HARVARD | BUSINESS | SCHOOL

N9-618-060
MARCH 8, 2018

ROBERT S. HUCKMAN
KARIM R. LAKHANI
KYLE R. MYERS

X: The Foghorn Decision

As she settled into her seat for her flight from Copenhagen back to San Francisco, Kathy Hannun reflected on her meetings earlier in the week with several of the world's leading experts in solid oxide electrolyzer cell (SOEC) technology. It was February 2016, and it had been nearly three years since she began leading the team at X – Alphabet Inc.'s so-called "moonshot factory" to develop radical solutions to major problems – working to turn sea water into fuel.

Hannun's project – codenamed Foghorn – had set out to develop a full-scale, cost-competitive, carbon-neutral process for converting sea water into fuel.[1] Foghorn aligned perfectly with the three-pronged blueprint for projects at X: addressing a **huge problem** (e.g., climate change) with a **radical solution** (e.g., use of sea water) using **breakthrough technologies** (e.g., the indirect ocean capture of carbon dioxide [CO_2]). Hannun was no stranger to sustainable energy pursuits, but Foghorn represented the most ambitious effort she had led to date, and it had come to define her tenure at X. As her plane touched down, Hannun could not help but be excited by the possibility that, if her team was successful, she might one day be taking this same trip on an airplane powered by Foghorn's carbon-neutral fuel.

The experts Hannun met in Denmark confirmed that her cost projections were as accurate as they could be. The estimates, however, implied that the current unit cost of producing the fuel was above the initial range they had targeted. Still, there was a tremendous amount of uncertainty around these predictions, and if her time with X had taught her anything, it was that breakthroughs were sometimes just around the corner. Sometimes.

For now, however, Hannun had to confront the reality that she had only a few days to prepare for a meeting with the leadership of X, who were anxiously awaiting her update and recommendation. To kill or not to kill the project? That was Hannun's question. If she wanted to justify continuing the project, she would need a solid plan for reducing the remaining uncertainty and improving a technology that already appeared to be at the frontier of science. Further, if she recommended killing Foghorn, was it simple enough just to stop? Could anything be salvaged from the team's efforts thus far? X had built a unique culture where "killing as fast as possible" was not only allowed but whole-heartedly encouraged and even celebrated. For Hannun, the reality of possibly killing her own project—one with tremendous potential for positive impact—had set in.

[1] "Carbon-neutral" referred to the fact that on net, the amount of new carbon released into the atmosphere during both the fuel's production and combustion (e.g., in a vehicle) was zero.

HBS Professors Robert S. Huckman and Karim R. Lakhani and Kyle R. Myers (National Bureau of Economic Research) prepared this case. It was reviewed and approved before publication by a company designate. Funding for the development of this case was provided by Harvard Business School and not by the company. Robert Huckman reports owning shares of Alphabet Inc. HBS cases are developed solely as the basis for class discussion. Cases are not intended to serve as endorsements, sources of primary data, or illustrations of effective or ineffective management.

Corporate R&D Labs and The Origins of X

The 20th century witnessed dramatic swings in how individuals and firms organized their R&D efforts. The individual inventors who drove innovation at the turn of the century, such as Thomas Edison and Nicola Tesla, soon were overshadowed by large industrial entities, most notably the Bell Laboratories (Bell Labs) subsidiary of AT&T and Western Electric. In these large labs, scientists and engineers of all sorts pursued cutting-edge technologies to solve the complex problems facing telecommunications firms. Though the projects at Bell Labs grew out of challenges in telecommunications, they were pursued with little regard for their immediate applicability or likelihood of success. The belief was that enough discoveries would be made that even if only a very few turned out to be "hits", they would justify the effort. Bell Labs would go on to make major contributions in radios, lasers, and programming languages. As of 2016, eight Nobel Prizes and three Turing Awards, the latter for outstanding contributions to the field of computers, were tied to work conducted at Bell Labs.

In 1970, Xerox Corporation decided to undertake a strategy similar to Bell Labs, establishing the Palo Alto Research Center (PARC). Much like Bell Labs, PARC aimed to separate radical R&D – literally putting it across the country from Xerox's New York headquarters – from more-incremental work. In its early decades, PARC was responsible for major advances in laser printing, graphical-user-interfaces, and Ethernet networks.

Despite many major scientific advances, by the 1990s these corporate R&D labs were struggling to justify their commercial potential. Bell Labs had not been able to produce a significantly profitable product and underwent large reductions in personnel. Similarly, PARC was infamously incapable of capitalizing on a number of computer-related advances it pioneered.

While these once giants of industrial innovation began to shrink, the advent of the microprocessor made it possible once again for independent inventors – the so-called "garage entrepreneurs" operating out of extremely modest facilities – to make major advances in commercial technologies. Yet given the returns to scale that defined the early stages of the internet age, it was not surprising that, by the turn of the 21st century, giants like Apple, Microsoft and Google emerged as the leaders of a new shift toward industrial innovation. Google proved to be one of the uniquely positioned firms in this regard, achieving a market capitalization of roughly $23 billion on the day it went public in 2004.

Over time, Google moved well beyond its search engine roots into a wide range of markets including operating systems, web browsers, and phones. Google and its subsidiaries had amassed a base of talented engineers who were well positioned to tackle any problem that arose. If users wanted a new Google Maps feature, the software engineers could create it. If Google Ads revenue was lagging in certain areas, the economists could diagnose why. If the Android team needed to shrink hardware, the electrical engineers could design the new system. Google's leadership, however, saw a growing need to identify and address problems that were not simply related to improving the performance of their core businesses.

A Moonshot Factory

What if a sculptor and a kite surfer worked together to rethink how we harness the power of the wind? Or if an aerospace engineer and a fashion designer teamed up to bring internet to everyone with balloons? – X's approach to team building[2]

Google's founders, Larry Page and Sergey Brin had always had a 70-20-10 philosophy of allocating resources: 70% on the core services (e.g., Google's web search engine and advertising network), 20% on products related to the core (e.g. Gmail, Google's email service), and 10% on "far afield ventures"

[2] Source: X's website (https://x.company/about/)

(see **Exhibit 1** for an overview of Alphabet's overall R&D expenditures).[3] An interest in far afield ventures was one of the reasons Google started working on self-driving cars. At the time, Google didn't have a logical home for such a highly speculative, hardware-intensive project. So Page, Brin, and Sebastian Thrun—who was working on the Google Street View team at the time— decided to create a unit that would work on long-term innovations different than the projects Google typically tackled.

In January 2010, Google's board of directors voted to formalize this unit, funding what would become known as Google[x]. Google[x]'s mission would be to generate and pursue "moonshots" — R&D projects that addressed a big problem with a radical solution based on a breakthrough technology. Much like PARC, Google[x] had its own facilities, staff, and organizational policies to ensure it had the flexibility to pursue its unique mission. With Google busy working on its own problems, Google[x[was a more formal representation of the "10" portion of the "70-20-10" philosophy.Thrun tapped Astro Teller to join him as Co-Director of Google[x]. Prior to joining Google[x], Teller—who earned his Ph.D. in artificial intelligence—led Cerebellum Capital, a machine-learning-based hedge fund, and Sandbox Advanced Development, a design and technology development firm. When Thrun turned his attention to leading the self-driving car initiative, Teller became Google[x]'s top manager – the Captain of Moonshots. At that time, Google[x] was a very small group of computer scientists, electrical and mechanical engineers, and designers.

In 2015, Google restructured itself as the conglomerate Alphabet Inc. As part of the restructuring, Google[x] was renamed X and established as a subsidiary of Alphabet. By this time, X was home to a range of other projects including Project Loon (a stratospheric internet balloon initiative), Project Wing (a delivery drone service), and Makani (a wind energy kite project).

Though X was inspired by the likes of Bell Labs and PARC, Teller was determined not to repeat their mistakes. He was quick to observe that these earlier entities were largely "solution factories". In comparison, he noted that the goal of X was to be a factory not just for *solutions*, but also for *problems* to be solved. The charge for X was to figure out what problems that were not related to Google's core business might one day be significant enough to be solved at "Google scale".

X characterized this mission as the intersection of three core requirements (see **Exhibit 2**):

1. **Huge Problem:** Would the project solve a problem that affects millions or billions of people and deliver a major (e.g., 10x) performance improvement over the status quo?
2. **Radical Solutions:** Was the solution a non-obvious way of approaching the problem, so much so that it sounded like science fiction?
3. **Breakthrough Technology:** Were the technologies involved at the edge or on the cusp of what was currently possible such that success within five to ten years was feasible?

As Alphabet's innovation engine, X was not intended to serve as the permanent home for any idea; the goal was to graduate projects. Teller noted that this edict aimed to ward off the so-called "innovator's dilemma" — the tendency for a successful company to invest in its existing, rather than new, businesses and customers.[4]

For example, Google Brain, which developed machine learning tools, became part of the research team at Google, where it played a role in multiple business units including search, ads, and YouTube. Similarly, Project Insight set out to map and provide navigation for major public indoor spaces and became part of Google Maps. Google Watch and Google Glass both began at X and were then further developed internally by Google. Other projects graduated to become separate companies under Alphabet's umbrella. These projects included the life sciences efforts eventually known as Verily, and

[3] For more, see the Alphabet 2004 Founders' Letter: https://abc.xyz/investor/founders-letters/2004.

[4] See: Christensen, Clayton. *The innovator's dilemma: when new technologies cause great firms to fail*. Harvard Business Review Press, 2013.

the self-driving car company Waymo (see **Exhibit 3**). Finally, some projects became independent business outside of Alphabet; one such example was Flux.io, a project to design buildings that were more environmentally friendly, which was set up as an independent company outside Alphabet in 2012.

Graduates, however, represented but a small portion of the hundreds of ideas that X had pursued over the years. By far, the most common outcome for a project was to be "killed". Yet despite the typical connotation, X prided itself on its ability to kill projects quickly and maintained this strategy as a key element of its approach to systematizing innovation. By killing ideas faster, X believed that teams could learn more quickly, thereby freeing up the organization's limited resources to work on the next promising idea.

Planning the Unplannable and "Tackling the Monkey First"

Let's say you're trying to teach a monkey how to recite Shakespeare while on a pedestal. How should you allocate your time and money between training the monkey and building the pedestal? The right answer, of course, is to spend zero time thinking about the pedestal.

– Astro Teller, Captain of Moonshots[5]

Prior to joining Google[x] in 2010, Teller had consistently found himself trying to devise ways of systematizing innovation. It seemed almost contradictory to try to formalize the process of invention, which had historically been characterized by randomness and a lack of formulation. But with each new project he pursued, Teller recognized a universal issue within R&D: it was hard to stop. With his moonshot mission in hand, Teller bet that the real constraint X would face would be the number of projects it could pursue at any given time. Thus, a key process he wanted to focus on as a part of X's innovation system was how to start projects quickly and, more importantly, kill them even faster. By churning through new projects as fast as possible, X hoped to explore more ideas without sinking excessive resources into less-promising pursuits.

Progressing Ideas at X

Though acknowledging that there was a typical progression path for ideas at X, Teller emphasized, "There is never going to be a manual. It doesn't work that way." This acceptance of ambiguity persisted throughout X. Helen Riley, X's Moonshot Mission Controller (i.e., Chief Financial Officer) noted that while the flow and funding of projects did depend on certain rules of thumb, "…it was still as much an art as it was a science". The typical progression of a successful X idea involved three stages—Rapid Evaluation, the Foundry, and X Project—with each step contributing to funneling the many hundreds of ideas initially pursued down to a few select projects that X hoped would eventually graduate. As of 2016, X had publicly graduated roughly one project per year since 2010.

Stage 1—Rapid Evaluation. X had a dedicated group of scientists and engineers referred to as "rapid evaluators" whose job it was to consider ideas at their earliest stages. Working in small teams, these evaluators had the freedom to pursue any new idea that reasonably aligned with X's mission. The primary focus in this stage was to prove (1) that the idea warranted X's attention by addressing a huge problem with a breakthrough technology that offered a radical solution and (2) that the solution was technically feasible. These two proof points had to be achieved with as small of a budget as possible, often as little as a few thousand dollars. Funds for these endeavors came from a specific budget item, but rarely were funds expressly allocated to any particular team or idea. The goal during the rapid evaluation process was for teams to develop a prototype as quickly as possible. Theoretical

[5] Teller continued, "Yet a common tendency is to rush off and start building a really great pedestal, both because you know how to and because it's human nature to want the boss to say, "Hey, nice pedestal, great job!"It takes a lot of faith in your boss (and the bosses above) to think that he or she will say a hearty thank you for helping to figure out whether and for how long your organization should invest resources in advanced monkey education."

investigations played a large role during this stage, but convincing leadership to commit further resources to any project would often require an actual working prototype.

Stage 2—The Foundry. In X's early days, its workforce was comprised largely of scientists and engineers who, unsurprisingly, focused on the *technical* challenges of each new idea. X leadership, however, quickly realized that the *non-technical* aspects of an idea, such as product-market characteristics, business planning, and financing, were just as relevant to its ultimate success or failure. To address these issues, Obi Felten, X's Head of Getting Moonshots Ready for the Real World, led the development of X's Foundry stage. She noted, "The goal of the Foundry is to answer fundamental business questions about a project. Who is the user? What problem are we solving for exactly? How might we turn this into a product and then, eventually, into a business? Ultimately, we want to make sure that we don't build technology that nobody wants."

Investigations during the Foundry stage also considered broader questions about the business opportunity associated with an idea. Was the problem better suited for philanthropic support? Was X really the best place to pursue this moonshot? The goal at this stage was to create a product prototype with a de-risked path forward, such that X would feel comfortable growing the size of the team and financial investment.

Stage 3—X Project. Some projects eventually reached a point where the technology, or prototype thereof, was fully operational and ready for testing in the market. At this point, the "idea" would officially become a "project" and would be given more resources and personnel. This stage would often involve beta-testing the technology outside of the lab or trialing the product in selective applications. These projects could maintain that status for anywhere from 2 to 10 years. Thus, these projects were not only the most promising and closest to completion in X's portfolio, but they defined the public's perception of the type of work pursued by X. Projects were by no means guaranteed successes but rather required market testing to refine predictions about their prospects.

Kill Metrics, Monkeys, and Milestones

The progress of ideas through each stage of development at X was determined by "kill metrics" and "risk lists". At the outset of its work, a team would make a list of all the risks facing the idea, an exercise designed to help identify "the monkey" – the most challenging part of the idea. The risks could be due to the technology—primarily related to feasibility and the product's capabilities—or the business—which included market conditions and the product's value proposition. The team members then rated the risks in terms of severity (i.e., how important was the risk) and comfort (i.e., how certain were they that they could address the risk). The risks that were both severe and uncomfortable became the idea's "monkeys" and were thus pursued first.

With the set of monkeys in hand, the team would set a series of milestones that, if successfully achieved, would enable it to request more resources from management. These milestones were systematically reviewed and updated every 1 to 2 quarters. Typically, the focal metrics in the early stages revolved around technical capabilities. Once those capabilities were achieved, the idea could enter the Foundry stage where the business and financial risks become more relevant.

The kill metrics–events or milestones that would justify cancelling the purusit of an idea–were determined at the beginning of this process and held fixed throughout its lifecycle. This was because kill metrics are only meaningful if teams committed to following them. Matt Eisaman, the PARC researcher responsible for much of the science that grew into the Foghorn project, highlighted the importance of X's emphasis on committing to kill criteria early in the pursuit of an idea. He noted, "It is important to set kill criteria right when the project is starting so you can't move the goal posts. Once you're invested in a project, no matter how clear-eyed and logical you are and try to be, it's always sad if something doesn't work and you have to kill it." The rigidity of kill metrics, however, was not absolute; in the event of dramatic changes to external factors deemed critical to an idea's success (e.g., a market-level surge in demand), kill metrics could be adjusted.

Kill metrics often included economic targets based on what X employees referred to as "techno-economics"–a process that incorporated predictions from subject matter experts about what was technically feasible with economic estimates of the value (e.g., production costs and sales price) of the technology given the anticipated technical feasibility. Having these estimates inform the kill metrics gave each team a constant source of focus.

Endpoints

In general, X's pursuits faced one of two fates: graduation or death. If a project continued to proceed without hitting any kill metrics and demonstrated success, it would graduate. What did "success" mean for an X project? According to Teller, "Once execution becomes the main challenge, we are no longer best suited to push the project forward." Success at X thus meant getting projects to the state where the primary goal was no longer to figure out what to do, but to do it. Upon graduation, a project could be integrated into other existing Google teams, developed into an Alphabet subsidiary, or completely spun out into an independent entity.

If a kill metric was reached, whether or not "project" status had officially been designated, efforts on the idea would be ceased. This process, however, could take many forms depending on the state of the technology and the specific reason for the kill. An idea could be completely discarded, with its team members being allocated to new efforts within X. This occurred if, for example, the kill metric was triggered by a barrier that was deemed insurmountable in the near future. Alternatively, an idea could be "shelved" until a future time that was or was not specified. Shelving occurred if a large barrier to progress was identified, but progress in overcoming the barrier outside X (e.g., by academic scientists) was expected. As Teller put it, someteimes X had to "…put a project in the refrigerator, because we're waiting for 'unobtanium'. We don't know how to make the unobtanium, but if someone else were to figure it out, the rest of the project would become compelling." Similarly, an idea might be shelved if the market conditions underlying a kill metric were expected to improve based on factors such as price shocks for key natural resources. Upon shelving an idea, X also had to decide to what extent it wanted to pursue intellectual proptery (IP) protection for any of the technologies that had been developed to that point and how much information, if any, to disclose publicly via press releases or scientific publications. Finally, an idea might also be repurposed at X. That is, if the progress made on one pursuit was relevant to another, then individuals or their work would be redirected accordingly.

The Value of Time: A Lesson from Loon

One challenge in killing a project at X was the possibility that a unknown breakthrough was imminent. X's experience with its project named Loon was instructive in this regard. In 2011, due to a combination of geographic challenges (e.g., jungles or mountains) and market challenges (e.g. the cost of delivering service to remote areas), more than half the world's population did not have access to fast, affordable internet service. X's radical solution to this problem was Project Loon – a network of high altitude balloons sailing on winds in the stratosphere designed to deliver Internet to people in rural and remote areas at speeds similar to 3G networks.

The initial vision for Loon was to create a ring of balloons around the world and control them just enough to act like floating cell phone towers in the sky. The idea was that as one balloon drifted away from a place that needed an Internet signal, the next balloon would be ready to move into place. Instead of requiring heavy and expensive thrusters to maintain or change position, Loon balloons would sail on winds in the stratosphere, steering by pumping air in or out of the balloon to make them lighter or heavier, and move into wind streams traveling in the desired direction.

The team ran its first sizable tests in 2013, launching dozens of balloons from New Zealand to see if they could circumnavigate the globe. During these tests they managed to get the balloons to sail thousands of kilometers around the world, making a range of discoveries that led to product improvements. Despite these positive early signs, creating a ring of balloons around the globe to deliver Internet access to a specific region involved large manufacturing and operating costs that the team would need to address if the project was going to avoid being killed.

Over the coming years, the team ran tests around the world, making steady progress to improve the flight system – including developing a more efficient altitude control system and more robust balloons that were capable of staying aloft for well over 100 days. And after years of flying, the team had a much better understanding of the winds in the stratosphere. By combining millions of miles of real flight data with 35 years of historical stratospheric wind data, they were able to build machine learning powered navigational algorithms capable of making real time predictions and adjustments about the best winds for the balloons to catch.

During the first four years of development, the team had never kept a balloon in one area for more than a few hours. But in early 2016, while running flight tests in Peru, the navigational improvements had improved to give the team a much higher degree of control, and the whole model for Loon changed. Rather than creating a ring around the world, small teams of balloons could be sent to form a cluster over a particular region where people needed internet access. Keeping a cluster of balloons dancing on the winds in small loops meant a dramatic reduction in both the total number of balloons and overall cost and operational complexity of getting a Loon-powered network up and running.

Managing People: Building a Positive Culture of Killing

In many traditional R&D organizations, individuals had incentives – sometimes explicit bonuses, sometimes implicit pride – that were tied to the survival of their projects. These incentives often rewarded individuals for keeping projects alive, even if progress on the content of the project had stalled. This incentive often led teams to pursue the easy, initial steps of a project—even with the knowledge of a future impasse—simply to extended its life. This tendency was compounded by the so-called "sunk-cost fallacy", whereby individuals would incorrectly intuit that the prior amount invested in a project was relevant to the future value of that project. Such incentives and perceptions were exactly what X needed to avoid.

X addressed these challenges through a number of mechanisms. Perhaps most importantly, X was highly selective when recruiting new employees. Management frequently sought out individuals who displayed a high tolerance for ambiguity, risk, and failure. Further, X placed emphasis on employees having a flexible set of skills that could be applied to a wide range of topics. These "generalists" would be more likely to contribute to any given idea, which was essential given that there was no way to predict the future problems X might pursue. Rich DeVaul, X's Director of Mad Science and the leader of its Rapid Evaluation efforts, contrasted the traditional notion of an expert with the ideal X employee. He noted, "The classic definition of an expert is someone who knows more and more about less and less until they know everything about nothing. People like that can be extremely useful in a very focused way. But these are really not X people. What we want, in a sense, are people who know less and less about more and more."

Beyond recruitment, X instituted a number of formal and informal programs to encourage employees to kill projects early, while accounting for the side effects of repeated failure on individual team members. If a kill decision was deemed important enough, employees could receive bonuses – a policy that Teller admitted was initially difficult to sell to Google's leadership. Similarly, promotions would not be withheld because an individual had killed projects with which they were involved. More informally, kill decisions were announced and celebrated within X, with meetings focused on maintaining comradery and positive attitudes amidst the continual churn of projects. Teller thought that these cultural aspects of promoting the kill-fast approach were essential. He observed, "A lot of this was about the attitudes, social norms, and a commitment to critically thinking and finding ways to be passionate and dispassionate in the same moments, or at least in the same month." Motivating this "passionate-dispassionate" attitude, without being oxymoronic, was easier when X's employees saw their peers celebrated, rewarded, and sometimes promoted following their project failures.

Why Not Pursue Everything? Headwinds and Tailwinds

Beyond killing projects that were no longer productive in the traditional sense, it was important for X to determine how each project fit into its current (and projected future) portfolio of projects. Despite the fact that Alphabet had cash reserves in excess of $65 billion in 2015, there was still only so much capital that Riley could reasonably request from Alphabet to support projects in X's pipeline. With this in mind, she sought to develop a sense of financial accountability without stifling X's ingenuity. In practice, this meant that Riley and her staff needed to become much more involved in understanding the technical aspects of each project to understand better both its prospects and how it fit into X's overall portfolio.

R&D organizations typically looked to build portfolios that diversified risk while maximizing complementarities between projects. Such strategies aimed to maximize expected average returns but typically required rigid rules about which projects would be pursued at certain times. To avoid this rigidity, Riley and the rest of X's leadership took a flexible approach to evaluating how each project fit within the portfolio.

Teller referred to this flexible approach as taking stock of X's "tailwinds and headwinds". To implement this approach, teams at X would discuss sectors, technologies or product applications where X currently had either a considerable advantage (i.e., a tailwind) or a disadvantage or preference to avoid (e.g., headwind). Headwinds and tailwinds were driven by a number of factors: the composition and skill mix of X's current workforce; ongoing or prior capital investments in technologies; and market conditions.

X was acutely aware of the possibility that continued operation in a certain sector or technology might lead to opportunity costs that would make it increasingly difficult to pursue different avenues in the future. Teller emphasized that X's mission was not to develop itself into an R&D firm of any particular type but rather to be the innovation engine of Alphabet. Thus, it was possible that certain tailwinds could eventually and intentionally be shifted to headwinds to keep X from becoming trapped pursuing an increasingly similar set of new projects. For example, Teller noted, "Once we had a cyber security project, there was a bit of a headwind about creating another cyber security project."

Foghorn: Turning Seawater into Fuel

The origins of Foghorn could be traced back to June 2013, when DeVaul came across a scientific paper by Eisaman and his colleagues from the journal *Energy & Environmental Science*. Entitled "CO_2 extraction from seawater using bipolar membrane electrodialysis,"[6] the paper excited DeVaul because it described the performance of "…a custom designed and built CO_2-from-seawater prototype, demonstrating the ability to extract 59% of the total dissolved inorganic carbon from seawater as CO_2 gas." That is, the technology appeared to be able to extract CO_2 from the ocean efficiently. This technology addressed a key remaining challenge in synthesizing carbon-neutral liquid fuel; with CO_2 in hand, there were well-known techniques to combine it with hydrogen to form liquid fuels like methanol. Eisaman and his team—at the time, based at PARC—were not the first to achieve this sort of CO_2 extraction, but they made a major stride in doing so at a cost that appeared within the realm of commercial viability. That was what got DeVaul excited. He discussed the paper during a dinner with X colleagues including Hannun, then a project manager on the Rapid Evaluation team, who was well versed in the renewable energy market.

Like DeVaul, Hannun found the technology promising and, most importantly, realized that it could form the basis of a project that aligned perfectly with X's three-part requirements (see **Exhibit 4**): (1) a carbon-neutral fuel ready for personal or commercial use would make a significant dent in global greenhouse emissions; (2) converting seawater into fuel was a radical approach to this problem; and (3) the technology underlying this process was at the forefront of energy science.

In August 2013, Hannun asked Eisaman to visit X for a seminar presentation of his work. Eisaman's talk struck a chord with the engineers at X. In the months following, Hannun and her Rapid Evaluation

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[6] Eisaman et al. 2012. CO2 extraction from seawater using bipolar membrane electrodialysis. Energy Environ. Sci.; 5:7346-7352.

team began constructing high-level, theoretical models of how the seawater-to-fuel system might perform and the resulting per-unit costs of operating it. Although the underlying science was complex, the general idea was simple: CO_2 and H_2 would be extracted from seawater and recombined as a hydrocarbon ready for commercial use (see **Exhibit 5**). Hannun's team developed a series of estimates that pointed toward an ultimate unit cost of $5-10 per gasoline gallon equivalent (gge), including all costs of production and distribution. The team decided to set its first and most important kill metric: the final unit cost of delivering the fuel to consumers would need to be under $5 per gge within five years. Global gasoline prices (i.e., retail pump prices) at the time were hovering around $4 per gallon and select markets had prices upwards of $8 per gallon (see **Exhibits 6-7**). The fuel would be a commodity, after all, and the team felt that the best price targets would be those for gasoline, the closest substitute.[7]

Though Hannun's team understood the technology well enough to theorize about its prospects, they quickly realized the value Eisaman and his colleagues could add through a joint venture. Not only would Eisaman bring needed technical expertise in electrochemistry to the group, but his appreciation of both the enormous commercial potential and major obstacles related to the technology made Hannun confident that he would be a good fit for X. "You want to work with somebody who has thought critically about the hard parts," she noted, "Because ultimately those are the things you'll be working on to make the idea a success." Together, the two decided to begin a joint venture between Eisaman and his former PARC colleagues and Hannun and her team at X. They codenamed it Foghorn.

The official goal of the Foghorn project was to develop a carbon-neutral liquid fuel alternative that would be competitive with fossil fuels. The four "monkeys" for Foghorn were: (1) obtaining industrial production amounts of carbon and (2) likewise for hydrogen; (3) combining the two in an end-to-end system that was carbon neutral; and (4) achieving the first three steps such that the ultimate fuel price possible in five years would be less than or equal to $5 per gge.

Unsure as to which monkey to pursue first, the team began by using the earlier work of Eisaman's PARC team to build a small (but complete) end-to-end prototype of the system at PARC. By September 2014, the prototype was complete. The system could successfully take in sea-water and generate a crude methanol product while staying carbon neutral. Although the prototype validated the technical feasibility of the design, it also highlighted many challenges that would come with full scale up. A chief concern was the fact that the electrodialysis membranes, where the CO_2 extraction occurred, were ruined quickly by the accumulation of minerals (e.g. scale and calcium carbonate) in the seawater. Because the membranes were one of the most expensive components in the system, continually replacing them at the required rate would drive unit production costs well above $30 per gge, far beyond Foghorn's target.

Momentarily stumped, the Foghorn team traveled to Singapore to visit leading experts on electrodialysis membranes. At the same time, engineers spoke with desalination experts, with the intent of devising a system to rid the water of salt and minerals before contact with the membranes. Yet, for months, little progress was made.

To reinvigorate efforts, X hosted a "Foghorn Summit" in March 2015, bringing together team members from X and PARC. During the summit, data from the prototype was circulated and new solutions to the membrane issue were hypothesized, explored, and refuted. One idea gained traction during these discussions: co-locating the Foghorn technology with water desalination plants. These existing plants were already removing the compounds that had plagued Foghorn's membranes and were doing so on an industrial scale. Early theoretical models suggested that if the Foghorn system could be incorporated into a standard desalination plant, then the membranes would have a much more reasonable lifespan.

[7] Relatedly, see **Exhibit 8** for trends in country-specific adoption of electric vehicles as a share of all automobiles.

With the newfound knowledge of desalination technology, some of the team began work on a second prototype that could either co-locate with a desalination plant or operate independently (albeit at higher cost). The Foghorn team also decided to hire a process engineer who specialized in modeling the costs of fuel refineries. This individual had experience projecting costs for all aspects of operations and quickly highlighted how the Foghorn team had been underestimating the overhead costs needed to get the fuel from sea to the consumer's gas pump. The team realized it had not fully accounted for costs related to factors such as equipment and their lifecycles (e.g., seawater piping and pumping and gas desorption membranes), as well as labor, taxes, and the evolution of fuel yields.

Third, Hannun and others on the team simultaneously began to tackle the question of whether it was more efficient to extract H_2 from seawater or to purchase it commercially. Thus far, the team had focused largely on the efficiency of CO_2 extraction, but low-cost, emissions-free H_2 extraction proved to be another "monkey". Initially, the team spoke with industry leaders in H_2 production and identified a number of technologies that were technically feasible, including polymer membrane electrolysis, but all proved too expensive. By June 2015, the team had identified solid oxide electrolyzer cell (SOEC) technology as a tool that could possibly extract H_2 from seawater. SOEC used electricity to break down steam – which would be generated using seawater – into hydrogen and oxygen gas. These cells could theoretically have been paired with Eisaman's electrodialysis methods for obtaining CO_2. Again wading into new territory, the Foghorn team visited the Idaho National Laboratory where Carl Stoots, a leader in SOEC technology, provided guidance on the state of the science. As in the case of the membranes, SOEC appeared on the verge of a breakthrough but faced many challenges should full-scale development be pursued.

Shortly after the Idaho visit, the cost model was complete and had generated two estimates that depended on whether or not the system was co-located with a desalination plant. Because the SOEC technology was not yet fully developed, the model assumed that Foghorn would need to purchase H_2 on the market. If Foghorn was able to integrate with existing desalination plants, the model predicted costs of \$8-16 per gge, whereas standalone operations suggested costs of \$16-28 per gge.

Realizing the importance of pairing with desalination plants, the Foghorn team visited the United Arab Emirates, where a large number of existing desalination plants were located. What they saw was promising. There was a wide variety of desalination technologies being explored, each offering unique possibilities. The team even identified a test laboratory within an existing desalination plant designed specifically for exploring technologies—exactly what Foghorn hoped to do. Furthermore, the local market was ripe with investment opportunities and talented workers skilled in renewable energy technology. However, the relatively small number of desalination plants and the amount of water they processed suggested that the co-location strategy would severely reduce Foghorn's impact on global carbon emissions, likely by a factor of about 200.[8]

The Foghorn team believed it had pushed the CO_2 extraction technology as far as it could. They continued to meet with SOEC experts around the world to better understand current capabilities with respect to extracting H_2. The team expected that, with further investment, X could likely develop a full-scale SOEC system that would provide a carbon-neutral method for producing H_2 at a cost roughly equivalent to the \$1 per gge cost of purchasing H_2 on the market (though purchased H_2 would likely not be produced via carbon-neutral methods, which was contrary to the initial vision for Foghorn). By December 2015, the Foghorn team had refined its estimates down to \$10-12 per gge given current technologies. Achieving this at full scale, however, was expected to require in excess of \$1 billion dollars in additional fixed costs and many more years of continued development work to push costs down to closer to their goal of \$5 per gge.

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[8] Eisaman's estimates indicated that under reasonable assumptions about the growth of the desalination plant industry—approximately 7% CAGR over 35 years—the maximum annual avoidance of CO_2 under the co-location strategy was 50 megatons, whereas the stand-alone strategy (which nearly doubled the cost per gge estimates) could avoid roughly 1,000 megatons of CO_2 per year, which would have amounted to roughly 3% of global CO_2 emissions during this period (worldwide CO_2 emissions in 2014 were approximately 36,000 megatons).

To Kill or Not to Kill?

By this point in the investigation the team had started "stacking moonshots": the CO_2 extraction *and* producing low-cost, carbon-neutral H_2. The prospect of such a large and continued investment before commercialization would make Foghorn unlike any other X project. But progress appeared possible. The team had developed a system that could convert seawater into a fuel source and do so without emitting CO_2. But Foghorn was close to the point that concerned Teller in the lifecycle of *any* X project—where *execution* was becoming the main challenge. As she began to think about her upcoming meeting with the leadership of X, Hannun knew that she had to decide whether her team should request further funding in pursuit of a unit cost of $5 per gge, whether it was worth adjusting the metric and moving the project closer to graduation using existing technologies, or whether it should be killed. If the decision was to kill the project, Hannun needed to suggest how X should handle the IP related to Foghorn that it had created and patented (**Exhibit 9** includes a list of patents related to Foghorn that were secured by X). Should it hold the information internally or should it publicize its work for the broader academic community?

Whichever path X pursued for Foghorn, Hannun knew that she would be asked for a plan to communicate that decision to the Foghorn team, the rest of the X organization, and potentially the overall leadership of Alphabet.

Exhibit 1 Alphabet Finanical Information, FY 2013-2015

Information about Segments

In conjunction with the Alphabet reorganization, in the fourth quarter of 2015, we implemented legal and operational changes in how our Chief Operating Decision Maker (CODM) manages our businesses, including resource allocation and performance assessment. Consequently, we have multiple operating segments, representing the individual businesses that are run separately under the Alphabet structure.

Google is our only reportable segment. None of our other segments meet the quantitative thresholds to qualify as reportable segments; therefore, the operating segments are combined and disclosed below as Other Bets. All prior-period amounts have been adjusted retrospectively to reflect the reportable segment change.

Our reported segments are described below:

- Google – Google includes our main internet products such as Search, Ads, Commerce, Maps, YouTube, Apps, Cloud, Android, Chrome, Google Play as well as hardware products we sell, such as Chromecast, Chromebooks and Nexus. Our technical infrastructure and newer efforts like Virtual Reality are also included in Google.
- Other Bets – Other Bets is a combination of multiple operating segments that are not individually material. Other Bets includes businesses such as Access/Google Fiber, Calico, Nest, Verily, GV, Google Capital, X, and other initiatives.

Please refer to Note 16 of the Notes to Consolidated Financial Statements included in Part II of this Annual Report on Form 10-K for further information.

Consolidated Revenues

The following table presents our consolidated revenues, by segment and revenue source (in millions), for the periods presented:

	Year Ended December 31,		
	2013	2014	2015
Google segment			
Google websites	$ 37,422	$ 45,085	$ 52,357
Google Network Members' websites [1]	13,650	14,539	15,033
Google advertising revenues	51,072	59,624	67,390
Google other revenues [1]	4,435	6,050	7,151
Google segment revenues	$ 55,507	$ 65,674	$ 74,541
Other Bets			
Other Bets revenues	$ 12	$ 327	$ 448
Consolidated revenues	$ 55,519	$ 66,001	$ 74,989

(1) Prior period amounts have been adjusted to reflect the reclassification primarily related to DoubleClick ad serving software revenues from Google other revenues to Advertising Revenues from Google Network Members' websites to conform with the current period presentation.

Consolidated Results of Operations

The following table presents our operating results as a percentage of revenues for the periods presented:

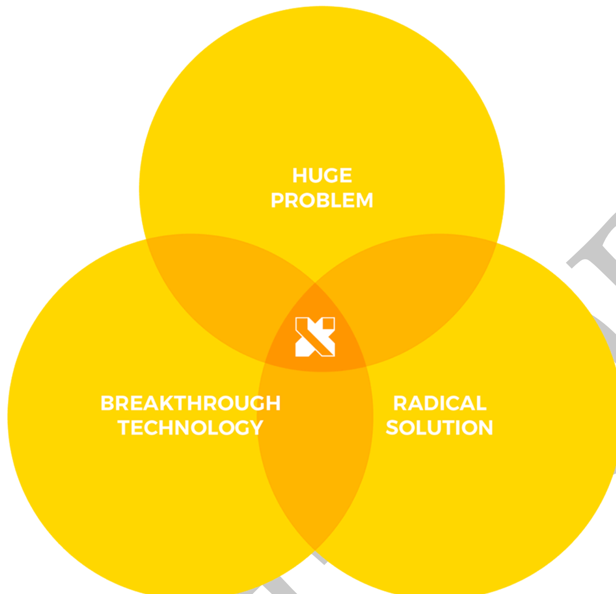
	Year Ended December 31,		
	2013[1][2]	2014[1][2]	2015
Consolidated Statements of Income Data:			
Revenues	100.0 %	100.0%	100.0%
Costs and expenses:			
Cost of revenues	39.6	38.9	37.6
Research and development	12.9	14.9	16.3
Sales and marketing	11.8	12.3	12.1
General and administrative	8.0	8.9	8.2
Total costs and expenses	72.3 %	75.0%	74.2%
Income from operations	27.7	25.0	25.8
Other income (expense), net	0.9	1.1	0.4
Income from continuing operations before income taxes	28.6	26.1	26.2
Provision for income taxes	4.9	5.5	4.4
Net income from continuing operations	23.7	20.6	21.8
Net income (loss) from discontinued operations	(0.8)	0.8	0.0
Net income	22.9 %	21.4%	21.8%

(1) Financial results of Motorola Home were included in net income (loss) from discontinued operations for the year ended December 31, 2013. Financial results of Motorola Mobile were included in net income (loss) from discontinued operations for the years ended December 31, 2013 and 2014.

(2) In the second quarter of 2015, we identified an incorrect classification of certain revenues between legal entities, and as a consequence, we revised our income tax expense for periods beginning in 2008 through the first quarter of 2015. Please refer to Note 1 and Note 17 of the Notes to Consolidated Financial Statements included in Part II of this Annual Report on Form 10-K.

Source: Alphabet 10-K SEC Filing, 2015.

Exhibit 2 X's Project Requirements



We're a moonshot factory. Our mission is to invent and launch "moonshot" technologies that we hope could someday make the world a radically better place. We have a long way to go before we can fulfill this mission, so today it's really an ambition.

This is our blueprint for X moonshots: we look for the intersection of a big problem, a radical solution, and breakthrough technology. We start with a large problem in the world that if solved could improve the lives of millions or even billions of people. Then we propose a radical solution that sounds impossible today, almost like science fiction. Lastly, we look for a technology breakthrough that exists today; this gives us the necessary hope that the solution we're looking for is possible, even if its final form is five to ten years away and obscured over the horizon.

We tackle ideas that have the riskiness and ambition of early-stage research and approach them with the focus and speed of a startup. Our goal is to develop and de-risk these early-stage ideas and turn them into proven technologies that make a real impact in the world.

Source: X company website (x.company)

Exhibit 3 Timeline of X Graduates

GRADUATED 2015

Verily

Google[x] Life Sciences was created to help shift healthcare from reactive to proactive through initiatives such as the Smart Contact Lens, the Baseline Project, and Nanodiagnostics. The project is now Verily, a separate company within Alphabet.

Glass

Glass Explorer Edition became a part of Google's hardware group, and the Enterprise Edition is now at X. Learn more about how Glass can work for businesses.

Gcam

Gcam improved mobile photography using techniques from computational photography. The project is now a part of Google Research.

GRADUATED 2013

Google Watch

Google Watch created technologies that were critical to the development of what is now Android Wear. The project is now a part of Android.

GRADUATED 2012

Project Insight

Project Insight's mission was to provide navigation to locations of interest in public indoor spaces. The project is now a part of Google Maps.

Google Brain

Google Brain enables revolutionary advances in artificial intelligence and machine learning, and allows computers to understand images, audio, and text inspired by some of what we know about the human brain. The project is now a part of the Research team at Google.

Flux

Flux was created to meet the world's demand for high-quality, sustainable buildings by providing a big-data-powered building platform to improve how buildings are designed, built, and maintained. The project is now an independent company.

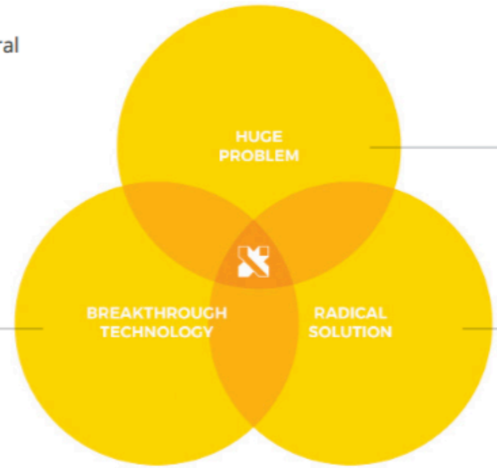
Project Tango

Project Tango combined advanced computer vision, image processing and vision sensors to allow mobile devices to "know" where they are and how they move through space. The project became part of Daydream, Google's Virtual Reality team. While Tango is now no longer supported, Google is continuing AR development with a new platform, ARCore.

Source: X company website (x.company)

Exhibit 4 Foghorn's Fit with X's Project Requirements

Foghorn aimed to reduce carbon emissions in the atmosphere by developing "sea fuel"—a carbon-neutral liquid fuel created from seawater.



Huge Problem

Transportation accounts for 14% of global greenhouse emissions

Liquid fuels like gasoline are extraordinary substances: just a dozen gallons can propel your average car for hundreds of miles. Unfortunately, burning such fuels to power cars, trucks, planes, and other vehicles has unfavorable side effects—like releasing carbon dioxide into the atmosphere.

Radical Solution

"Sea fuel"– a carbon-neutral liquid fuel alternative

Might it be possible to create a liquid fuel that has all the advantages of fuels used today, but could be produced and burned in a closed cycle, without any of the carbon dioxide emissions that contribute to climate change? Could it work in existing vehicles and with our existing gas station refueling infrastructure? Could it be cost-competitive with fossil fuels?

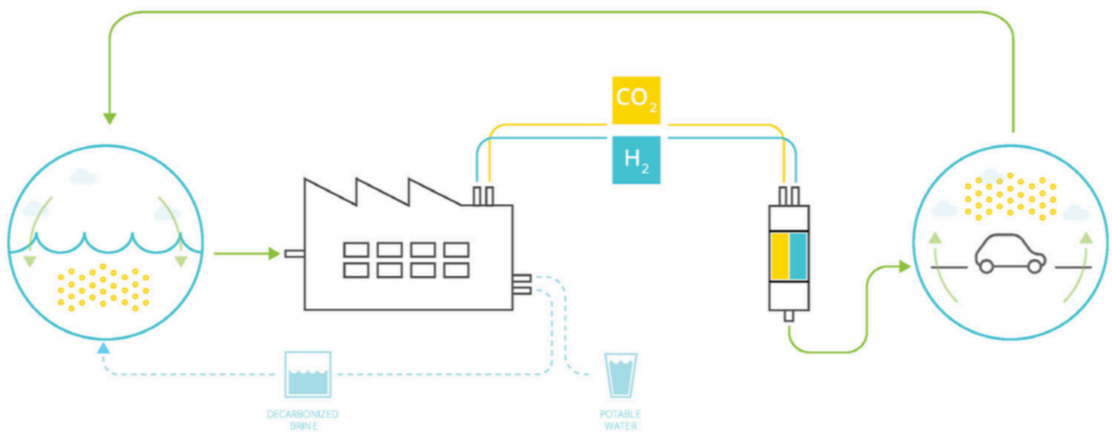
Breakthrough Technology

Electrochemical processes to create fuel from seawater

Seawater contains not only hydrogen and oxygen (water is H_2O), but also carbon dioxide that has been naturally absorbed over time from the earth's atmosphere. Electrochemical processes could pull the existing carbon and hydrogen out of seawater, which could then be combined to make a clean, carbon-neutral "sea fuel".

Source: X, Foghorn Public Relations Document

Exhibit 5 Foghorn System Overview



1

Absorption

The sea naturally absorbs carbon dioxide from the atmosphere.

2

Processing

Carbon dioxide is extracted from sea water and hydrogen is produced via electrolysis using renewable energy sources. Optionally, potable water can be produced via desalination.

3

Synthesis

Inside a catalytic reactor, hydrogen is reacted with carbon dioxide to make a liquid fuel for vehicles - what we call **sea fuel.**

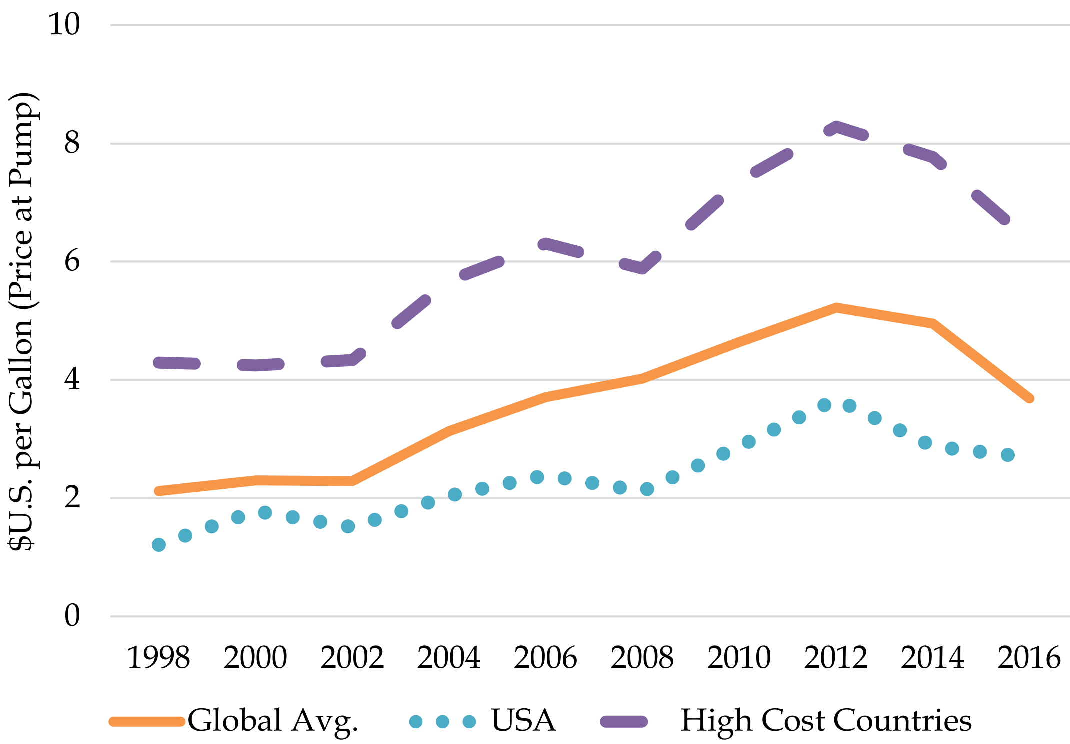
4

Consumption

Vehicles are powered by sea fuel. Carbon dioxide from vehicles is re-absorbed into the sea to be used again.

Source: X, Foghorn Public Relations Document

Exhibit 6 Trends in Global Gasoline Prices



Source: German Agency for International Cooperation (GIZ) via the World Bank

Note: High Cost Countries: Hong Kong, Norway, Iceland, Netherlands, Italy, Israel, Denmark

Exhibit 7 Country-Specific Gasoline Prices and Quantities, 2014

Country	$ per Gallon	Gallons per Year (Millions)	Country	$ per Gallon	Gallons per Year (Millions)
Norway	8.59	169	Palestine	6.70	31
Netherlands	8.14	698	South Korea	5.87	1,541
Italy	8.10	1,541	Argentina	5.75	1,019
Hong Kong	7.80	72	Japan	5.22	7,266
Denmark	7.61	238	Brazil	4.81	4,193
Greece	7.50	475	Australia	4.66	2,399
UK	7.27	2,345	South Africa	4.50	1,594
Ireland	7.27	207	China	4.43	18,879
Belgium	7.19	215	Canada	4.43	6,239
Finland	7.15	276	India	4.16	3,066
Portugal	7.15	192	Mexico	3.90	5,833
Israel	7.12	468	Indonesia	3.52	4,093
Iceland	7.00	24	Russia	3.07	6,393
Sweden	6.89	491	USA	2.88	67,782
Barbados	6.85	16	Malaysia	2.57	2,162
Germany	6.81	3,273	Nigeria	2.12	1,280
Uruguay	6.81	92	UA Emirates	1.78	1,027
France	6.78	1,226	Iraq	1.63	1,027
Slovenia	6.74	84	Iran	1.40	2,828

Source: German Agency for International Cooperation (GIZ) and the U.S. Energy Information (in U.S. Dollars). Gallons used per year is approximated based on an assumed conversion of 20 gallons of motor gasoline per barrel imported.

Exhibit 8 Country-Specific Trends in Electric Vehicle Market Share

Electric cars: Market share

Table 11 • Electric cars (battery electric and plug-in hybrid), market share by country, 2005-15

	2008	2009	2010	2011	2012	2013	2014	2015
Canada				0.0%	0.1%	0.2%	0.3%	0.4%
China			0.0%	0.0%	0.1%	0.1%	0.4%	1.0%
France				0.1%	0.3%	0.5%	0.7%	1.2%
Germany				0.1%	0.1%	0.2%	0.4%	0.7%
India			0.0%	0.0%	0.1%	0.0%	0.0%	0.1%
Italy					0.0%	0.1%	0.1%	0.1%
Japan		0.0%	0.1%	0.4%	0.5%	0.6%	0.7%	0.6%
Korea				0.0%	0.1%	0.1%	0.1%	0.2%
Netherlands			0.0%	0.2%	1.0%	2.5%	3.9%	9.7%
Norway	0.2%	0.1%	0.3%	1.5%	3.2%	5.8%	13.7%	23.3%
Portugal				0.1%	0.1%	0.2%	0.2%	0.7%
South Africa								0.1%
Spain				0.1%	0.1%	0.1%	0.2%	0.2%
Sweden				0.1%	0.3%	0.5%	1.4%	2.4%
United Kingdom				0.1%	0.1%	0.2%	0.6%	1.0%
United States			0.0%	0.1%	0.4%	0.6%	0.7%	0.7%
Others*				0.0%	0.1%	0.1%	0.3%	0.7%
Total**	0.0%	0.0%	0.0%	0.1%	0.2%	0.3%	0.5%	0.9%

* Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Greece, Hungary, Iceland, Ireland, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Poland, Romania, Slovak Republic, Slovenia, Switzerland, Turkey.

** The total market share is calculated for all the countries covered above.

Source: Global EV Outlook 2016. OECD/ International Energy Agency. 2016.

Exhibit 9 Patents related to Foghorn

The following patents stemming from Foghorn's development were granted to X:

1. Pat. No. 9,915,136: Hydrocarbon extraction through carbon dioxide production and injection into a hydrocarbon well
2. Pat. No. 9,914,683: Fuel synthesis from an aqueous solution
3. Pat. No. 9,914,644: Energy efficient method for stripping CO.sub.2 from seawater
4. Pat. No. 9,873,650: Method for efficient CO2 degasification

Below are excerpts from Patent No. 9,914,644:

1

ENERGY EFFICIENT METHOD FOR STRIPPING CO_2 FROM SEAWATER

FIELD

This disclosure relates generally to the field of carbon dioxide separation and collection.

BACKGROUND

The separation of carbon dioxide (CO_2) from a mixed-gas source may be accomplished by a capture and regeneration process. More specifically, the process generally includes a selective capture of CO_2, by, for example, contacting a mixed-gas source with a solid or liquid adsorber or absorber followed by a generation or desorption of CO_2 from the adsorber or absorber. One technique describes the use of bipolar membrane electrodialysis for CO_2 removal from potassium carbonate and bicarbonate solutions.

For capture/regeneration systems, a volume of gas that is processed is generally inversely related to a concentration of CO_2 in the mixed-gas source, adding significant challenges to the separation of CO_2 from dilute sources such as the atmosphere. CO_2 in the atmosphere, however, establishes equilibrium with the total dissolved inorganic carbon in the oceans, which is largely in the form of bicarbonate ions (HCO_3^-) at an ocean pH of 8.1-8.3. Therefore, a method for extracting CO_2 from the ocean would effectively enable the separation of CO_2 from atmosphere without the need to process large volumes of air.

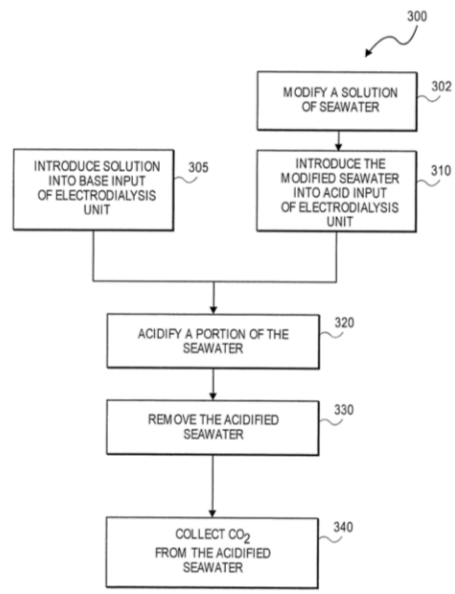


FIG. 3

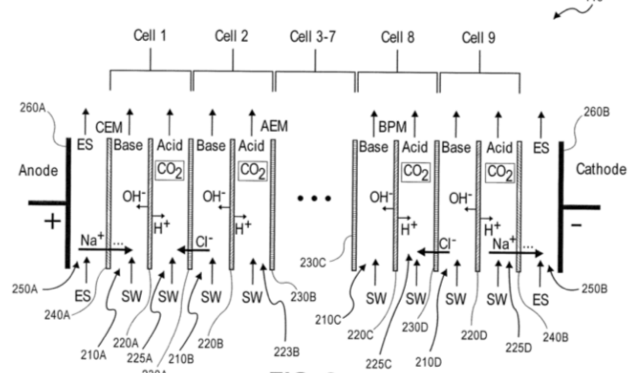


FIG. 2

Exhibit 10 Foghorn Development Timeline & Milestones

Time Period	Major Events	Fuel Cost Range
2012		
Feb.	• PARC paper published	
2013		
June-Aug.	• X discovers PARC paper and Dr. Matt Eisaman gives presentation at X	
Oct.	• Rapid Evaluation team begins theoretical modeling of carbon-neutral CO2-based fuel	$5-10 per gge
2014		
Jan.-March	• Eisaman joins X as a consulting scientist • Form partnership with PARC • Begin work on seawater-to-methanol prototype	
Sep.	• Prototype #1 complete • Salt water mineral deposits on the filtering membranes identified as key challenge • Consult with membrane and desalination experts in Singapore	> $30 per gge
2015		
March	• Host "Foghorn Summit" at X • Analyze data from Prototype #1 • Decide that co-location with desalination plants is promising solution to membrane challenge • Outsource techno-economic modeling of end-to-end costs of production	
June	• Initiate work on Prototype #2 • Identify potential of solid oxide electrolyzer cell (SOEC) technology to produce Hydrogen	
Aug.-Sep.	• Complete Prototype #2 • Visit desalination plants in United Arab Emriates	$8-16 per gge (with desalination plant) $16-28 per gge (stand-alone)
Dec. 2015 – Feb. 2016	• Continued experimentation with SOEC technology • Visit SOEC experts in US and Europe to confirm accuracy of model estimates	$10-12 per gge

Source: Casewriters, based on internal X documents and interviews