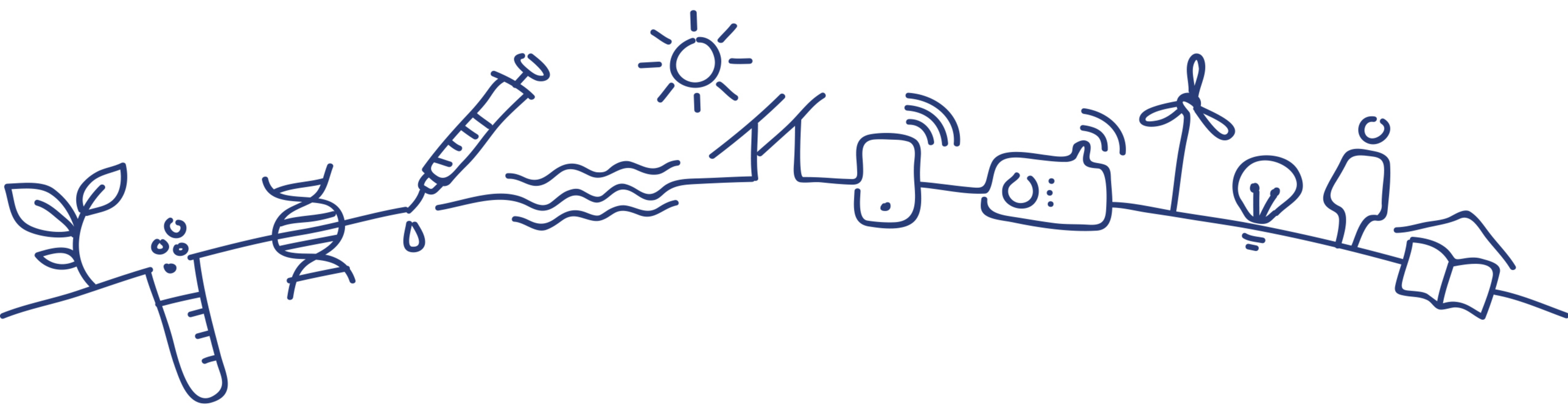
50 BREAKTHROUGHS

Critical scientific and technological advances
needed for sustainable global development



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NOTES ON METHODOLOGY AND LAYOUT

Traditionally studies focused on future-facing topics have relied on surveys of experts, using approaches like the Delphi Method[1], a structured iterative process of interviews and reviews. Early in our study, we discovered two challenges with such a process. First, the absence of a broad, credible evidence base about what works has led to entrenched opinions. Second, such an approach would likely have led to a laundry list of 50 *technologies* or *devices*, rather than to a robust problem analysis which logically leads to the *breakthroughs* required—agnostic to specific technologies.

Hence, this study employs a six-part approach to reach its conclusions:

1. Describe and analyze the 5-10 most important contextual facts about the specific problem.
2. Identify the key challenges, which have kept effective solutions from becoming a reality.
3. Identify, based on input from recognized topic-specific experts, the most promising interventions to overcome those hurdles.
4. Determine the dependence of each of these interventions on: policy reforms, infrastructure development, education and human capital development, behavior change, access to user finance, an innovative business model, and finally, a new breakthrough technology.
5. We focus on interventions with a significant dependence on a breakthrough technology, and identify the important parameters the technology needs to fulfill. Based on the underlying technical challenges, we then estimate the time-to-market by when these breakthroughs may become deployable products.
6. Finally, we identify the most important hurdles to sustainable, large-scale deployment, based on many of the factors listed above (e.g., policy reforms, etc.), and score the difficulty of deployment on a 5-point scale: simple, feasible, complex, challenging, and extremely challenging. The purpose of this final analysis is to encourage technologists and funders to understand these challenges before making major investments in their work.

Each chapter is divided into three parts: Core Facts and Analysis, Key Challenges, and Scientific and Technological Breakthroughs. The 5-point scale and the complexity we ascribe to each of the factors and constraints relevant to the deployment of a particular technology are illustrated in **Table A**. The lowest score (feasible) is reserved for cases when the particular constraint is not relevant to deployment; the constraint is given the highest score (extremely challenging) if it can be a serious bottleneck to deployment. The aggregate score reflects the overall degree of difficulty, considering the collective weight of the individual constraints. The methodology is clearly subjective. **Exhibit A** is a sample of how we have illustrated the difficulty of deployment for each breakthrough across the study. This particular sample highlights a CHALLENGING breakthrough.

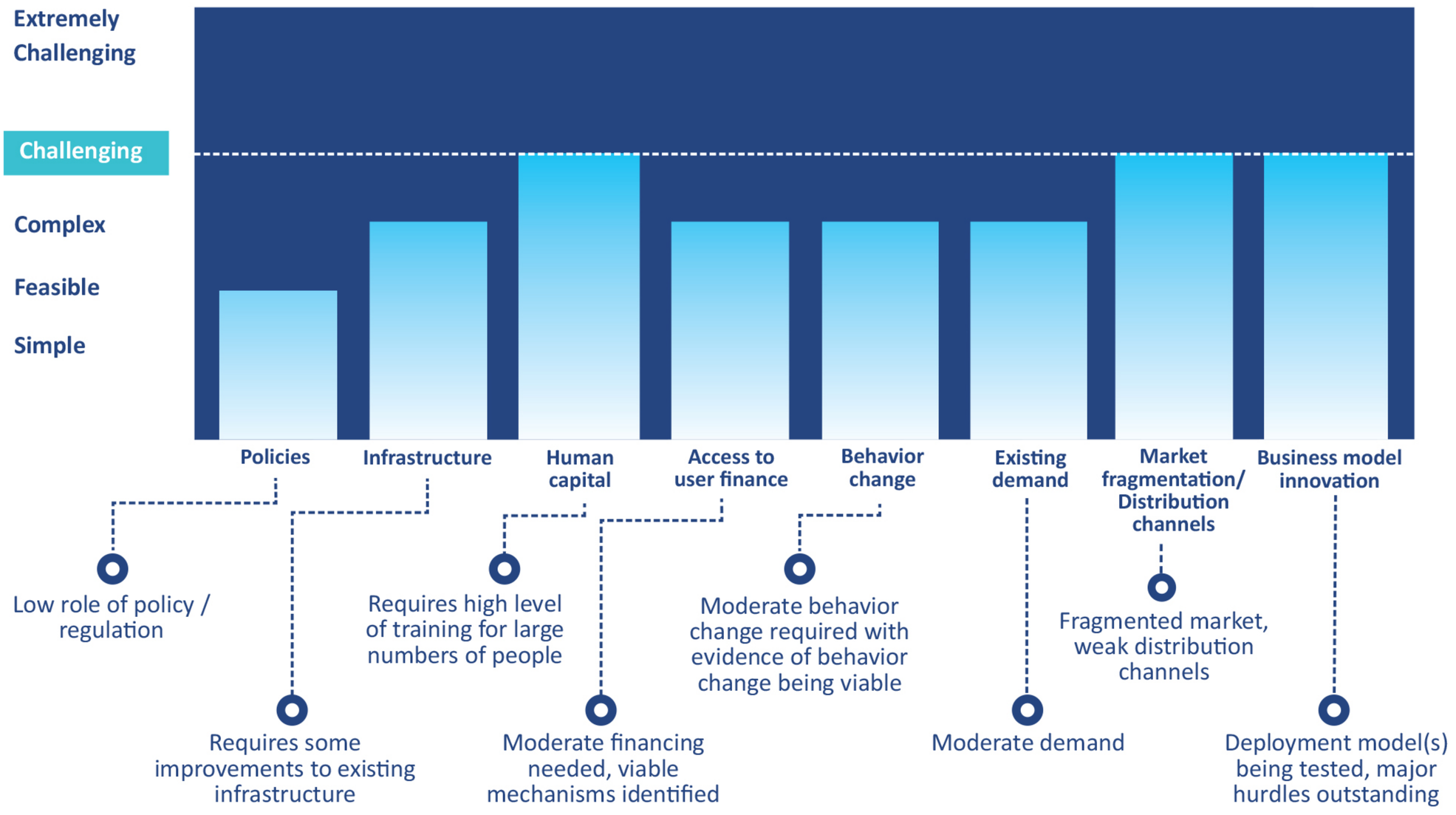
[1] A structured communication technique, originally developed as a systematic, interactive forecasting method which relies on a panel of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the 'group response', after which the process repeats itself. The Delphi method is based on the assumption that group judgments are more valid than individual judgments. It was originally developed by the RAND Corporation in the 1950's to forecast the impact of technology on warfare.

Table A

	Simple	Feasible	Complex	Challenging	Extremely Challenging
Policies	Minimal role of policy/regulation	Low role of policy/regulation	Regulated market with supportive policies	Highly regulated market with policy changes required	Highly regulated and controversial changes required
Infrastructure	Minimal need for infrastructure	Dependent on existing infrastructure	Requires some improvements to existing infrastructure	Requires moderate improvements to infrastructure	Requires major improvements to infrastructure
Human capital	Minimal need for human capital development	Low-moderate need for human capital development	Moderate need to train a limited number of people	Requires high level of training for large numbers of people	Requires national scale training programs
Access to user finance	Financing not required	Limited financing required	Moderate financing needed, viable mechanisms available	Significant financing required, limited mechanisms available	Significant financing required, no identified mechanism
Behavior change	No behavior change required	Minimal behavior change required	Moderate behavior change required with evidence of behavior change being viable	Major behavior change required, potentially on daily basis	Significant behavior change needed on daily basis, changes contrary to cultural norms
Existing demand	Strong existing demand	Existing demand	Moderate demand	Low demand, needs to be built	Extremely low demand or not a perceived need
Market fragmentation/ Distribution channels	Highly concentrated market or well defined channels	Fairly concentrated market and/or well defined channels	Moderate fragmentation of customers, under-developed channels	Fragmented market, weak distribution channels	Highly fragmented, challenging to reach customers
Business model innovation	Clear deployment models existing at scale	Deployment model in process of scaling	Deployment model(s) being tested	Deployment model(s) being tested, major hurdles outstanding	No identified deployment model, major hurdles identified

Exhibit A

Breakthrough – Difficulty of deployment



THE 50 BREAKTHROUGHS

Across the 9 areas covered in this study, we have identified 50 breakthroughs which can make a substantial difference to the lives of the poor, especially those living in South Asia and sub-Saharan Africa. Not surprisingly, many of these breakthroughs address issues in multiple areas of this study (and are color-coded accordingly; color key below). In some cases, several individual—but related—breakthroughs have been consolidated into one which is more expansive. While it is difficult to rank these 50 in terms of their relative importance, we have identified a list of top 10. These 'top 10' are in no particular order of importance; neither are the rest. Over and above these 50, we also mention here a particular breakthrough that repeatedly emerged as a cross-cutting theme, taking our total tally in this list to 51.

The 9 areas of this study

- Global health
- Food security and agricultural development
- Education
- Human rights
- Gender equity
- Water
- Access to electricity
- Digital inclusion
- Resilience against climate change and environmental damage

1 A new method for desalination: scalable, low cost, and using renewable energy.

Water scarcity is one of the most critical problems the world is facing today, and this problem is likely to get significantly worse in the coming years. An increasing amount of the world's freshwater is becoming brackish, and more is being dissipated into oceans and other bodies of unusable water. Reclaiming this seawater and inland brackish water through desalination will need to be a significant part of the larger solution to meet the needs of the growing global population. Current forms of desalination (e.g., reverse osmosis) are prohibitively expensive and energy-intensive.

2 – 4 Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, Malaria and TB.

Collectively, HIV/AIDS, Malaria and TB kill almost 4 million people a year, and represent a significant disease burden for low income populations in sub-Saharan Africa and South Asia. Effective vaccines for these diseases do not exist yet due to the intrinsic complexity of the pathogens causing them, and a lack of understanding of the specific mechanisms through which our immune systems protect against these diseases.

5 'Smart' electronic textbooks which dynamically adapt content for different skill levels, languages and other user specific needs.

Education for low income students is fundamentally constrained by the absence of qualified teachers and adequate instructional tools. As smartphones and tablets become increasingly affordable and feature-rich, and as so much of the world gets connected to the Internet, there is a tremendous opportunity to leapfrog current education methods, and create new models of content development, content delivery and instruction. 'Smart' electronic textbooks will require curated and up-to-date

content, 'wiki' interfaces for vernacular and other locally relevant and gender-inclusive material, visual and dynamic learning tools for students, interfaces and tools for teachers, student-teacher interaction and peer-to-peer collaboration.

6 **Biometric ID systems, linking birth registry, land title registry, financial services, education history, medical history, and other information critical for ICT enabled services.**

Individuals born in industrialized countries have formal IDs, which are linked to a range of services vital to their wellbeing and empowerment, and are an intrinsic part of their day-to-day lives. ID systems are inadequate in most developing countries, in part due to the absence of the institutional framework necessary for issuing and using IDs for individuals and businesses. This is one of the reasons why a majority of citizens in many low income countries operate in informal economies, cannot assert all the rights they are entitled to, and cannot hold their governments accountable for services. Biometric technologies can enable developing countries to bootstrap ID systems, empowering individuals to assert ownership of land and other assets, have accurate medical, educational and financial histories available to service providers, and truly become part of formal economic structures. Stringent safeguards are required to ensure privacy, and to protect individuals from being targeted by repressive regimes.

7 **Affordable (under $50) smartphones that support full-fledged Internet services, and need limited electricity to charge.**

The recent penetration of mobile phones across the broader developing world has been nothing short of dramatic. However, most low income consumers still use basic phones which do not offer advanced functionality beyond voice and SMS text. For true digital inclusion, we believe that smartphones—with their ability to exchange information via a range of modalities (e.g., touchpad, voice-driven control, various ports), and their ability to support a wide array of Internet-based services—are essential. Unfortunately, today's smartphones are too expensive for low income users.

8 **A new generation of homes with advanced construction material, especially for the urban poor: durable, lightweight, and affordable, with integrated solar-powered lighting, ventilation, and toilets.**

The majority of the poor—particularly in urban areas—live in densely packed shacks made with found material, which have very limited light or ventilation, and no running water or sanitation. This contributes to a range of health problems such as TB, diarrheal disease, pneumonia, and other respiratory conditions. Improving living conditions by reinventing the home for the poor, with the characteristics listed above, can significantly improve quality of life and is critical for improving health outcomes in developing countries.

9 **New methods to produce fertilizers to replace current processes, which are extremely capital intensive and have significant environmental footprints.**

Production of synthetic fertilizers—a mainstay of agricultural yields for many decades—depends on processes that are very capital intensive (manufacturing plants and mines costing hundreds of millions to billions of dollars), and in the case of nitrogen, extremely dependent on natural gas (nitrogen fixation factories must be located close to natural gas sources). As a result there are no fertilizer manufacturing plants in sub-Saharan Africa, and this creates a cost burden for African farmers who must buy fertilizer from international sources. From a more global perspective, current production processes have a large

ecological footprint, create dependence on fossil fuels for food, and introduce volatility in fertilizer and food prices tied to volatility in fossil fuel prices. New research is required to explore options like simulating natural nitrogen fixing mechanisms (found in crops such as legumes), foliar nutrient uptake (instead of roots, to reduce fertilizer runoffs from farms), etc. In addition, it will be important to improve the safety and effectiveness of existing sustainable methods like composting biological waste.

10 A 'utility-in-a-box' for making it simpler, cheaper and faster to set up and operate renewable energy mini-grids.

Currently, setting up mini-grids in rural areas is time consuming, complex and costly, due to weak and fragmented supply chains, poor roads, a lack of skilled workers, and the absence of standardized, modular components. A 'utility-in-a-box'—a bundled package of mini-grid components that can be easily integrated and installed, and whose parts work seamlessly, making operations simpler—would make mini-grids much more attractive to both service providers and investors, and significantly reduce barriers to expansion. In short, it would make the business of running rural mini-grids more profitable and less risky.

11 Short course TB treatment drugs that will lead to significant improvements in treatment adherence, and curb the spread of drug resistance.

Currently, treating drug-sensitive TB with the typical cocktail of antibiotics takes more than 6 months. As a result, patients often stop treatment prematurely, leading to treatment failure and causing drug resistance. A short course drug can significantly increase treatment adherence, and therefore also reduce the spread of drug-resistant TB.

12 Microbicides to provide a method of protection against HIV/AIDS and Human Papillomavirus (HPV) for women who are otherwise vulnerable to infection through sexual contact with their partner.

Women often struggle to get their male sexual partners to use condoms. Vaginal or rectal microbicides, if effective, can be a viable and discreet alternative to condoms for controlling the spread of HIV/AIDS and other sexually transmitted diseases, especially HPV which causes cervical cancer.

13 Improved, longer-lasting antiretroviral therapy (ART) formulations to control HIV viral replication and increase patient adherence.

ART formulations currently on the market require continuous, long-term treatment, the cost of which is difficult for low income populations to bear. Reformulation of current ART drugs for higher effectiveness, simplified treatment regimens (e.g., single fixed-dose pill), and reduced toxicity can help significantly increase access and adherence.

14 PrEP (pre-exposure prophylaxis) to reduce the risk of HIV infection.

PrEP is the use of antiretroviral therapy (ART) by those at a high risk for HIV infection (e.g., among couples where one partner is infected), to reduce the risk of contracting the disease. Very recently, a promising combination ART, Truvada, has been approved by the USFDA. However, Truvada needs to be taken daily, for as long as the user wants protection. This is challenging for low income populations, who do not have access to adequate healthcare and counseling. A range of oral and long-acting injectable

ART drugs are under development, which could help overcome these challenges. However, despite early encouraging signs, gaps remain in understanding the safety, effectiveness, and long-term implications of the emerging suite of PrEP drugs.

15 A complete cure drug for Malaria that eliminates all malarial parasites, at every stage of the lifecycle, from the human body.

Existing drugs for treating malaria do not completely destroy the malarial parasite from the patient's body, and lead to an asymptomatic reservoir among patients who have been successfully treated. These individuals can then transmit the disease to others when bitten by mosquitoes capable of carrying the parasite. A complete cure—which eliminates all malaria parasites in the patient's body—will be a pivotal tool in controlling malaria.

16 New long-lasting chemical mosquito repellents delivered in novel ways.

While a number of chemical mosquito repellents are already available, it is unlikely that they will provide sustained control, given the ability of mosquitoes to develop resistance. To tackle this, new classes of long-lasting chemical repellents are required. To achieve scale, they will have to be delivered through novel mechanisms that are easy to use and adopt. While research is progressing, and some chemicals and delivery devices (e.g., topical patches) are showing promise, their long-term spatial efficacy has not yet been sufficiently field-tested or demonstrated.

17 New long-lasting non-chemical spatial mosquito repellents or attractants for vector control.

The most effective repellents or protectants currently used in malaria-endemic countries are indoor insecticide sprays and insecticide-treated bed nets. As effective as these methods have been, they have their limitations. They offer protection only when people are under the nets or indoors. Mosquitoes develop resistance to chemical insecticides, and anecdotal evidence suggests that the effectiveness of commonly used indoor sprays has been declining. Spatial non-chemical repellents or attractants have the potential to overcome the challenge of vector resistance while providing coverage over a broad area (e.g., a room or a home). Some such repellents (e.g., based on sound) exist in the market, but have not proven effective. An ideal repellent or attractant must be designed to be energy efficient and long-lasting (possibly powered by ambient light), targeting the mosquito's sensory receptors. Such a device would need to be able to run uninterrupted for several months without frequent replenishment.

18 An integrated, easy to operate, affordable, and solar-powered suite of medical devices specifically for maternal, child and primary care in low resource settings.

Currently, building a reasonably equipped clinic costs more than $100,000. In addition, essential devices are often difficult to install, complicated to use, and expensive to maintain. A suite of the key 10-15 devices that are designed for ease of installation and use (e.g., a 'clinic-in-a-box') and collectively cost $10,000 or less can serve as a building block for expanding healthcare in rural areas. Integration needs to occur with respect to power supply and management, patient data, diagnostics, and communication. Potential devices include: diagnostics for critical maternal conditions (malnutrition, anemia, malaria, HIV, syphilis, hypertensive disorders); sterilizers; ultrasound; devices to care for preterm or low birth-weight infants (continuous positive airway pressure or CPAP, warmers if skin-to-skin warming is not possible, phototherapy); medical refrigeration; and ICT devices or interfaces for tracking patient data and coordinating care.

19 Low cost, off-grid oxygen concentrators.

Oxygen therapy is a valuable intervention for treating children with severe pneumonia, but is seldom used in developing countries, especially in rural areas. While various types of oxygen concentrators are available in industrialized countries, these are expensive (over $1,000), require reliable power, regular maintenance, and significant training for users. The oxygen concentrator needs to be redesigned to be less expensive, robust, easy to maintain, and not dependent on grid power. An ideal system should include oximetry as part of the system.

20 Automated and multiplex immunoassays that can test for a wide range of diseases, and are compatible with easily collected sample types.

Currently, a patient presenting a particular symptom, for example fever, needs to be tested for the range of conditions that could cause the symptom—each with its own diagnostic—until a positive result is achieved. Most rural clinics serving low income patients do not have the necessary diagnostics available to test the full range of conditions linked to specific symptoms. As a result, some conditions are misdiagnosed, often resulting in inappropriate treatment. One common problem is presumptive treatment, which happens often in the case of malaria where the disease is endemic. Instead of being tested for the actual febrile illnesses they have, patients are simply treated for malaria. Point-of-care immunoassays that can use different types of samples (e.g., saliva, whole blood, urine), and test for multiple biomarkers from a single patient sample, represent a major breakthrough in diagnosis and patient care.

21 Point-of-care nucleic acid tests (NATs) that are simple, robust, and compatible with easily collected sample types.

Nucleic acid tests (NATs) are a highly reliable method of detecting the presence of pathogens in a patient, by detecting the presence of the pathogen's genetic material (DNA or RNA). This method can be used to accurately quantify the level of infection, identify pathogen strains, and determine drug resistance profiles, which is essential for diagnosing and treating diseases like TB and HIV. Currently, NATs are expensive and complex, and require trained laboratory technicians. They are mainly used in hospitals and centralized laboratories. Low cost point-of-care NATs represent a major breakthrough in disease detection. These tests should be compatible with simple sample types (such as whole blood), rapid, user-friendly for minimally trained technicians, robust (despite high heat and humidity), and not reliant on refrigeration, running water, or stable electricity.

22 Fully integrated single diagnostic platforms that eliminate the need for individual platforms for separate disease conditions.

Even as progress is made on individual diagnostic technologies and platforms—immunoassays, nucleic acid tests (NATs), etc.—the ultimate breakthrough is a bench-top diagnostic platform that can integrate a wide variety of individual platforms such as optical readers (e.g., for HIV screening), bench-top chemistry analyzers, and NATs (e.g., for TB and viral load testing). Such a platform needs to perform all diagnostic test menus required at the point-of-care in peripheral health clinics. As with other point-of-care diagnostics, the ideal technology would be portable, rapid, not reliant on refrigeration, running water or grid electricity, able to function effectively in high heat and humidity, and easy to use for minimally trained technicians. It should cost no more than a few thousand dollars.

23 Low cost off-grid refrigerators for preserving vaccines (and other temperature sensitive pharmaceuticals) in remote settings.

Vaccines and a number of other life saving pharmaceuticals are highly temperature sensitive, making it very difficult to administer them in remote, low resource settings. Currently, most rural clinics have neither electricity nor refrigerators, and cannot provide vaccinations. The equipment used for vaccination outreach campaigns in remote areas—insulated boxes with freezer packs—is highly ineffective; many vaccines freeze, others get too warm, and outreach trips are limited to 1 or 2 days. A solar-powered vaccine refrigerator in the $500-$1,000 range will significantly improve the ability of remote clinics to immunize rural populations. A reliable, portable 'passive' cooling mechanism that is considerably less expensive (under $100) and can keep the vaccines from either freezing or getting too warm for several days, will also be very helpful.

24 Thermo-stabilizing mechanisms for preserving vaccines and other temperature sensitive, lifesaving pharmaceuticals so that they do not require refrigeration.

While a new generation of low cost refrigeration (or passive cooling) technologies can address the problem of vaccine preservation, the long-term solution is to obviate the need for refrigeration altogether. This can be done by making the pharmaceuticals thermostable, through stabilizing additives, novel molecular formulations, or other means. While a number of promising technologies are in the early stages of development, none has been extensively field tested, or proven applicable to the full set of essential vaccines.

25 Nutrient-dense and culturally appropriate foods for infants to complement breast milk during the weaning period.

Malnutrition underlies nearly half of all childhood deaths in sub-Saharan Africa and South Asia. A key problem is that during the weaning period, many infants are fed thin, grain-based porridges as a complement to breast milk. This does not provide sufficient nutrition during this critical period of growth. Affordable, nutrient-dense and culturally appropriate complementary foods for infants can make marked improvements in childhood nutrition.

26 Affordable off-grid refrigeration for smallholder farmers and small agribusinesses.

The absence of affordable refrigeration and electricity severely limits the ability of smallholder farmers to produce, preserve and sell high-value perishable commodities like vegetables, fruits, meat and dairy. A new kind of refrigerator that costs less than $50 and can run on solar power will help smallholder farmers take such high-value commodities to market, thereby increasing their incomes.

27 Low cost refrigerated vehicles, sturdy enough for unpaved roads in rural areas.

The ability to transport food to markets while preserving its freshness will help farmers increase their incomes from higher-value produce like vegetables, fruit, meat, and dairy products. Currently, the absence of refrigerated transportation is one of the factors contributing to the lack of a market for such commodities. Refrigerated trucks available on the market today are unaffordable for small agribusiness entrepreneurs, and are generally built for paved roads. In order to be useful in sub-Saharan Africa, refrigerated transportation vehicles must be built for unpaved, rough terrain, and cost less than $5,000.

28 **Low cost systems for precision application of fertilizers and water.**

Overuse of fertilizers and water contributes to significant environmental damage. In South Asia, since the Green Revolution, groundwater has been severely depleted, and fertilizer runoffs are causing 'dead zones' in waterways around the world. Overuse can also be a tremendous economic waste for smallholder farmers. Precision application systems for irrigation and fertilizers, calibrated to crop type and soil conditions, can be a very cost effective way to increase agricultural yields, while also reducing negative impacts on the environment.

29 **A low cost drilling system for shallow (rain-fed) groundwater wells, combined with portable sensors for measuring groundwater depth. Such systems should reduce the cost of drilling wells to under $100 per farmer in Africa.**

Most smallholder farmers in sub-Saharan Africa do not have access to irrigation. Wells are expensive to dig, drilling equipment is expensive to hire (and typically needs to be transported by truck), and it is hard to precisely locate groundwater. A new type of lightweight drill for shallow groundwater (e.g., one that can be transported by motorcycle instead of truck) can decrease capital costs. In addition, equipment for detecting groundwater can change the hit-or-miss nature of digging for water. It will be important to ensure that non-renewable groundwater is not overused.

30 **Low cost (under $50) solar-powered irrigation pumps.**

Currently available manual irrigation pumps are expensive and strenuous to use, especially for women farmers. Motorized pumps available on the market are even more expensive, and the cost hurdle is compounded by the recurring cost of fuel. A solar powered pump that is under $50 can dramatically increase access to irrigation. As with other irrigation solutions, it will be important to ensure that non-renewable groundwater is not overused.

31 **Affordable herbicides or other mechanisms to control weeds, ideally ones that are more environmentally friendly than herbicides currently on the market.**

Weeds are among the biggest causes of on-field losses for smallholder farmers. General herbicides—not specifically targeting particular types of weeds—can damage the food crops they are intended to protect. An herbicide specifically targeting the biological vulnerabilities of the most destructive weeds can dramatically reduce crop waste. Ideally, such herbicides will be more environmentally friendly than herbicides currently available in most markets.

32 **A low cost (under $50) tilling machine.**

Weeds are responsible for significant on-field losses for smallholder farmers. A commonly used method of eliminating weeds is to till the soil before planting. Mechanized tillers currently on the market cost 4-5 times more than what a typical smallholder farmer can afford. Animal-drawn tilling has not proven entirely effective, and manual tilling is simply too cumbersome and too slow. A mechanized tiller that costs under $50 can greatly improve weed control and lead to major improvements in agricultural yields.

33 A low cost alternative to liquid nitrogen for preserving animal semen.

Artificial insemination (AI) is an effective mechanism for breeding cattle and other animals, leading to significant improvements in livestock health and productivity. Preservation and transport of animal semen requires extremely low (sub -100°C) temperatures, currently achieved with liquid nitrogen. Production of liquid nitrogen at a large scale is expensive (although it appears more feasible at a small scale). A mechanism to preserve and transport animal semen without the need for a substance as cold as liquid nitrogen, thereby avoiding the capital costs associated with producing liquid nitrogen, can lead to a greater adoption of AI in Africa. This, in turn, can lead to major improvements in livestock health and farmer incomes.

34 High-nutrient and low cost, sustainable animal fodder.

Currently, most livestock farmers in sub-Saharan Africa practice extensive forms of livestock production, which involves animals grazing over large tracts of land but with limited access to nutrient-dense food. This grazing also contributes to deforestation and desertification. Affordable, nutrient-rich animal fodder made with sustainable and locally available ingredients can make a significant contribution to productivity (i.e., more and better quality of milk and meat), while also reducing environmental damage.

35 A portable toolkit for agricultural extension workers and livestock veterinarians.

Extension agents can provide valuable training for farmers, helping them optimize yield and improve produce quality. However, most extension agents do not have the tools to perform many of the services farmers need. An ideal extension worker toolkit should help them test soil quality, install and repair irrigation and other on-farm equipment, test the quality of produce (e.g., through chemical probes), and show videos or other instructional material to farmers. A similar toolkit for veterinarians and livestock extension agents, including point-of-care diagnostics for major diseases, a vaccine cooler, and other tools to provide on-farm care for animals can significantly improve the health and productivity of livestock.

36 Spatial repellent for on-farm pests.

Insects and other pests reduce potential yield by up to 15% for smallholder farmers in Africa. While crop damage is caused by several pests, a small number—borers, mealybugs, mites—cause a disproportionate share of these losses. A low cost spatial repellent that irritates pests (e.g., based on particular sound frequencies) could be an effective and sustainable mechanism to protect crops. It can also reduce the need for chemical pesticides, which can be harmful to health and the environment.

37 New seed varieties that are tolerant to drought, heat, and other emerging environmental stresses.

Climate change and water shortages are putting heavy stresses on crops and agricultural output. These stresses will continue to increase in the coming years. Just as new seed varieties were critical to the Green Revolution in Asia and Latin America, new varieties of seeds for essential cereals (e.g., maize, rice) that are tolerant to drought, heat, and other emerging environmental stresses will be necessary for agricultural development and food security in the near future.

38 Low cost (under $50) wearable, or otherwise easily concealable, cameras with automatic geocoding and timestamps, capable of 'SOS' data preservation (e.g., via satellite).

The rapid proliferation and falling cost of digital cameras, especially those integrated into mobile phones, has dramatically increased the number of human rights violations that are documented. This unprecedented level of transparency has made perpetrators more likely to face justice, and would-be perpetrators more wary. Cameras that are more inconspicuous and affordable, and capable of recording exact time, date and place where the images and videos are captured, will likely lead to greater levels of documentation of human rights violations. Note that such technologies will cause legitimate privacy concerns.

39 Low cost aerial vehicles to capture high resolution imagery for use by civil society groups, to document large-scale human rights violations.

Many large-scale human rights violations occur in the open, partly because perpetrators have no fear of accountability. In recent years, satellites are being increasingly used to document large-scale destruction of habitats such as villages, forests. However, continuous coverage of at-risk locations requires satellite data that is currently not accessible to civil society groups; and neither is imagery of high enough resolution to be actionable. Low cost (under $100,000) satellites are now being developed, and may make focused monitoring and documenting of violations more feasible. In addition, very inexpensive drones—increasingly available today—can be a valuable tool for collecting detailed imagery. However, drones are typically deployable over a specific location only after an incidence has taken place, and therefore more likely to be useful in contexts where there are recurring violations.

40 A simple point-of-use, low cost DNA-based rape kit.

One key hurdle in holding perpetrators of sexual violence accountable is the lack of hard evidence. A simple device that captures biological evidence in the form of DNA, and rapidly analyzes and digitizes the data can be very valuable. Such a technology will be truly useful only when social and legal barriers to prosecution of sexual crimes are removed, making it possible for victims to seek immediate recourse in the first place.

41 A new generation of network technologies that radically cut the cost of expanding broadband coverage to rural areas.

Even as the penetration of mobile phones, tablets and other computing devices increases, their usefulness depends on the availability of broadband connections. Expanding access to rural areas is challenging—populations are less dense, further from main networks, and have lower purchasing power. Instead of the traditional network infrastructure used for broadband connectivity (i.e., blanket coverage with many adjacent cells each supported by a base station), a new set of network technologies is required. This could include low/medium altitude satellites, other aerial devices, and innovative use of unused portions of the radio frequency spectrum.

42 A new generation of 'Internet of Things' (IoT) devices which enable new services for low income populations.

The Internet of Things (IoT) is a paradigm in which distributed sensors, probes, actuators and other devices are used to collect environmental data and monitor objects and systems (including people)

remotely and in realtime. This can enable a wide range of services that are currently missing for low income populations due to gaps in infrastructure, institutions and human capital. Examples of IoT applications in this context include Internet enabled point-of-care diagnostics, automated irrigation based on soil sensing, and distributed monitors for detecting environmental toxins.

43 A scalable method for sustainable integrated aquaculture production.

Aquaculture, the farming of fish and other seafood, is currently the fastest growing animal food producing sector, and an increasing source of fish for human consumption. Despite its increasing importance, current aquaculture methods are neither sustainable nor scalable. Nearly two-thirds of global production relies on artificial feeding, where the feed comes from wild fish (e.g., by grinding small pelagic species of fish like anchoveta). This puts additional stresses on over-exploited wild fish stocks, and is not tenable in the long run. In addition, current aquaculture production is extremely vulnerable to disease, pollution and changing environmental conditions. A breakthrough is needed to improve aquaculture, by integrating flows of energy, nutrients and biomass (e.g., by using waste material from terrestrial food production as nutrients).

44 Affordable homes that are resilient to extreme weather events, for the poor living in areas vulnerable to extreme weather.

The increased frequency and intensity of extreme weather events is putting vulnerable communities at greater risk of losing their homes. It is unlikely that improved architecture with existing materials, by itself, will suffice. Improved materials are required for robust, affordable, environmentally and culturally compatible housing, and for designs that can scale-up to meet global demand.

45 A retrofitted filter to reduce particulate matter exhaust from old heavy-duty vehicles.

Outdoor air pollution, primarily due to automobile exhaust from older vehicles, is a significant contributor to respiratory ailments and poor quality of life in urban centers of most developing countries. While the practice of extending the lives of automobiles to span generations is beneficial on the whole, poor maintenance of engines leads to high levels of particulate matter pollution. An inexpensive filtering device that can be retrofitted to the existing fleet of vehicles—especially the heavy-duty vehicles which cause most of the pollution—can significantly reduce particulate emissions from vehicular exhaust.

46 Low cost, distributed monitoring sensors to identify environmental toxins and their concentrations.

Environmental regulations in many countries are either lax, or poorly enforced. As a result, toxins such as heavy metals and persistent organic pollutants (POPs) are increasingly affecting human health, especially among the poor. The absence of reliable data on the presence and the concentrations of various toxins is a major hurdle to addressing this challenge. Robust, reliable and affordable monitoring technologies are required to identify toxins, their concentrations, and the health threats those concentrations pose. Such devices, if connected to Internet-based aggregation systems, can be a powerful component of the Internet of Things (IoT) paradigm to improve the lives of the poor. The monitoring technologies should be able to analyze water, soil, food or other substances using simple preparation techniques, and detect a range of pollutants including inorganic materials (such as mercury,

lead, arsenic), synthetic organic chemicals (such as dioxin, PCBs and specific harmful pesticides), and volatile organic compounds (such as benzene and formaldehyde).

47 Suite of solar photovoltaic mini-grid components, to significantly reduce upfront costs.

Renewable energy mini-grids, particularly those using solar photovoltaics (PV), will be a critical part of the solution for electricity access in rural sub-Saharan Africa. Currently, the cost of electricity generated by solar PV mini-grids is too high for low income rural users. While affordable financing can close some gaps, steep reductions in upfront costs can make universal electrification a reality. This will require cheaper and more efficient PV technology through improvements in design, manufacturing and materials, and streamlining of 'balance of system' costs.

48 Appliances for household use (e.g., TV, refrigerator) and income generation (e.g., irrigation pump), which are significantly more affordable and energy efficient than those on the market today.

Electricity itself does not change people's lives, it is what people do with electricity that does. In recent years, there has been a proliferation of devices such as portable solar powered lights and charging kits for mobile phones. However, to meet basic needs for development, a suite of appliances like TVs, refrigerators and irrigation pumps are required. Even if such appliances were affordable currently, the cost of powering them would far exceed the 'energy budget' of low income users. Hence, the energy efficiency of these appliances also needs to increase significantly.

49 New bulk storage technologies for decentralized mini-grids, which provide improved performance at a significantly lower cost.

Bulk storage for backup power and load balancing is crucial for reliable electricity in decentralized mini-grids, especially renewable energy ones, where supply (sun, wind) is intermittent. However, storage technologies that can be applied at mini-grid scale are not commercially available at the desired cost and performance. Lead acid batteries, the only commercially available option, are too expensive (often comprising 50% of total system cost) and have performance issues (low energy density, short life). Alternative and emerging battery technologies—e.g., flow batteries, lithium-ion (Li-ion) and sodium sulphur—are still pre-commercial and need significant cost and performance improvements. Li-ion will benefit from growth in the electric vehicle sector.

50 Affordable and easy-to-use grid management solutions for decentralized renewable energy rural mini-grids.

Currently, mini-grid installations in low income rural areas face several challenges: there can be overuse (or theft) by individual users; collection of user fees can be cumbersome; and it is difficult to pinpoint sources of breakdowns or system failures. Existing solutions for managing mini-grid systems are not affordable, and are too complicated for rural settings where there are few skilled workers with the technical expertise required for installation and maintenance. New, inexpensive and simpler solutions are required for forecasting demand, calibrating generation, 'smart' metering, and monitoring consumption and leakage.

51 Low cost (under $500) transport for families, ideally using renewable energy.

Through our analysis, a small number of potential breakthroughs kept emerging as important in individual sections, but never made it to the top of the list of any of the sections. Affordable transport, in particular, is one that is worthy of mention.

Personal and family transport has been a critical component of improving productivity and quality-of-life for large portions of the global population. Yet, for most of the rural poor, especially women, walking long distances and carrying heavy loads remains a daily reality. A number of promising low cost vehicles (e.g., three-wheeled solar and electric rickshaws) are becoming available in the $500-$1,000 range, although the full system (including power charging) is more expensive. An affordable automobile that runs on renewable energy will be transformative.

THE BREAKTHROUGHS 'HEATMAPS'

Beyond the list of breakthroughs, there are a number of important questions that warrant discussion: Are there any quick wins? Which breakthroughs have the most difficult path to impact? Which of these are commercially attractive for profit-seeking businesses, and which are important public goods without commercial prospects? What are the most appropriate funding mechanisms for these breakthroughs? How can various governments, funders and other institutions shape their agendas to enable the realization of these breakthroughs?

Some of these issues are discussed below, some in the concluding section of the study, and others will need to be part of the ongoing conversation this study hopes to spur. To that end, the following groupings—matrices—of the breakthroughs may be helpful.

Matrix A shows the technical complexity of each breakthrough (measured by the time-to-market, on the x axis), against the difficulty of deployment (y axis). Based on this analysis, there are 4 categories.

- The relative quick wins (bottom-left of the matrix), which appear to on the horizon from the technical point-of-view, with relatively achievable deployment models. It is important to note that categorizing a breakthrough as a quick win does not mean that it is guaranteed to happen. It simply suggests that anyone wishing to invest effort or funds into a problem with a likelihood of relatively quick results should consider this set of issues.

- Problems with seemingly imminent technical solutions (top-left of the matrix), but with significant barriers to deployment. The biggest risk facing current projects attempting to address these issues, is that there will be excessive focus on the technical solution without an appreciation of the deployment challenges.

- Problems which have significant technical hurdles (bottom-right of the matrix), but with seemingly surmountable deployment challenges. In such cases, once the technology problems are solved, there is a good chance that they will lead to impact.

- Issues which face major hurdles on both the technological and deployment fronts (top-right of the matrix). These represent the most difficult challenges in the technology-for-development space. For those investing in technologies to address these issues, it is important to be equally demanding of solutions to deployment hurdles.

Matrix B analyzes the funding models appropriate to each of the breakthroughs, based on their commercial attractiveness. The x axis shows the projected time to market, as a proxy for the amount of funds required. Along the y axis, it groups them into 4 categories.

- Technologies which have attractive commercial prospects in industrialized markets, as well as in developing country markets (bottom row). In all likelihood, there are ongoing investments to take advantage of these commercial opportunities. For funders seeking to invest in a true 'double-bottom-line' this space represents fertile territory.

- Some of the identified technologies will have an attractive market in developing countries (second row from the bottom). However, the profits will not be attractive enough for investors motivated

to maximize commercial returns. These represent very promising investments for funders focused on profitable ventures in emerging markets. Philanthropic grant capital may not be appropriate for these technologies, because such funding often does not require adequate rigor on sustainable deployment models.

- In many cases, technologies and products will (and should) be commercially sustainable in the long run, but the seed R&D capital may not be recouped. These are ideal for early-stage grants to lay the platform. These are identified in the second row (from the top).

- Some technologies (top row) can have significant social impact, but will not (and should not) earn profits. The only mechanism for these technologies to materialize, is through grant funding.

Matrix A

Difficulty of deployment	0	3	6	8	10	>>10
Extremely Challenging		**6.** Biometric ID systems **14.** PrEP antiretrovirals for HIV prevention **30.** Solar powered irrigation pumps **37.** New seed varieties tolerant to drought and heat	**20.** Automated multiplex immunoassays **21.** Point-of-care nucleic acid diagnostics **25**. Nutrient-dense infant weaning foods **42**. IoT for low income populations	**12.** Microbicides for HIV/ HPV **27.** Low cost refrigerated vehicle **40.** DNA-based rape kit	**8.** New generation of homes for the poor 9. New fertilizer production systems **22.** Fully integrated diagnostic panels
Challenging	**34.** High-nutrient animal fodder **10.** Utility-in-a-box for solar mini-grids	**18.** Clinic-in-a-box **32.** Low cost tilling machine **39.** Low cost aerial vehicles for imagery **41.** Wireless broadband technologies	**19.** Oxygen concentrator **28.** Precision agriculture systems for irrigation and fertilizer **45.** Retrofit filter for vehicle exhaust	**17.** Non-chemical spatial mosquito repellent/attractant **29.** Low cost shallow water drilling system **33.** Alternative to liquid nitrogen for preserving animal semen **36.** Spatial on-farm pest repellent **43.** Sustainable aquaculture systems	**31.** Herbicides for weeds
Complex	48. New generation of low-cost, energy efficient appliances	**26.** Off-grid refrigerator for households and farmers **51.** Low cost family transport **38.** Wearable cameras	**44.** Affordable homes resilient to extreme climate events **46.** Distributed sensors for environmental toxins	**1.** Energy efficient desalination **49.** New bulk storage technologies **50.** Mini-grid management solutions **16.** Long-lasting chemical mosquito repellent **35.** Portable toolkit of extension workers and veterinarians	**2-4.** Vaccines for HIV, TB, Malaria **47.** Low cost PV mini-grid installation
Feasible	**7.** Affordable smartphones	**11.** Short-course TB treatment **23.** Off-grid vaccine refrigerator **5.** Smart electronic textbooks	**15.** Complete cure for malaria	**13.** Long-lasting antiretroviral for HIV	**24.** Thermo-stabilizing mechanism for vaccines
Simple						

Likely time to market (years)

- Potential quick wins
- Mostly a technology challenge.
- Breakthroughs appear imminent. Innovative business models need to be developed soon.
- The most difficult challenges: very complex technologies and daunting deployment hurdles.

Matrix B

Commercial potential	0	3	6	8	10	>>10
Non-commercial		**6.** Biometric ID systems	**46.** Distributed sensors for environmental toxins	**40.** DNA-based rape kit		
Emerging markets potential, with initial grant support	**34.** High-nutrient animal fodder	**11.** Short-course TB treatment **18.** Clinic-in-a-box **37.** New seed varieties tolerant to drought and heat	**15.** Complete cure for malaria **19.** Oxygen concentrator **20.** Automated multiplex immunoassays **21.** Point-of-care nucleic acid diagnostics **25.** Nutrient-dense infant weaning foods **28.** Precision agriculture systems for irrigation and fertilizer	**1.** Energy efficient desalination **12.** Microbicides for HIV/HPV **16.** Long-lasting chemical mosquito repellent **17.** Non-chemical spatial mosquito repellent/attractant **33.** Alternative to liquid nitrogen for preserving animal semen **43.** Sustainable aquaculture systems **35.** Portable toolkit for extension workers and veterinarians	**3-4.** Vaccines for HIV, TB, Malaria **9.** New fertilizer production systems **22.** Fully integrated diagnostic panels **24.** Thermo-stabilizing mechanism for vaccines **31.** Herbicides for weeds
Attractive for emerging markets	**7.** Affordable smartphones **10.** Utility-in-a-box for solar mini-grids **48.** New generation of low-cost, energy efficient appliances	**23.** Off-grid vaccine refrigerator **26.** Off-grid refrigerator for households and farmers **30.** Solar powered irrigation pumps **32.** Low cost tilling machine **41.** Wireless broadband technologies **51.** Low cost family transport	**42.** IoT for low income populations **45.** Retrofit filter for vehicle exhaust **44.** Affordable homes resilient to extreme climate events	**27.** Low cost refrigerated vehicle **29.** Low cost shallow water drilling system **50.** Mini-grid management solutions	**8.** New generation of homes for the poor **47.** Low cost PV mini-grid installation	
Attractive for industrialized markets		**5.** Smart electronic textbooks **14.** PrEP antiretrovirals for HIV prevention **38.** Wearable cameras **39.** Low cost aerial vehicles for imagery		**13.** Long-lasting antiretroviral for HIV **36.** Spatial on-farm pest repellent **49.** New bulk storage technologies	**24.** Thermo-stabilizing mechanism for vaccines	

Likely time to market (years), as proxy for funding required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