offer the possibility of largely eliminating anthropogenic carbon dioxide (CO_2) emissions. (This must be accomplished within decades to avert the impacts of climate change, which include increased mortality from floods, droughts, infectious disease, malnutrition, decreased agricultural productivity at low latitudes, and extinctions of species, among other impacts (Intergovernmental Panel on Climate Change 2007, Meinshausen et al. 2009, Schneider et al. 2010).) Zero Energy Technology and Architecture (ZETA) Communities manufactures affordable, energy-efficient buildings that generate more electricity (using photovoltaics) than they consume. Buildings currently account for half of U.S. energy use and associated CO_2 emissions (Randolph and Masters 2008, p. 216), and a similarly large fraction worldwide, which could largely be eliminated by such innovation. First Solar manufactures photovoltaics at a cost that is declining rapidly and could become competitive with natural gas turbines as the cheapest form of new generation capacity to meet daytime peak electricity demand (Lazard 2009, Energy Information Administration 2010). Meanwhile, vehicles account for 17% of anthropogenic CO_2 emissions (Intergovernmental Panel on Climate Change 2007), which might be eliminated by using electric vehicles powered by the wind and sun for road transport, and biofuels for aviation; Better Place aims to speed adoption of electric vehicles by leasing batteries for electric vehicles to drivers and optimizing their charging. Amyris makes jet fuel from sugar cane, which removes CO_2 from the atmosphere as it grows. Calera converts the CO_2 from a conventional power plant into calcium carbonate, a substitute for Portland cement, production of which accounts for 8% of anthropogenic CO_2 emissions. These innovative companies offer hope that humanity can avert dangerous climate change.

However, the companies might not survive. They face operations management (OM) challenges, entwined with policy, technology, market, and, hence, bankruptcy risk. Some of these challenges raise new questions for OM and multidisciplinary research. This paper highlights a few such questions, which I hope will help motivate readers to develop and pursue many others.

Except where otherwise noted, information in this paper stems from my interviews with executives of Amyris (Jeff Lievense), Better Place (Jeff Johnson), Calera (Aurelia Setton and Michael Weiss), First Solar (Brian Kelly, Tor Schoenmeyr, and Mark Zeni), 5N Plus (Marc Suys), and ZETA (Naomi Porat and Karl Tarango), and from these companies' public financial statements and websites. I thank all of these executives.

2. OM Challenges for Cleantech Companies

Each subsection describes OM challenges faced by a cleantech company, provides reference to a teaching case on the company (if available), and then poses research questions (shown in italics).

2.1. ZETA Communities

Because of fragmentation of the supply chain and poor coordination, the building industry fails to adopt technologies and processes that would profitably reduce CO_2 emissions. Work tends to be allocated based on low-cost competitive bidding for each functional component of a building project. As a result, a new team forms for each project—thereby interrupting the transfer to future projects the lessons learned—and each building component is designed largely in isolation (Sheffer and Levitt 2010). In contrast, optimal energy efficiency requires integrated design. For example, using high-performance windows, doors, and insulation to prevent heat loss can eliminate the need for expensive heating and cooling systems. The marginal benefit of thermal efficiency in one component of a building depends on the efficiency of all the other components (Randolph and Masters 2008, Chap. 6).

ZETA Communities manufactures buildings that use solar photovoltaics to generate at least as much energy as they consume[1] (Marshall 2012). Remarkably, ZETA produces these green buildings at a cost below that of conventional buildings. It does so by integrating architecture, engineering, green material sourcing expertise, and the various functional construction specialties, and by constructing buildings in a factory, which promotes integrated design. Whereas on-site construction is a sequential and adaptive process, factory construction requires advance planning of every aspect of a building's design, "down to the last screw," according to CEO Naomi Porat.

Launched in 2008, ZETA purchased and refitted a modular home factory in Sacramento to make customized green buildings. Traditional factory builders make simple homes with minimal variation. Yet ZETA has developed the flexibility to manufacture a wide variety of customized structures, ranging, for example, from a seed research facility, to a school, to a high-rise affordable housing project. In its production line, pieces of future buildings—called building modules—are positioned on casters and move every two hours from one "station" to the next. Each module, which can be up to five floors high, 65 feet long, and 16 feet wide, will later be transported to the building site for assembly. Each of its 21 stations equips a module with one aspect, such as framing or plumbing. Unlike in a traditional modular home production line, ZETA has some equipment (such as spray foam insulation) that moves between stations and several "surge" stations to accommodate additional or nonstandard processes. Furthermore, ZETA flows R&D projects into the production line, to take advantage of workers and equipment that would otherwise be idle.

Through integrated design and factory construction, ZETA minimizes material requirements in an industry where environmentally friendly materials tend to be costly. For example, the cost of Forest Stewardship Council–certified lumber may be 30% higher than the cost of conventional lumber, but the quantity of lumber required for a house can be reduced by 20% (relative to conventional practices) by using integrated design and accurate, factory-enabled cutting and assembly processes (Delmas et al. 2007). In addition, ZETA's factory shields materials from rain damage and vandalism, and enables ZETA to sort, store, and reuse scrap materials.

Factory construction also enables ZETA to pay lower wages and use less labor. According to CEO Naomi Porat, "ZETA is about 15% lower priced [than traditional builders] in urban markets. Part of that differentiation is that any project that has public financing (city, state, or federal) requires prevailing union wages. Off-site construction is exempt from prevailing wages, which gives us an immediate 15%–20% discount. But in addition to that, labor hours are just less." Indeed, labor productivity is maximized by ZETA's advanced design, ergonomically optimized equipment, and in-factory coordination of the functional specialties.

According to Porat, ZETA's factory approach also reduces transport costs for materials and equipment by requiring less than half of the vehicle travel of on-site construction, resulting in roughly 70% fewer CO_2 emissions. The company targets projects within a 300 mile radius of the factory to limit the costs and emissions associated with trucking the finished modules to a site.

Finally, factory construction reduces lead time and neighborhood disruption. Compared with the many months of work that on-site construction demands, ZETA's process occurs within weeks. It manufactures a building in modules while the site is being prepared, then utilizes a crane to stack modules into a finished building.

One might think this all sounds too good to be true. Why isn't the factory approach already ubiquitous? The answer is that demand for construction is highly cyclical. Firms that sink capital into factories to meet demand during a "boom" time face bankruptcy in the next "bust" (Sheffer and Levitt 2010).

[1] Specifically, a building is designed to produce at least as much energy as it consumes on average, assuming building occupants behave in a responsible manner and excluding the energy required to make the building. Currently, the emissions from manufacturing of building materials, such as cement, are substantial. However, as described below, ZETA requires less material per building than with conventional on-site construction, and Calera offers a cement substitute with net negative emissions.

Another concern is that for a building to truly generate more energy than it consumes (a key marketing point for ZETA and source of state subsidies in California), occupants must behave responsibly. ZETA records occupants' energy use and related behavior to give them feedback and suggestions for improvement, and also to improve its ongoing design and production decisions.

My coauthored teaching case on ZETA (Levitt et al. 2011) contains much of the above information and more.

Questions for OM and Multidisciplinary Research
What is the structure of an optimal policy for a multiarmed bandit problem that incorporates risk of bankruptcy? With limited capacity, ZETA must repeatedly decide which type of building project to pursue. Types include, for example, schools, luxury townhouses, affordable high-rise apartment buildings, and office buildings. Each type corresponds to a different "arm." ZETA is a price taker in that it must set a price competitive with that of a conventional builder to win business. However, its design and manufacturing costs are uncertain and history dependent. Pursuing a particular type of building project provides an opportunity to both learn about and reduce the cost of manufacturing that type of building again in future. Moreover, building type arms may be correlated as in Mersereau et al. (2009) due to commonality in some materials and components. ZETA is developing a "design library" of available materials, component parts (such as wall systems), and larger building modules that it has built in the past and may adapt for similar, future projects. ZETA also records costs, material requirements, and manufacturing time requirements to better estimate costs and reduce them by improving upon its designs and production processes. The multiarmed bandit literature assumes an objective of expected discounted profit maximization or of expected total profit maximization (see Gittins et al. 2011, Auer et al. 2002, and references therein). In contrast, ZETA and many other cleantech firms have limited capital and face the risk of bankruptcy. Section 2.2 shows that Amyris faces a multiarm bandit problem similar to that of ZETA.

How should business processes be designed to facilitate cross-disciplinary collaboration? Innovation for environmental sustainability may arise through cross-disciplinary collaboration. ZETA's employees hail from a wide variety of disciplines—from the architect to the electrician in the factory—and from the vastly different sectors of modular and site-built construction. They have different perspectives, languages, and expectations regarding work processes. According to CEO Naomi Porat, coordination of this multidisciplinary workforce is probably the greatest operational challenge for ZETA, and requires "new ways of working ... with a great deal of teaching, learning, collaboration and respect for other disciplines." OM researchers might build upon the literature on multidisciplinary teams (Van Der Vegt and Bunderson 2005 and references therein).

Is environmental sustainability at odds with social justice? ZETA's factory approach enables the firm to pay lower wages and use fewer labor hours per building, with presumably negative implications for construction workers, a group at the low end of the income distribution and with currently high unemployment. *Categorically, what sorts of operational changes will firms make in response to policy that imposes a cost of carbon, and will those changes tend to promote social justice*? *What are the policy implications*?

2.2. Amyris

Amyris genetically engineers yeast to ferment sugar into farnesene, a precursor for fuels, emollients, and other direct substitutes for petrochemicals. The fermentation occurs in a semicontinuous "fill and draw" process. Initially, a seed culture of yeast is placed in a tank approximately half full of sugar water. Additional sugar is added continuously, as the yeast multiplies and converts the sugar into farnesene, which floats to the top of the tank. When the tank is full, the farnesene is removed mechanically, which completes one cycle. (The cycle time typically ranges from one to four days, depending primarily on the strain of yeast selected by Amyris.) Then the tank is roughly half full of yeast and sugar water, and a second cycle begins. After a limited number of cycles, the process is stopped and the tank is cleaned. Then the process is restarted with a new seed culture of yeast.

Amyris is a price taker in the world market for fuels and petrochemicals. CEO John Melo explained, "For our customer, the price discussion is simple. We cannot be more expensive." If Amyris can match the price and quality of its petroleum-based competitors, customers will choose its "green" products, and demand will exceed its production capacity for the forseeable future (Lane 2011).

Amyris has a vaunted "capital light" business model for expanding its product-mix flexibility and production capacity. The company has joint ventures and R&D contracts with prospective customers and competitors to develop various derivatives of farnesene and other products. (Firms that engineer microbes to process biomass have the potential for much greater product-mix flexibility than their petrochemical competitors (Williamson 2012).) Amyris built its first commercial production facility through a joint venture with one of the largest producers of sugar and ethanol in Brazil. The company has also used contract manufacturers. Unfortunately, efficiency in commercial production has been lower than

Amyris anticipated based on its laboratory R&D, and sugar prices have been high. The company has had to pay contract manufacturers to exit from its take-or-pay contracts, and to write off specialized equipment that it had placed with them. Amyris must rapidly improve productivity in its Brazilian facility or face bankruptcy.

In striving to improve productivity, Amyris (like ZETA) has a multiarmed bandit problem. For Amyris, each arm is a strain of yeast. Each time Amyris initiates its process, it chooses a yeast strain, and also has the opportunity to experiment with over 50 additional process variables (including temperature, pH, and sugar feed rate). Thus, Amyris learns about the productivity of the yeast strain and how to obtain higher productivity with that yeast strain in future. Productivity has two dimensions: capacity efficiency (production rate of farnesene) and input efficiency (farnesene output per unit of sugar input). Amyris must also decide how much to invest in R&D to engineer new strains of yeast.

Questions for OM and Multidisciplinary Research
How should a firm dynamically choose the operating mode of a production facility, while learning about and improving its capacity efficiency and input efficiency in each operating mode? When input prices rise relative to output prices, the firm may switch to an operating mode with relatively high potential for input efficiency as opposed to capacity efficiency. Cleantech firms characteristically face this trade-off in capacity efficiency versus input efficiency (Plambeck and Taylor 2013).

What sorts of policies will best spur R&D and process improvement by cleantech firms? Candidates include expanded patent protection, prizes for innovation, R&D subsidies, a renewable portfolio standard in electricity generation, a carbon tax or cap-and-trade system, and advantageous tax treatment for equity investors. Innovation by cleantech firms will generate environmental and broader societal benefits, which should be weighed against the social costs of any proposed policy to stimulate innovation. (The analysis should also account for social benefits; e.g., a carbon tax could reduce the need for other taxes that distort the economy and exacerbate unemployment.) Regarding the social cost of patents, the standard concern is that a patent holder may prevent rival firms from adopting an innovation, leading to wasteful "invent around" effort by those rival firms, and may restrict output to charge a high price. However, the latter concern is alleviated for cleantech firms that are price-taking entrants to commodity markets.

What OM insights are reversed when a firm is a price taker (*as opposed to having downward-sloping demand or "newsvendor" demand*)? Amyris, ZETA, and many other cleantech firms are price takers, at least initially, in commodity markets for their inputs and/or outputs. OM researchers could build upon models of industrial dynamics that drive cyclical fluctuations in commodity prices (Sterman 2000).

2.3. First Solar

First Solar began commercial production of photovoltaic modules in late 2004, and by 2009 became the largest photovoltaic manufacturer in the world, with \$2.1 billion in revenue and production facilities in the United States, Germany, and Malaysia. First Solar's key innovation is high-rate vapor deposition of a microns-thin layer of the semiconductor material cadmium telluride (CdTe) onto glass (Stevenson 2008). CdTe is a substitute for crystalline silicon, the semiconductor traditionally used in solar photovoltaic manufacturing, which quadrupled in price during 2004–2008 as silicon production—which has a three-year lead time for capacity expansion—constrained the growth of the photovoltaic industry (Gunther 2009, Fisher and Rogol 2005, Price and Margolis 2008).

During 2004–2010, First Solar dramatically improved input efficiency and capacity efficiency. It reduced the thickness of the CdTe layer in its modules by 30%, while increasing the modules' light-conversion efficiency from 7% to over 11% (Green 2010). It doubled throughput per production line. Its cost to build a production line dropped from \$100 million to \$50 million as equipment vendors also became more proficient.

In a complementary business model innovation, First Solar entered into the design, construction, and operations/maintenance for utility-scale solar photovoltaic installations. In a typical installation, the "balance-of-system" costs—which include things like grid interconnection equipment, inverters, and installation labor—are roughly equal to the cost of the modules. By optimizing the construction process and subsequent operations/maintenance, First Solar reduces the balance-of-system costs and improves the yield of electricity, which increases demand for its modules. Building utility-scale solar plants may also reduce First Solar's risk of bankruptcy, because this activity tends to become more profitable when market forces depress the prices of photovoltaic modules.

First Solar's future growth might be limited by availability of tellurium. Supply is inelastic because tellurium is obtained only as a trace by-product of mining for other metals, primarily copper, or through recycling. The market price of tellurium rose from below \$29/kg in 2004 to above \$360/kg in early 2012, and has become highly volatile (U.S. Geological Survey 2012) in part due to the rise of CdTe photovoltaic manufacturing (by First Solar, GE, and various start-ups). First Solar commits to collecting and recycling its modules, and pays insurance premiums to Swiss RE to guarantee the recycling in the event that it is bankrupt. However, depending on the future price of tellurium, the recycling could become profitable for First Solar. First Solar has long-term contracts to buy CdTe at prices that reflect the cost of manufacturing CdTe—as opposed to its scarcity and spot market price—but such contracts are subject to renegotiation.

Currently, First Solar sources much of its tellurium (in the form of CdTe) from a single supplier, 5N Plus, which was founded in 2000 by a management buyout from mining giant Noranda, with which it maintains close ties for its supply of metals. To grow with First Solar, 5N Plus invested in the capability and capacity to extract tellurium from a variety of metal-oxide sludges. In 2007, it built an adjacent facility to supply First Solar's German plant, in part by recycling CdTe from faulty modules. To motivate that capacity investment by 5N Plus, First Solar committed to a long-term supply agreement. It would purchase a minimum quantity of CdTe at a specified price per unit and pay a lower price for any additional quantity. The contract stipulated that First Solar could buy 5N Plus's production facility at a specified price if 5N Plus were to default on the specified timing, minimum quantity, or quality.

In 2012, First Solar reduced output and closed its German production facility (though it continued to buy CdTe from the adjacent 5N Plus facility) because of adverse business conditions. European governments had dramatically reduced subsidies for solar power. Competitors' silicon prices had dropped precipitously, because of capacity overshoot. Natural gas prices had dropped because of fracking in the United States, which favored investment in natural gas turbines, rather than photovoltaics, to meet peak daytime demand for electricity.

Questions for OM and Multidisciplinary Research

How should a durable goods manufacturer contract with a customer to be able to recycle its product at an optimal time, when it most needs the material contained in that product and/or can supply a better-performing product to the customer? Interface, for example, pioneered the leasing of carpet, hoping to profit from recycling the carpet, rather than purchasing oil as feedstock, in the event of rising oil prices. However, the leasing program failed due to a host of incentive problems (Oliva and Quinn 2003, Plambeck et al. 2008). Conceivably, a firm could contract to recycle and replace a customer's product at a time that is contingent on the stochastic performance of the product and the value of its constituent materials. For example, the light-conversion efficiency of a solar photovoltaic module degrades stochastically over time. First Solar could contract to replace modules when light-conversion efficiency drops below a threshold, which could be an increasing function of the spot-market price of tellurium. Over time, First Solar is learning to make new modules that achieve higher light-conversion efficiency with less tellurium. Both the design of a recycling contract and design of a photovoltaic installation should reflect this improvement process. For example, the grid-connection infrastructure for a solar photovoltaic installation should be oversized, from the outset, to allow for generating capacity to increase with the future installation of modules with higher light-conversion efficiency.

How much and when should a firm invest in capacity expansion, accounting for its risk of bankruptcy, which increases its cost of capital and reduces demand for its products? This question is relevant for all manufacturers that have long-term, mutually beneficial relationships with their customers. It is critical for cleantech manufacturers because, as described in Eilperin (2012), they have high capital requirements for production facilities, high technology and policy risk, and hence high bankruptcy risk. For a firm with unlimited capacity and constant unit production cost, Hortacsu et al. (2011) show the existence of multiple equilibria: In a "negative" equilibrium, capital providers and customers anticipate a high risk of bankruptcy, which becomes a self-fulfilling prophecy. (*How*) *Should policy makers promote a "positive" equilibrium with capacity expansion in cleantech industries*?

How much of its future output should a firm presell? One means to reduce bankruptcy risk (and thus reduce the cost of capital and stimulate demand) is to contract with buyers for sale of future output at a specified price. Both Amyris and First Solar do so. The optimal quantity to presell depends on uncertain future capacity efficiency and input efficiency. A firm with private information that these will be high might signal that information to investors and customers by preselling a large quantity.

Should a firm "copy exactly" in building new production lines? First Solar has adopted Intel's "copy exactly" approach that calls for making all of its production lines identical (Cheyney 2009). This approach prevents experimentation and learning with regard to the design and layout of equipment that could dramatically improve productivity, especially in the long run. A countervailing benefit is that the copy exactly approach allows for a process improvement on one line to be immediately adopted at all other lines. Second, it minimizes the lead time to complete construction of a new line, which minimizes capital investment that is not yet generating revenue, and thus reduces risk of bankruptcy. Third, it avoids the initial, temporary reduction in productivity caused by process change, as modeled by Terwiesch and Xu (2004).

2.4. Calera

At a natural-gas-fired power plant on the shore of Monterey Bay, California, Calera combines CO_2-rich flue gas with water and sodium hydroxide (NaOH) to produce sodium carbonate (Na_2CO_3), and then adds calcium chloride ($CaCl_2$) to form calcium carbonate ($CaCO_3$). Calera sells the $CaCO_3$ to builders as a partial substitute for Portland cement: The builders can combine the $CaCO_3$ with Portland cement, which enables them to use less Portland cement while achieving the same functionality. Thus, CO_2 emissions from a power plant can be stored in roads and buildings rather than released into the atmosphere.

Calera is a potential competitor with its suppliers of feedstock NaOH and $CaCl_2$, which may help the company to negotiate low prices for those feedstocks. As an alternative to purchasing NaOH, Calera is developing an electrochemical process for making NaOH that will require less electricity than does the conventional method. In many regions of the world, the largest and cheapest source of $CaCl_2$ is the $CaCl_2$ by-product from conventional manufacturing of Na_2CO_3, some of which goes to landfills. (Na_2CO_3 is used in wastewater treatment and the manufacturing of paper, glass, textiles, and detergents.) Calera currently produces Na_2CO_3 as an intermediate product—and could sell that Na_2CO_3 rather than use $CaCl_2$ to convert it into the cement product $CaCO_3$. A conventional manufacturer of Na_2CO_3 might be better off paying Calera to use its $CaCl_2$ than having Calera compete in selling Na_2CO_3.

Unlike the $CaCO_3$ cement product, though, Na_2CO_3 does not sequester CO_2; the industrial uses of Na_2CO_3 immediately release its embodied CO_2 to the atmosphere. Nevertheless, the climate would benefit from Calera producing Na_2CO_3 from a power plant's CO_2 emissions insofar as that would displace conventional manufacturing of Na_2CO_3, which generates high CO_2 emissions.

For Calera, optimal facility location and sizing is a matter of industrial ecology. An ideal site is proximate to proportionally large waste streams of CO_2 and $CaCl_2$, has cheap electricity for making NaOH, and offers a favorable market for cement.

There is a teaching case on Calera (Meier and Larson 2010).

Questions for OM and Multidisciplinary Research

How should a manufacturer address the problem that if it grows (and is imitated) then input costs may rise. This is particularly problematic for cleantech manufacturers like Calera and First Solar that rely on the waste product or by-product of another industry, so that supply is inelastic.

How should a manufacturer optimize its production and inventory management under time-varying and uncertain energy costs? For example, Calera's primary cost driver is electricity consumed in manufacturing NaOH. In Calera's California location, the spot market price of electricity can vary from below \$0 to \$750/MWh in a 24-hour period; it tends to be low at night and high on hot summer days (Knittel and Roberts 2005). Currently, many manufacturers contract for a deterministic (either fixed or time-varying) price of electricity. In contrast, the availability of wind and solar power is stochastic. I believe that manufacturers have an important role to play in balancing demand with supply in a future electricity system based on renewables, by dynamically optimizing the rate of production. Wind and solar power exhibit considerable seasonal variation (Hart and Jacobson 2012), and seasonal inventory may be far cheaper than other approaches to long-term electricity storage.

A few papers address production and inventory management with a time-varying cost of production (Smith and Zhang 1998, Cheevaprawatdomrong and Smith 2004), but not the stochasticity and special structure of electricity prices, or the following salient issues. The first is the trade-off in capacity efficiency versus energy efficiency. Calera can increase energy efficiency (NaOH output per kilowatt hour of electricity) by reducing the production rate of NaOH below the maximum feasible level. The second is that energy is required to start up or shut down a process. Those two issues arise commonly in conventional basic material manufacturing (which accounts for 80% of industrial energy use; Intergovernmental Panel on Climate Change 2007) as well as cleantech.

2.5. Better Place

Better Place aims to overcome three primary barriers to the adoption of electric vehicles: high cost, limited range, and inconvenient charging. A customer of Better Place need not purchase an expensive battery, but he or she instead pays a flat monthly fee for a battery and sufficient electricity to drive a chosen maximum number of miles. Better Place will own the batteries and optimize their charging. It intends to build charging stations at customers' homes and in public places. Moreover, to enable customers to drive long distances without stopping to charge the battery, Better Place intends to build "swap stations" where drivers can exchange depleted batteries for charged ones. The company is launching its service in Israel and Denmark now, and has longer-term plans and governmental support to deploy charging infrastructure in targeted locations in the United States, Canada, Australia, and Japan.

However, Better Place faces daunting "chicken and egg" problems. First, investment in a dense and widespread network of swap stations and charging stations is justified only if a large number of drivers will utilize them. However, manufacturers will develop compatible vehicles, and people will buy them only if the charging infrastructure is in place (Struben and Sterman 2008). More specifically, ubiquitous charging infrastructure would promote adoption of all-electric vehicles with small batteries, which cost less than either hybrid-electric vehicles (with a gasoline engines) or all-electric vehicles with large batteries, and also weigh less, which reduces operating costs and CO_2 emissions per mile driven (Shiau et al. 2009). Second, batteries of electric vehicles could provide the storage needed for an electricity system based on intermittent wind and solar power. However, without complementary investment in renewable electricity generation, Better Place may increase emissions by encouraging people to drive more, using cheap, CO_2-intensive electricity (Avci et al. 2011). That could cost Better Place its green public image, governmental support, and the loyalty of employees and customers.

Operationally, Better Place must decide, over time, where to build charging infrastructure and how to contract with customers. Given the infrastructure and customers' needs for electricity for driving, Better Place must decide when to charge each battery in its swap stations and customers' vehicles. It must also decide when to discharge batteries to sell electricity. In charging and discharging, the objective is to minimize the expected net cost for electricity, battery degradation costs from rapid charging and discharging, and costs associated with having drivers run out of charge. In the event that a driver runs out of charge, the company may compensate the driver for using an alternative mode of transportation, direct the driver to a swap station, or have the driver wait while his or her battery is charged.

Optimization of charging and discharging is challenging for several reasons. First, the price of electricity is nonstationary and stochastic, as discussed in §2.4 on Calera. Second, the rate at which batteries can be charged and discharged is limited by local transmission capacity, charging infrastructure, and the batteries themselves. Third, Better Place has uncertainty regarding customers' requirements for electricity and regarding when and where they will plug in their vehicles. Fourth, customers vary in their tolerance for delay or for taking an alternative mode of transportation, so Better Place may offer a menu of contracts that differ in service level and cost for drivers. For example, the company might stipulate the maximum frequency that a driver would need to use an alternative mode of transportation.

Better Place is developing software to continuously monitor the charge levels of all its batteries in vehicles and swap stations and to track each customer's unique pattern of driving and plugging in or swapping a battery. From these data, Better Place can estimate each vehicle's future electricity requirements, charging opportunities, and proximity to swap stations.

The company will also communicate with drivers and enable drivers to communicate with it. For example, to accommodate an atypical trip, a driver may press a "charge me now" button in the on-board computer. Better Place may also use the on-board computer to alert the driver to a low state of charge and then direct that driver to a particular charging point or swap station for replenishment. The recommendation could be based on real-time information about drivers' travel plans, traffic congestion, and the charge levels of batteries in swap stations and drivers' vehicles throughout the Better Place network.

In its swap stations, Better Place faces a battery inventory management problem. Each "line" in a swap station can exchange a car's battery in three minutes. Therefore, assuming 100% utilization of each line and 30 minutes to charge each battery, Better Place has computed an upper bound on the optimal inventory: 10 batteries per line. This calculation relies on the batteries being identical. However, in the future, Better Place might be required to support a large number of different types of batteries as manufacturers introduce new electric vehicles and associated batteries. An optimal inventory policy will depend on the number of drivers with each battery type, the service level guaranteed to each driver (which in turn might depend on the driver's choice of service contract and battery type), driving patterns, and the space available at the swap station. The optimal inventory policy will also depend on the stochastic price of electricity over time, since holding more batteries will allow more flexibility in charging them when the price of electricity is low.

Better Place might choose to limit the types of batteries supported by its swap stations. However, electric vehicle manufacturers are unlikely to limit themselves to a small number of standard types of batteries, since battery and electric vehicle technologies are evolving rapidly, and vehicle manufacturers can provide higher performance by jointly optimizing the design of vehicle and battery. As battery variety increases over time, Better Place's inventory management problem will become increasingly difficult. (Perhaps Better Place should instead invest in quick-charge stations that have no need for battery inventory and, according to Top (2012), cost much less to build than swap stations.)

Recent technological advances suggest that flow cell batteries might dominate road transport in the near future (Duduta et al. 2011). Such a situation would make Better Place's swap station equipment and conventional batteries obsolete, but it would also greatly simplify inventory management by eliminating variety. In a flow cell battery, the cathodes and anodes are composed of particles suspended in a liquid electrolyte, separated by a thin membrane. The cathode suspension and the anode suspension can be charged in advance and then pumped into an electric vehicle, much like gas, or charged within the vehicle. Flow cell batteries could be of different shapes and sizes, but they would all use the same two suspensions.

Like ZETA, Better Place depends on cooperative participation by its customers. Better Place must motivate its customers to drive in a responsible manner (e.g., accelerating gently), to follow dashboard messages regarding when and where to plug in or swap a battery, to provide advance notice of unusual driving requirements, and, conversely, to hit the "charge me now" button only when necessary. The firm will seek to raise customers' awareness of the environmental benefits of such behavior and to establish social norms for it; for instance, Better Place will provide a dashboard view of how electricity use or utilization of renewable energy compares to that of friends in a social network and to the fleet average. In all of its investment and operational decisions, Better Place must account for uncertain customer behavior.

There is a teaching case on Better Place (Girotra et al. 2011).

Note that since this paper was written, Better Place has filed for bankruptcy (in May 2013).

Questions for OM and Multidisciplinary Research

How can firms motivate customers to behave in a manner that improves operational and environmental performance? *How should firms adapt their operations to mitigate or deal with variability in customer behavior*? Existing OM literature examines the optimal design of financial incentives for customers to exert effort in service operations (Xue and Field 2008, Roels et al. 2010). However, financial incentives might backfire by reducing customers' intrinsic motivation for prosocial or proenvironmental behavior (Frei and Morriss 2012, pp. 144–145). The rich literature on motivating people to adopt energy-saving or other environmentally responsible behaviors (see Alcott 2011, Delmas and Lessem 2012, Precourt Energy Efficiency Center 2012, and references therein) holds implications for OM. For example, that literature shows that social comparison strongly motivates people to reduce their energy consumption; Roels and Su (2013) suggest how policy makers and service operations managers can design and exploit social comparisons. Even for manufacturers and retailers, influencing consumer behavior may be the most cost-effective approach to substantial environmental impact reduction, as in the example of Walmart motivating customers to wash clothes in cold water to reduce CO_2 emissions (Plambeck and Denend 2010).

What policies and innovative business models will enable renewables to displace fossil fuels in electricity generation and transportation? The current literature that estimates the feasibility and cost of meeting society's demand for electricity with renewable power sources instead of fossil fuels takes electricity demand as given, reflecting the historical pattern (see, e.g., DeCarolis and Keith 2006, Denholm and Margolis 2007, Lund and Mathiesen 2009). Future research should incorporate the potential to improve energy efficiency in buildings (reducing both the mean and variance of electricity demand) and the potential to time-shift electricity demand in buildings, manufacturing industries, and transportation. A nascent literature addresses the dynamic optimal control of distributed devices that store, generate, and/or consume electricity; see Xi et al. (2011), Kraning et al. (2013), Mak et al. (2013), Wu and Kapuscinski (2013), and references therein. Multidisciplinary research (spanning engineering, meteorology, finance, law, economics, political science, psychology, and OM) is needed to characterize the socially optimal investments in energy efficiency, renewable electricity generating capacity, electricity transmission infrastructure, and electric vehicles and their charging infrastructure, and then to identify policies and business models that will overcome the chicken and egg barriers to such investments.

3. Concluding Remarks

This paper focuses primarily on questions for model-based research, but empirical analysis is also an important path for OM researchers to address environmental sustainability. This paragraph highlights some relevant sources of data. In this special issue on the environment, Jira and Toffel (2013) use data from the Climate Disclosure Project to examine a supplier's willingness to disclose its greenhouse gas emissions, and Muthulingam et al. (2013) use data from the U.S. Department of Energy's Industrial Assessment Center program to examine energy efficiency improvement by small manufacturing firms. Popp (2002) and Linn (2008) measure manufacturers' improvements in energy efficiency using data on patents, and data on output and energy expenditures from the U.S. Census of Manufactures, Annual Survey of Manufactures, and Manufacturing Energy Consumption Survey. Industry-level energy expenditures are captured in the National Income Product Accounts and Benchmark Input–Output Matrix published by the U.S. Bureau of Economic Analysis. The Greenhouse Gas Inventory Report by the U.S. Environmental Protection Agency gives emissions by sector and industrial processes. The Global Carbon Project is a repository of data on energy use and greenhouse gas emissions by country. TrueCost collects data on greenhouse gas emissions and other environmental impacts for a wide variety of firms. Cachon et al. (2012) use weather data and production data from automobile plants to estimate the extent to which severe weather (which could become more frequent with climate change) reduces manufacturing productivity.

This paper focuses primarily on climate change. However, humanity faces other environmental problems that are of commensurate importance. Examples include the widespread use of toxic and persistent chemicals, water pollution and scarcity, and loss of biodiversity. The OM research community has critical knowledge and skills for addressing these environmental problems as well as climate change. For example, in this special issue on the environment, Kraft et al. (2013) suggest how activists can motivate firms to eliminate hazardous chemicals from their products.

This paper focuses on questions for OM and multidisciplinary research that arise from the OM challenges faced by existing cleantech firms. The OM community also stands to play a role in inventing or, as teachers, helping others to invent the radically new business models needed to achieve environmental sustainability; Girotra and Netessine (2013) offer suggestions for how we can do so.

In my experience, people in nonprofit and for-profit organizations tackling issues of environmental sustainability recognize the importance of OM and, therefore, are open to conversations and collaborations with OM academics. (The caveat is that secrecy regarding details of a technology or process innovation is often the best protection against imitation.) I hope that readers will pursue such opportunities to develop new research directions and teaching materials.

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