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Strategies for successful field deployment in a resource-poor region: Arsenic remediation technology for drinking water

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ABSTRACT

Strong long-term international partnership in science, technology, finance and policy is critical for sustainable field experiments leading to successful commercial deployment of novel technology at community-scale. Although technologies already exist that can remediate arsenic in groundwater, most are too expensive or too complicated to operate on a sustained basis in resource-poor communities with the low technical skill common in rural South Asia. To address this specific problem, researchers at University of California-Berkeley (UCB) and Lawrence Berkeley National Laboratory (LBNL) invented a technology in 2006 called electrochemical arsenic remediation (ECAR). Since 2010, researchers at UCB and LBNL have collaborated with Global Change Program of Jadavpur University (GCP-JU) in West Bengal, India for its social embedding alongside a local private industry group, and with financial support from the Indo-US Technology Forum (IUSSTF) over 2012–2017. During the first 10 months of pilot plant operation (April 2016 to January 2017) a total of 540 m^3 (540,000 L) of arsenic-safe water was produced, consistently and reliably reducing arsenic concentrations from initial 252 $\pm$ 29 to final 2.9 $\pm$ 1 parts per billion (ppb). This paper presents the critical strategies in taking a technology from a lab in the USA to the field in India for commercialization to address the technical, socio-economic, and political aspects of the arsenic public health crisis while targeting several sustainable development goals (SDGs). The lessons learned highlight the significance of designing a technology contextually, bridging the knowledge divide, supporting local livelihoods, and complying with local regulations within a defined Critical Effort Zone period with financial support from an insightful funding source focused on maturing inventions and turning them into novel technologies for commercial scale-up. Along the way, building trust with the community through repetitive direct interactions, and communication by the scientists, proved vital for bridging the technology-society gap at a critical stage of technology deployment. The information presented here fills a knowledge gap regarding successful case studies in which the arsenic remediation technology obtains social acceptance and sustains technical performance over time, while operating with financial viability.

1. Introduction and background

Drinking water is deemed unsafe if it contains more than 10 parts per billion (ppb) of arsenic (World Health Organization, 2011). Even at this provisional guideline value, or maximum contaminant level (MCL), the excess cancer risk from lifetime exposure to arsenic is 700 per 100,000 people (National Research Council, 2001). This lifetime cancer risk is about 60 times larger than the next highest lifetime cancer risk, which is linked to ethylene dibromide, in rank-ordered risks from consuming water with carcinogens permitted in water at their respective MCLs. Besides cancer, other health impacts of chronic exposure to arsenic include skin lesions, gangrene, cardiovascular diseases, and possible reduction in children's IQ (Naujokas et al., 2013). Health damages resulting from chronic exposure to high levels of arsenic add a huge health-cost burden on resource-poor communities in West Bengal, India (Roy, 2008).

Despite large expenditures by multilateral, bilateral, and national government programs (Adams, 2013), previous technology-based

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efforts to address the arsenic problem proved unsustainable in resource poor communities such as rural South Asia. This devastating fact emerged from research which looked at arsenic remediation technologies employed in one of the most arsenic-affected districts of West Bengal: the Murshidabad District. In this district, 93% of seventy implemented arsenic removal technologies failed within one to eight months (Das and Roy, 2013). Household- and community-scale arsenic treatment units installed in West Bengal, India during the past decade typically became dysfunctional within one year of installation due to multiple reasons (Das et al., 2016). In a water supply program for arsenic mitigation in Bangladesh, attempted solutions included dug wells, pond sand filters, rainwater harvesting, deep tube wells, piped water, and arsenic removal filters. The installed household arsenic removal filters were ineffective in removing arsenic and were abandoned after a few months (Hoque et al., 2004).

Technologies do not work in a vacuum. They have dozens or may be hundreds of threads connecting them to invisible social constructs such as belief systems, expectations, institutions and cultural norms, systems of incentives and disincentives, competing resource demands, and priorities of political and social hierarchies. Although external agencies were often willing to invest in remediation projects in resource-poor regions, those invested solutions proved to be unsustainable because they were not installed with a corresponding long-term sustainable societal placement strategy (Ahmad et al., 2003; Das et al., 2016). While proximate reasons for project failure include lack of maintenance, improper operational training, and cultural insensitivity, ultimate or deeper reasons include partisan politics, lack of genuine public consultation, lack of understanding of legal structures, and absence of sustainable business model-frameworks (Das et al., 2016; Etmannski and Darton, 2014; Sarkar et al., 2010).

Such continued poor results, despite the continued expenditure of effort and funds, suggest that scholarly research may shed light on what goes wrong with such efforts and why such failures continue to be repeated. The progression of electrochemical arsenic remediation (ECAR) from an effective bench-top laboratory beaker at University of California-Berkeley (UCB) and Lawrence Berkeley National Laboratory (LBNL), to a prototype in small field tests in West Bengal, India in collaboration with Global Change Program of Jadavpur University (GCP-JU), to a full-scale pilot plant with additional collaboration with a local industry partner, offers a case study of addressing some common challenges that arise during the advanced stage of the innovation chain. During this advanced stage, the technology needs to be scaled-up for an intended community for long-term sustenance, which requires social acceptance of the new technology.

The deployment of ECAR addresses the major global health crisis resulting from arsenic exposure in contaminated drinking water. Moreover, the United Nations has created a set of sustainable development goals (SDGs) which seek to meet milestones for human well-being (Griggs et al., 2013; United Nations, 2015). Addressing and mitigating the detrimental health and socioeconomic effects of arsenic will ultimately help meet the SDGs by the intended deadline of 2030. Thus, the deployment of ECAR, and this unique social placement strategy contribute to several of the 17 SDGs.

This paper presents the technical and social obstacles that were overcome during the case study to deploy the most recent and largest version of ECAR—a pilot plant with 2500-L reactors, with the capacity to produce 10,000 L per day (LPD) of safe, affordable drinking water in a rural village in India. It is important to note that this is a case study, not a hypothesis testing effort. The latter requires a randomized trial with large number of controlled experiments, and has its own value. In contrast, a single case-study can be hypothesis-generating, based on observations and experiences of the researchers from intense long-term efforts such as the one reported here.

2. ECAR: from lab to field

ECAR was invented in 2006 at LBNL and from 2008 onward developed at UCB. Information gathered during the past 13 years of the ECAR scale-up project, some of it in collaboration with Indian scientific collaborators, has resulted in a deep understanding of the process (Amrose et al., 2014; Delaire et al., 2017a; Gadgil et al., 2014; van Genuchten et al., 2016). This technology has matured, scaling-up in successfully larger designs from a 0.2-L beaker (in 2006) to a 10,000-LPD pilot plant (in 2016), as illustrated in Fig. 1.

During the ECAR process, a small voltage applied to steel plates immersed in arsenic-contaminated groundwater leads to the anodic dissolution of Fe(0), to produce Fe(II) ions. These ions then diffuse into the water being treated. In the water, the Fe(II) ions react with dissolved oxygen (DO) and convert into insoluble oxyhydroxides of Fe(III). Before completion, however, this complex oxidation process forms an intermediate byproduct: highly reactive intermediate oxidants (Fenton-type products). These effectively oxidize non-ionic As(III) to readily absorbed As(V) oxyanion (Amrose et al., 2013; Delaire et al., 2017; Hug and Leupin, 2003; Li et al., 2012). The insoluble Fe(III) ions polymerize *in situ*, producing Fe(III) (oxyhydr)oxides with a high affinity for binding As(V) (van Genuchten et al., 2012). In a subsequent step, the As-laden precipitates are separated from treated water by flocculation and sedimentation. In previous work in laboratory and field environments, ECAR reliably lowered initial arsenic concentrations between 90 and 3000 ppb in typical synthetic and real groundwater matrices from Bangladesh, India, and Cambodia (Amrose et al., 2013) to below the World Health Organization (WHO) guideline value of 10 ppb. Further fundamental science on ECAR will not be repeated in this paper, which focuses on the holistic aspects of implementation in the field.

2.1. The first large-scale ECAR plant

The pilot plant has a spatial footprint of 1400 ft^2 and is situated in a classroom on the south end of Dhapdhapi high school in West Bengal, India. The plant is set up in two adjoining sections: the ECAR Room and the Tube Settler Room (Fig. 2). A control board (Fig. S1) in the Tube Settler Room supplies power to all parts of the plant.

The schematic below depicts the treatment train at the pilot plant (Fig. 3). The influent water has an average arsenic concentration of 252 ± 29 ppb and is pumped from the school's shallow tubewell of 32 m in depth.

The arsenic-bearing groundwater flows into two 1250-L tanks where the ECAR process occurs. After delivering a specified Coulombic dose to the water using a custom-designed power supply (Fig. S1), treated or iron-dosed water is transferred to the first holding tank. A flocculation chamber aids in floc formation and agglomeration, and a subsequent tube settler allows the floc to settle out as the water flows up through angled media. Under normal operation, the tube settler achieves less than 5 nephelometric turbidity units (NTU) in the effluent water. Subsequent tertiary treatments include a rapid sand filter, a set of polishing filters and a disinfection step with an ultraviolet light. The final processes ensure that ECAR product water is both aesthetically pleasing and free of any potential biological contaminants. The process from groundwater pumping to ultraviolet (UV) disinfection consumes about 2.3 kWh of energy per m^3 of water treated. Finally, water is transferred to overhead tanks in the school courtyard where automatic dispensing units (ADUs) are placed for water access by students, teachers, and staff. The water access is based on an understanding made with the school authorities at the start of the pilot project, that if the project is successful, in exchange of permission granted for use of indoor and outdoor space for the ECAR plant, the school's students teachers and staff will all receive free arsenic-safe potable drinking water.

The Dhapdhapi plant was operated consistently by local operators, employed by the industrial licensee (Livpure Ltd), under technical supervision from UCB field engineers, five days a week, from April 2016 to

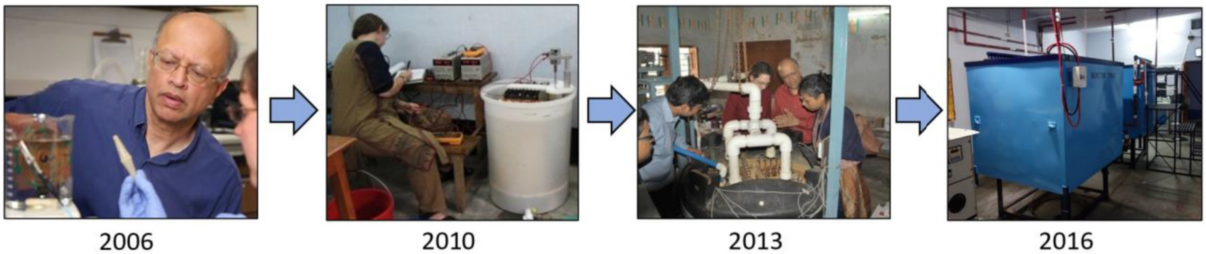

Fig. 1. Over the course of 10 years, ECAR scaled successfully and progressively from a 0.2-L beaker, to 100-L and 600-L prototypes, to a 10,000-LPD capacity field pilot plant.

Fig. 2. Digital photographs of the 10,000 LPD capacity pilot plant at Dhapdhapi High School. a) ECAR Room: Contains the two ECAR reactors in which electrolysis occurs b) Tube Settler Room: Contains the tube settler, flocculation chamber, and subsequent tertiary treatment systems for particle separation.

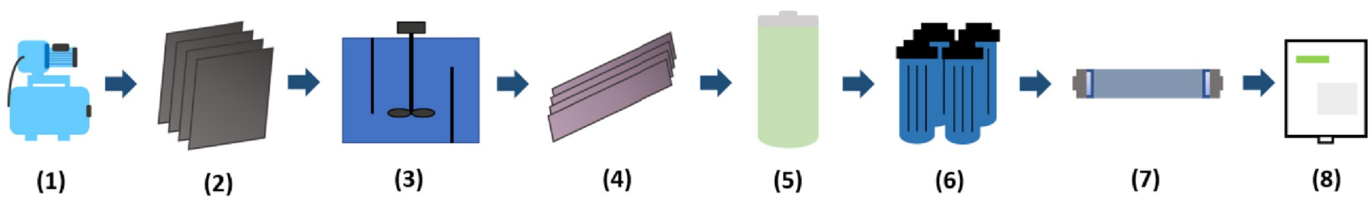

Fig. 3. Schematic representation of the treatment process at the Dhapdhapi pilot plant: 1) raw water pump, 2) ECAR reactors, 3) flocculation chamber, 4) tube settler, 5) rapid sand filter, 6) micron filters, 7) ultraviolet disinfection system, 8) automatic dispensing unit.

January 2017. Previous field trials of ECAR in India had demonstrated that a semi-skilled person (with high school education) can effectively operate the plant after appropriate training from the technical staff (Amrose et al., 2014). During the April 2016–January 2017 period, bi-weekly samples of raw and product water were collected and sent to UCB to test for arsenic and other relevant elements using inductively coupled plasma atomic emission spectroscopy (ICP-OES), and ICP-OES with hydride generation for arsenic levels below 10 ppb. Raw water parameters, including the ion concentrations relevant for arsenic removal efficiency, are shown in Table 1. Phosphate and silicate are known to compete with arsenic for adsorption sites on iron oxides, while calcium and magnesium aid in arsenic removal (van Genuchten et al., 2012, 2014). Moreover, the effects of pH and redox potential on arsenic removal are not investigated in this paper, but such conditions and mechanistic understanding are found in previous literature (Cherry et al., 1979; Smedley and Kinniburgh, 2002).

Table 1
Raw water average element concentrations as tested by ICP-OES at UC Berkeley.

Element	Concentration	Unit
As	250 ± 14	ppb
Fe	15.5 ± 0.4	ppm
P	0.61 ± 0.9	ppm
Ca	80.4 ± 3.5	ppm
Mg	40.8 ± 1.0	ppm
Si	17.2 ± 0.5	ppm

To comply with local norms necessary for obtaining national accreditation in India for technology operation, weekly product water samples were collected and measured for arsenic by two National Accreditation Board Laboratories (NABL), both of which used ICP-MS, and each of the laboratories had been earlier separately validated by sending them calibrated unlabeled samples. Product water samples were also tested monthly to ensure compliance with the full Indian Standard IS10500:2012 for drinking water for all physical, biological and chemical properties in the standard (Bureau of Indian Standards, 2012). Throughout the entirety of this period, ECAR's field performance showed reduction in arsenic concentrations from initial 252 ± 29 ppb, to final arsenic well below 10 ppb, and often below 5 ppb (average 2.9 ± 1 ppb) as seen in Fig. 4. After five months of ensuring the water met consistently all drinking standards, the water was made available to the 2500 students, staff, and teachers of Dhapdhapi High School. Currently (as of October 2019) the plant continues in stable and active operation under control of the industrial partner (Livpure Ltd), serving arsenic-safe water daily through a financially viable business model to the local community.

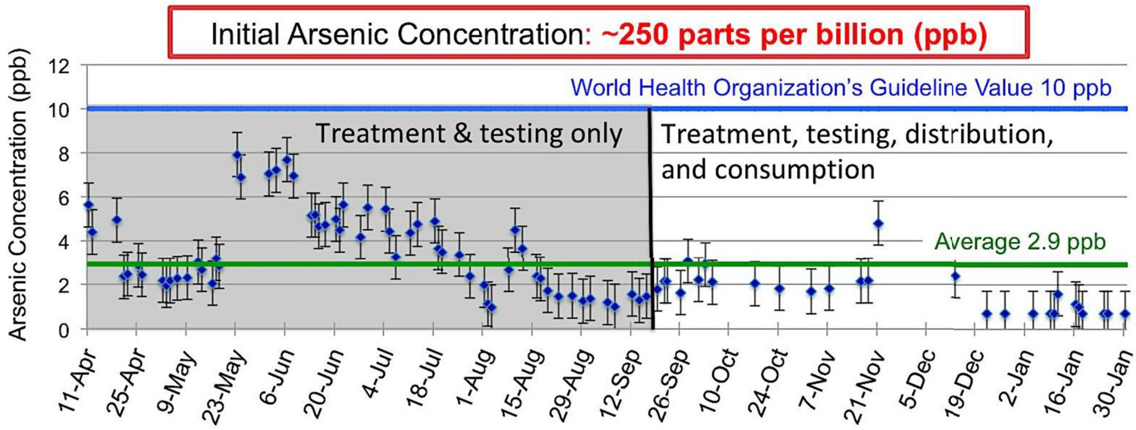

Fig. 4. Results from the plant in West Bengal, India, from April 2016 to January 2017, depicting continuous effective arsenic removal to less than 10 ppb during both pilot and distribution phases. The spike in arsenic concentration around 23-May and excellent performance after 1-Aug are explained in Section 4.1.

3. Critical Effort Zone

Deploying the 2500-L ECAR pilot plant as a community-scale water access technology within rural India required persistent experimentation within the socio-cultural context. The concept of the "Critical Effort Zone" is introduced as part of the innovation chain that is commonly defined, and both are shown in Fig. 5. The Critical Effort Zone matches the period in the innovation chain for which the expected cash flow of a project reaches its largest negative value. In the social embedding process of technology maturation, this zone requires intense efforts for trust building with key social actors, and ultimately, for acceptance of the technology by the society that will use the innovation. These efforts require understanding of human behavior, strategic planning and deep scientific understanding of the local social context. If efforts during this period are unsuccessful, the innovation can stagnate or perish. In contrast, if the efforts are successful, the technology may move towards commercialization and scale-up. The Critical Effort Zone necessitates the participation of a locally reputed and trusted scientific partner. The team can then deploy and implement strategies to build local capacity beyond the large prototype phase, and aim for long-term sustainability of the project beyond the pilot plant completion.

As one might expect, the duration of the Critical Effort Zone varies from project to project, but it is generally concluded with the demonstration of the first large-scale prototype. The Critical Effort Zone consists of successful operation of the field pilot, well designed communication to the public by the scientists in field operations, and flexibility towards any technology redesign needed to fit cultural practices. The actions taken during this zone must ensure good fit of the technology to the market needs, or "Product – Market Fit" (Andreesen, 2007), and must build the technical, management, and financial (TMF) capacity for a transition to commercialization. For this project, the Critical Effort Zone stretched just over 4 years (Dec. 2012–Jan. 2017),

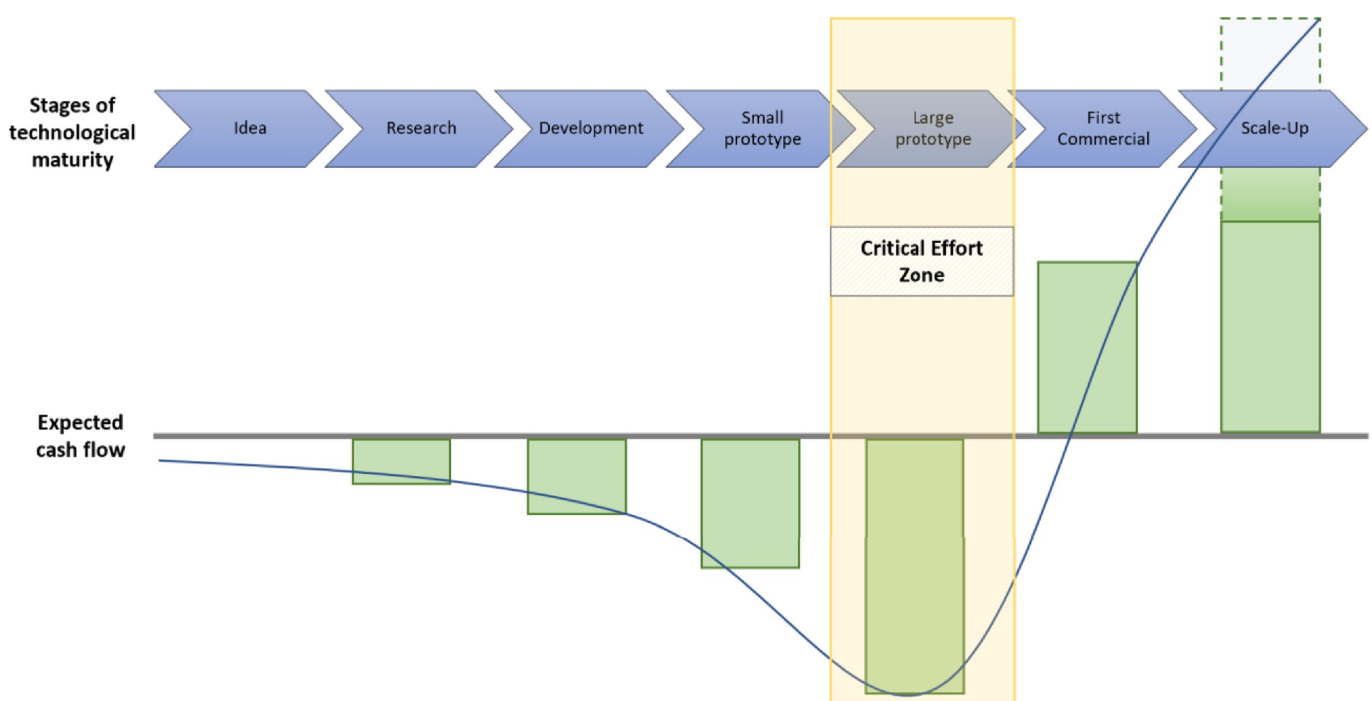

Fig. 5. Navigating the innovation path. The Critical Effort Zone requires more than technology efficacy—acceptable social placement within unique environmental contexts is also necessary. This figure is modified from a presentation to the United Kingdom parliament (UK Parliament Publications, 2013) and public presentations about technology-maturation programs at the U.S. Department of Energy.

during which the project team with its own secure project funding worked closely with a rural community in India suffering from arsenic contaminated groundwater to deploy and socially embed the first ever large-scale ECAR pilot plant, and deliver arsenic-safe drinking water to the first few thousand people daily for long-term health security.

Based on the team's decades-long experience, a prerequisite to cross the Critical Effort Zone requires secure financial support, and formal agreements documented indicating full commitment among the technology's inventor(s), local scientific partner(s), and the local industrial partner/commercial license holder. Commitment among partners includes transparency, knowledge sharing, sharing of financial costs, and field work time. Manufacturing and project objectives are agreed upon by all parties and preceded by multiple virtual and face-to-face meetings to clarify doubts and queries, and to build trust among partners avoiding false promises. In the ECAR project, all parties needed to be involved together in the larger-scale design and address all anticipated threats and opportunities. UCB provided adequate training about ECAR fundamentals and operation to the local science-technology partner and the industry partner. A 600-L ECAR prototype pre-tested in the field (Amrose et al., 2014) was re-installed in the scientific partner's laboratory for day-to-day training, capacity building, and to generate teaching and research interest in the technology. The industry partner (Livpure Ltd) in this project was an integral part to the commercialization of affordable, arsenic-safe drinking to the local community surrounding the pilot plant.

The first step in the Critical Effort Zone was selecting an acceptable site with promise for long-term hosting of the water treatment plant if it was successfully installed. Based on past (Das et al., 2016) and field experience (Gadgil et al., 2014; Amrose et al., 2014) the team determined four criteria for an ideal location: 1) measured high arsenic concentration in the groundwater, 2) absence or serious inadequacy of piped municipal water supplies, 3) clear and strong support from the school administration and governing council as local champions for the project, and 4) in-kind support through allocation of sufficient space and other resources (i.e. water, electricity, and security) to conduct the work. A previous school site had proven unsuccessful because the location was too far to maintain daily visits from collaborators based in Jadavpur University (JU) in Kolkata. In addition, the team lacked at this time an industry partner, and the school administration lacked the patience to support the project experimentation. As the demands of those school officials could not be met, the ECAR prototype was removed and reinstalled at the JU laboratory.

A school in Dhapdhapi—a village outside of Kolkata, in West Bengal, India—met the above four criteria for project location. Over a year of water testing at the NABL-certified facility of the Public Health Engineering Department (PHED) demonstrated a clear need for groundwater remediation—arsenic concentrations ranged between 150 and 300 ppb. Other reasons for choosing this site location included: 1) the local research team's familiarity with the geographical region and cultural practices, 2) positive political will (created through formal and informal articulation of the IUSSTF project expectations, and funding availability) among the stakeholders at various levels in the school, surrounding community and local government administration from top to bottom, and 3) confirmation of interest obtained through consultations, focus group meetings, and pre-tested formatted questionnaires. The JU research team practiced patience and care while introducing the ECAR project and surveying the community. Communities in arsenic exposed districts of West Bengal confirmed the economic benefit and individual interest in purchasing arsenic-safe water (Delaire et al., 2017b; Roy, 2008) that ECAR could provide.

Lessons from past projects indicated that grant-funded projects fail quickly after funds are spent, unless there is long-term financial viability built *a priori* into the project structure beyond the initial grant period (Das et al., 2016). In the business world, the conceptual framing of a financially viable business operation is captured into a "business model". For this ECAR project, the team developed a business model to achieve financial sustenance beyond the IUSSTF-funding period (which ended in 2016). In this model, the potable water produced would be provided free of charge to the students, staff, and teachers of Dhapdhapi high school in exchange for indoor space and access to resources (i.e., electricity, raw water, and security). After the hand-off of the plant from the research team to the industry partner, the industry partner would sustain plant operation and maintenance costs by selling the excess water at an affordable price to the surrounding households (at less than 1 cent per liter). The latter was determined through an on-site survey of the community's willingness to pay (WTP) under the project, and through comparison with observed household spending on safe drinking water (Delaire et al., 2017b; Roy et al., 2004). The industrial partner acquired a license for the patented ECAR technology from the University of California — to have a legal basis for commercial use of the technology, and its future commercial expansion. Thus, from the start, the industrial partner had "skin in the game" and was exposed to some financial risk if the project failed or stood to gain if the project succeeded.

4. Critical effort strategies

This paper presents four critical effort strategies to address the penultimate barriers to successful social placement of community-scale technologies. Critical effort strategies that address contextual challenges during the Critical Effort Zone are termed as 1) appropriate design of community-scale technology, 2) increasing economic opportunity, 3) bridging the scientific knowledge divide, and 4) local legal compliance. All four activities were conducted in parallel, not sequentially.

4.1. Community-scale technology design

In resource-poor areas of developing countries, a community-scale technology such as ECAR requires social trust and acceptance to be sustainable (Etmannski and Darton, 2014). To gain this trust and acceptance, the local research team repeatedly visited the site and formally explained the project objectives. As a community is made up of diverse individuals with diverse interests, behavioral response patterns become equally diverse. These behavior patterns must be in alignment for a technology to be accepted. This condition is different from a private-sector technology buy-in that is focused on the individual or household consumers. Individual technologies (e.g., mobile phones) target individual behavior for incentives and promotion materials. Community-scale technologies, on the other hand, demand greater social placement efforts than an individual-scale technology.

The technical field trial was separated into three phases: 1) design, fabrication, assembly, and testing of pilot plant, 2) pilot plant continuous operation and testing of product water, and 3) pilot plant continuous operation and distribution of arsenic-safe water for consumption as drinking water. Interdisciplinary collaboration was necessary for effective integration of the ECAR project into the Dhapdhapi community. The three partners (UCB, GCP-JU, and industry partner) contributed insights into socio-cultural nuances at the site location, legal issues, marketability of ECAR, and the technology development itself. Manufacturing ECAR reactors was assigned to a trusted third-party small-scale manufacturer under close and direct supervision of field engineers from Berkeley. Researchers (both international and national) and the industrial partner oversaw installation and necessary modifications. The ECAR plant was commissioned using locally sourced materials and trained local plumbers as plant operators, offering a sustainable approach to safe water access.

This ECAR field trial served as a social placement experiment while simultaneously resolving engineering problems that were not anticipated from laboratory-scale studies. At lab-scale, ECAR is operated under controlled conditions (e.g., fully controlling the pH, dissolved oxygen, initial arsenic concentration and co-occurring ions) with a reliable supply of electricity. In the field, ECAR must be capable of operating with many unknowns, such as intermittent power supply and week to week variability in raw water quality (e.g., with rainfall or dry weather, and seasonal temperature swings). The temperature in West Bengal, India reaches high levels in the summer, accompanied by heavy rain and high humidity. Winter is moderate and dry. Such extreme seasonal variation influences the performance of the treatment train in the ECAR pilot plant.

After a year of completing the manufacture and installation of the pilot plant, the electrical components of the ECAR reactors and power supply experienced overheating and occasional melting. The electrical connections to the electrode plates in the ECAR reactors became loose, which induced overheating and burning of the plastic on the wires (Fig. S3). Secondly, the busbars, which distribute current from the power supply to the ECAR electrode plates, made of aluminum had to be replaced with electrical grade copper busbars. Third, to ensure future ease of cable replacement, all cables were dug out from underground conduits and re-installed near the ceiling on a cable tray (Figs. S4 and S5). This change reduced the voltage drop in the electrical system and reduced the heat generation in the wires and at the polarity switch junction.

The plant also experienced numerous power outages during the summer and monsoon seasons. Although ECAR's arsenic removal efficiency is resilient to intermittent power supply, outages do cause delays in water production. This was mitigated by installing adequate storage capacity for ECAR product water. Storage tanks were installed at a height to allow adequate gravity flow to the distribution points (Fig. S7).

During normal plant performance, the tube settler produces water at less than 5 NTU. However, as the weather cools down in autumn through winter, the effluent turbidity from the tube settler unexpectedly reached levels as high as 30–50 NTUs. This was discovered through regular monitoring of the water for various parameters through multiple sampling ports. In winter, groundwater is warmer than the ambient-temperature water stored overnight in the tube settler. The inverted temperature gradient inside the tube settler caused a short circuiting of the settling flocs. To alleviate this issue, the scientific research team determined that during winter the groundwater must be pumped the night before, and stored in the ECAR reactors as to cool it down to ambient temperatures. This avoids the unexpected failure of the tube settler operation.

Although the plant produced water meeting all drinking water quality parameters by the end of 2015, the research team resisted pressures to immediately distribute water for human consumption. The research team needed to first acquire extremely high confidence in long-term operation of the plant by monitoring final arsenic concentration over a ten-month period. Starting April 2016, product water was monitored weekly for arsenic, and monthly for all drinking water parameters (IS:10500:2012), i.e., physical, chemical and biological contaminants. Samples were sent to UCB and NABL labs in India. In the second month of monitoring, the research team observed an unexplained spike in arsenic concentration of 7.9 ppb on 23-May-2016 (Fig. 4). After several weeks of effort, the spike was traced to the operator shutting down the recirculation pumps in the ECAR reactors blaming the high level of pump noise interfering with the operator's personal cell phone calls. After this problem was resolved, the arsenic levels declined, but remained higher than expected (though always below 10 ppb). The research team traced this to lack of deep cleaning of electrodes since start of operations in 2014. Deep cleaning is a regular maintenance process performed semi-annually which involves removing the electrode plates from the reactors and mechanically removing the surface layers. This is different from regular cleaning of the plates, which is performed daily with hard wired brushes between the electrodes in each reactor. After deep cleaning the electrodes in late July 2016, the arsenic levels in the finished water returned to the expected level.

Only in mid-September 2016, the research team allowed the water for distribution to school children, teachers, and staff. Everyone could now receive 30 L of free arsenic-safe water per month, after submitting proper written signed consent forms, either self-filled (for adults), or filled and signed by the guardian (for students). The finished water continued to be monitored and data is shown in Fig. 4 until January 2017 when the plant's operation was fully handed over to the industrial partner. Since then, the industry partner sustains the plant financially by operating the plant for 22 days a month, and selling water at INR 6 per 10 L to the nearby community. The partner reports that selling 10,000 L of water per day at this price for 22 days a month would yield a monthly profit of INR 100,000. For water quality monitoring, the industrial partner sends monthly water samples to an NABL accredited laboratory to test for arsenic, and the results are shared with UCB and JU.

The water distribution phase had its own challenges. Water distribution was scheduled to start mid-September, with the monsoon season over but temperatures still high. The ECAR plant was connected to an existing pipe network at the school and pumped to storage tanks placed on top of the school building. The layout exposed the dark green water distribution pipes and the storage tanks directly to the blazing sun. Thus, the water became extremely hot and unpleasant by the time it reached the automatic dispensing units and end users. Furthermore, an unexpected precipitate of white particles started appearing in the dispensed water, which caused additional concerns to everyone. The research team discovered that the high temperature of water caused precipitation of calcium carbonate through decreased solubility. To mitigate this issue, the water pipes were relocated to an underground trench, allowing the drinking water to stay naturally cool while minimizing the formation of the white precipitates. The overhead tanks were placed directly above the dispensing units, reducing solar exposure while maintaining the gravity flow to the tap. The overhead tanks were also retrofitted with a port at the bottom where settled calcium carbonate precipitates could be flushed out each morning. As a result, the drinking water maintained an appropriate temperature and was free of precipitates.

Placing a water treatment plant and distribution point at a school may promote daily student attendance. Similar to the mid-day meal lunch programs implemented in schools in India, clean water availability through the automatic dispensing units (ADUs) may contribute to education and gender equality (Dréze and Kingdon, 2001). Although Dhapdhapi High School was practicing the mid-day meal program, access to reliable arsenic-safe drinking water had not been ensured. Students demonstrated great enthusiasm on the day that water distribution began, with long lines at the ADUs (Fig. 6). A total of four ADUs were installed, with two each designated separately for girls and boys at request of the school. The ECAR water distribution may potentially increase school attendance of young girls who otherwise may have been required to collect good quality water for their families (UN Women, 2014). The fact that additional long walks are not needed to collect drinking water, and that children can attend school and still return home with (some) arsenic-safe drinking water, are major benefits to both the child's education and health (SDG 4 and SDG 5).

Upon distribution of drinking water to the school, the research team initiated the transfer process of the plant to the industrial partner. This necessitated the preparation of clear technical instructions in the form of written operations and maintenance manuals, both in English and Bengali. The research team also prepared an engineering manual to explain the detailed engineering logic behind the maintenance and operations manuals to the management of the industry partner. The preparation of manuals by the inventor is necessary for effective knowledge transfer. The technical challenges that were encountered early in the pilot phase allowed the research team to establish an operation manual and a maintenance schedule, foreseeing methods to mitigate potential problems, to ensure long-term performance beyond the IUSSTF funding phase.

4.2. Increasing economic opportunity

Dhapdhapi High School is located at a central point within the Dhapdhapi village. Rickshaw-pullers transport mothers and children to

Fig. 6. This figure shows a) sample of the cards distributed to the students and teachers of Dhapdhapi. In Bengali, the card say, "Let us keep our health and our family's health safe by accessing arsenic-free water from arsenic-safe sources," b) school girl who has just received her own card with spaces for name, grade level, roll number, and water card number, c) automatic dispensing units installed, and d) water queue formed during first water distribution.

the school, and local "*cha*" or tea makers sell snacks and tea to students and teachers. The influence of the ECAR plant on the local economy depended on the design of the technology. In the United States, a fully automated plant would have significantly lower operating costs; in rural India, a labor-intensive design was optimal due to the much lower cost of labor relative to cost of capital. Two local operators with less than formal high school training were hired to work at the plant. Anecdotally, they perceived the opportunity as a new decent job (SDG 8) that also enhanced their social acceptability and status. This contextual engineering design promoted a modest amount of economic development through job creation, demonstrating that technology deployment is much more than the technology itself. Additional local employees who were hired to support the project included a guard and an electrician. This level of manual labor did not cause a financial hardship for the industry partner, while improving the livelihoods of the employed workers who took interest in promoting the commercialization process locally. In addition to earning a living wage, their pride in working at an arsenic remediation plant to provide water to the community contributed to the project's acceptance in the community, and eventual success.

4.3. Bridging the knowledge divide

Prior literature in this field discusses the social stigma associated with visible signs of arsenic poisoning (Das and Roy, 2013; Das et al., 2016). In Bangladesh, for example, arsenic poisoning is considered contagion or a curse. Case studies have shown that awareness campaigns have helped reduced the negative social stigma associated with arsenic poisoning (Uddin and Huda, 2011). In this project, educating the community about the harmful effects of arsenic consumption and its natural causes were critical to alleviate such social stigma, and improve the social acceptance of the ECAR-treated water based on sound understanding of arsenic-exposure through drinking water.

Before knowledge can be effectively disseminated, building community trust is critical (Etmannski and Darton, 2014). In social science literature, trust is considered as social capital (Dasgupta, 2005), especially for an area that has experienced numerous unkept promises and failed intervention projects. In order to overcome immediate suspicion or cynicism, intervention groups need to patiently earn the trust of the local community. Some heavily arsenic-exposed villages in West Bengal have become cynical owing to numerous international groups visiting to study their conditions and then leaving never to return or share their findings, and without bringing positive change in the lives of the affected. Communication between academics and arsenic-prone communities is often poor, and an unwelcoming attitude can result due to growing frustrations from a problem that is being studied but not solved (Das et al., 2016). Given the historical context, groups planning interventions must not make any false promises, exaggerate statements of likely benefits, or underestimate costs.

ECAR is most suited for a local economy where there is at least partial reliance on arsenic-contaminated water and the community is already seeking a safe water source. For example, in Dhapdhapi area, a business was selling untreated mechanically-filtered water at 30 INR per 20 L. The school was buying this drinking water for its teachers and staff under the belief that its quality was better than their own borewell water. General ignorance about arsenic is also common. For example, in our interactions with the school community, it became clear that even the science students did not know that boiling or simple filtration of water does not remove arsenic. In such conditions, introducing an effective, affordable arsenic-remediation technology (such as ECAR) may give rise to hostility and resistance from incumbent business interests that feel threatened. For example, during public meetings held during this project, business interests tried to compromise the community's perception of the ECAR project objectives. They questioned the efficacy of ECAR and quality of the product water. Other challenges came from political interests in a multi-party democratic social system. These groups—that sometimes have hidden agendas—sowed suspicion in the public regarding the actual severity of the problem.

The project team did not ignore any of these questions and actively listened to the concerns of the community. For example, the local community were led to believe by some scientifically unfounded hearsay that the proposed water treatment plant would be too much of a drain on the village groundwater aquifer. This concern was allayed by research partners investing in a hydrogeological study on the region's aquifer. Hydrogeologists of highest repute were hired with full remuneration to assess whether pumping groundwater at a rate of 10,000 LPD would deplete the aquifer for nearby wells, and for future generations. The experts submitted a written report explaining the method of their third-party verifiable study, and the team shared it with the public to maintain transparency. The team and the community gained confidence in the process through transparency of the scientific assessment that the local aquifer would not be depleted. The community was convinced that the environment would be preserved while improving public health through safe water access.

Outreach meetings with stakeholders were held by the project team 3 to 4 times a year starting from December 2012, which is considered as start of the Critical Effort Zone. Some of the meetings included active participation from the technology inventor Professor Gadgil and local social scientist partner Professor Roy. The community was invited to public meetings which were open to all and organized within school premises on multiple occasions. With support of the School's Student Assembly, and the school administration, the ECAR team held general student body meetings, smaller meetings for student leaders from each class, and separate meetings exclusively for all the teachers in the school. In addition, multiple meetings were held with student groups preparing posters about arsenic for display in the school, and with student teams working on science projects about ECAR for the annual district-level science fair. From the team's perspective, all meetings were crucial for the community understanding and acceptance of ECAR, and to ensure clear communication of the science to the rural community. Moreover, as the ECAR product water was tested for a 10-month period, NABL reports on product water quality were printed monthly, and posted on the walls of the plant in public view, for the community to check, discuss, and disseminate the results among all those interested.

On January 31, 2017 at Dhapdhapi High School, Professor Gadgil and Professor Roy, leaders of U.S. and Indian research teams, respectively, and the VP from the industrial partner together signed a plant handover agreement, with the public as witness, signaling the formal hand-off of the ECAR plant to the industry partner for provision of arsenic-safe drinking water to students, teachers, and staff. This event provided one more opportunity for the community's questions to be heard and answered by the experts about sustainable operation of the plant beyond the project lifetime.

4.4. Compliance with local regulations

A final, but crucial, hurdle for successful technology implementation is compliance with local regulations. This project required compliance with hazardous waste management standards set by the Government of India, which are adopted and enforced by the state government via the State Pollution Control Board. Complying with regulations also required the involvement of Ramky Group, an environmental management group recognized by the state government for handling hazardous wastes. The project's industry partner signed a contract with Ramky to collect sludge once the distribution and commercialization process began. Prior to this, the local scientific partner, the Civil Engineering Department at JU, collected sludge for their use in a research project experimenting with successful immobilization of arsenic sludge in concrete (Roy et al., 2019).

Prior to commercialization of ECAR water, the industry partner needed to obtain a trade license from the local government authorities. The two licenses, Consent to Establish (COE) and Consent to Operate (COO), were acquired from appropriate authorities in West Bengal's government, the West Bengal Pollution Control Board (WBPCB) and District Industries Center (DIC). All such contracts were preceded by multiple, formally organized visits and answers to scientific inquiries by local government agencies, coordinated by the local scientific institutional partner. After transparent, patient and skillful efforts, and a final submission of written applications, WBPCB and DIC issued the COE and COO licenses to the industry partner. The COE and COO allow the legal operation of a water treatment plant that generates sludge (as occurs in ECAR reactors seen in Fig. 2a) and follows the specified norms. This permit is received as a "No Objection Certificate" (NOC), for the full operation of the ECAR plant. Working with policy organizations and environmental groups have shaped the ECAR project as a contextual technology capable of adapting to local requirements and regulations.

4.5. Addressing sustainable development goals (SDGs)

Iron-based treatment technologies are effective at removing arsenic from drinking water (Amrose et al., 2013, 2014; Martínez-Cabanas et al., 2015), but alone cannot improve human well-being. The critical effort strategies discussed in this paper explore the complex nature of human behavior, cultural norms, and political maneuvers in the social integration of ECAR into the community. Thus, deployment of the first large-scale ECAR plant has addressed not only SDG 6 of safe drinking water, but several SDGs as set by the United Nations (Table 2).

The careful collaboration between UCB, GCP-JU, and the Indian industry partner financed by IUSSTF, is an ideal example of SDG 17 of setting up an international partnership model which can be emulated by teams addressing different global health issues (e.g., water quality, air quality, birth control, infectious diseases). Specifically, the roles of each partner were clearly established early in the project. Towards the end of the Critical Effort Zone, UCB "handed off" the pilot plant to the industry partner to enter the commercialization phase. Monthly "all-partner" calls, tackling problems among the three partners, and the development of a "hand-off" folder for the industry partner allowed a successful and continued operation of the ECAR plant and water sales to the villages surrounding the school.

The team's water distribution design was contextual to rural West Bengal, addressing SDGs 1, 4, 5, and 6 (briefly described in Table 2). Water distribution at a school provides an avenue for achieving gender equality, since equal access is assured for male and female students. This may also potentially reduce poverty levels by increasing education for rural children. As previous poverty reduction efforts include meal plans at rural schools in India (Tilak, 2002), a similar approach of clean water provision may promote similar outcomes. Establishing the first large-scale ECAR plant also contributed to SDG 8 by hiring local plumbers and electricians to operate the pilot plant. Throughout the project, transparency was maintained with school officials and the surrounding community, regardless of gender, education levels, and economic standing.

Moreover, it is possible to achieve the multiple SDGs, as mentioned above, while benefiting the intellectual endeavors of an academic institution (SDG 9) as well as the industrial objectives (SDG 8) of a commercial partner. Lastly, ECAR was designed to minimize waste

Table 2
Actions taken during the Critical Effort Zone to address the UN's SDGs.

SDG	Action towards goal	SDG	Action towards goal
1 NO POVERTY	Affordable arsenic-safe drinking water	8 DECENT WORK AND ECONOMIC GROWTH	Job opportunities at pilot plant
4 QUALITY EDUCATION	Educational campaign at rural school	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Research of socially impactful electrochemical technology
5 GENDER EQUALITY	Water distribution at co-ed school	15 LIFE ON LAND	Sustainable sludge management
6 CLEAN WATER AND SANITATION	Distribution of arsenic-safe drinking water	17 PARTNERSHIPS FOR THE GOALS	Collaboration across academic institutions and industry (United States and India)

generation and negative ecological impacts (SDG 15), which complies with local regulations and strengthens governance. ECAR operates as a Zero Liquid Discharge (ZLD) technology, meaning that the technology does not generate wastewater that must be discharged into surface water bodies or injected into clean aquifers. The only reject material stream is about 40 mg of dry sludge per liter of treated water (Roy et al., 2019), and is easily managed without negative ecological impacts.

5. Concluding remarks

The first large-scale ECAR pilot plant at Dhapdhapi High School located in a resource-poor area in rural India provides evidence of an effective commercial community-scale deployment of an arsenic removal technology for the distribution of safe drinking water. The success of the technology implementation lies in contextualizing the design for community-scale placement and trust building among stakeholders led by the research team. This case study can serve as a template for future arsenic exposure-mitigation projects, and other social placement efforts of community-scale technology. The Critical Effort Zone is defined in this paper as the time period in which simultaneous efforts are required, with close coordination and cooperation among the institutions offering financial support, inventors working with manufacturers, local technology licensee holder, and local social science group. The social science group's active role in creating social capital in the social embedding process, beyond the technology trial itself, is critically important for success.

In scaling-up from lab to field, the ECAR team discovered and overcame new challenges that could not have been previously anticipated. Some of these challenges required redesign (e.g., keeping the water pipes cool by burying them underground) within the cultural and environmental context. All throughout the process, the scientific and technical staff were personally involved and invested in directly communicating with the local rural Indian community. With commitment, skill and patience, the team encountered and overcame infrastructural, regulatory and political hurdles. During the Critical Effort Zone, the SDG framework was directly addressed by combining technology challenges, economic opportunities, scientific transparency, and legal compliance. The water quality data demonstrate ECAR's technical efficacy in the field implementation, and its social placement success shows promise for commercialization in other arsenic-affected regions of India, and in developing economies across the globe. Given the recorded failures of previous arsenic remediation plants in West Bengal, the success of the ECAR project, and the fact that the Dhapdhapi field trial is the first of its kind established under R&D efforts, the UCB team has continued to monitor the technical performance of the plant. They obtain monthly water quality data and plant operation updates from the industry partner, by working with the local scientific institutional partner GCP-JU. The future work of UCB researchers is to develop ECAR into a more compact and energy efficient arsenic removal technology. Meanwhile, the industry partner may choose to install additional ECAR plants in India. Beyond the Critical Effort Zone, maintaining the cooperation and community relations built during the project continues to be crucial, and is carried forward through dialogue and transparency, as ECAR projects reach many other arsenic-exposed regions in West Bengal, and world-wide.

Declaration of competing interest

None.

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Appendix A. Supplementary data

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