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BEYOND THE GAP
HOW COUNTRIES CAN AFFORD THE INFRASTRUCTURE THEY NEED WHILE PROTECTING THE PLANET

Background Paper

Scenarios

Leapfrog, Lock-in, and Lopsided

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Abstract

This paper presents the details of three scenarios—leapfrog, lock-in, and lopsided—that describe an illustrative set of technological states. Based largely on expert interviews, the paper argues that the technology outcomes are heavily attributable to the actions (or in some cases, inaction) of policy makers and incumbents. For each scenario, the paper presents descriptive levels of technology achievement and market outcomes for the energy, transport, and water sectors. One of the central differentiating features of the three scenarios is the extent to which governments perform their roles as enabling, that is, whether the policies are designed to help or hinder innovations that improve service levels, and distributive, that is, whether the policies are designed to ensure that multiple segments of society reap the rewards of innovation. A question raised as part of that theme is how countries can avoid lock-in, or how they might become derailed into a lopsided scenario. Some institutional behavioral markers of the scenarios were identified in these discussions and are noted in the paper. It is important to recognize that multiple combinations of these behaviors can lead to a lock-in or lopsided scenario. In addition to describing the scenarios in detail, the paper discusses the rationale for their creation, along with a brief discussion on the nature of uncertainty. The paper also describes the methodology employed in the creation of the scenarios, including expert interview methods and a day-long workshop.

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Scenarios: Leapfrog, Lock-in, and Lopsided

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Introduction

As a complement to the infrastructure services modeling described in the World Bank Group's report: "Beyond the Gap: How countries can afford the infrastructure they need while protecting the planet," the World Bank's Sustainable Development Vice Presidency engaged in a scenario-building exercise, to address uncertainties not readily modeled. The three scenarios, called "Leapfrog," "Lock-in" and "Lopsided" describe different levels of deployment of new technologies. The scenarios were built in consultation with sectoral and technology experts, both internal and external to the World Bank, using informal interviews, expert elicitation and a full-day workshop. The scenarios, their intended use, our methodologies, and several themes that emerged during our interviews and workshop, are discussed below.

Uncertainty, Knightian Uncertainty and Black Swans

Numerical models and quantitative forecasts, no matter how rigorously developed their inputs and assumptions, rely on the availability of observed data. The greater the degree to which modeled phenomena are based on imputed data, or minimal data, the greater the uncertainty in the modeled results. For example, if large swaths of a country lack electricity or lack regular availability of electricity, there is inherent data uncertainty in predictions of how electricity demand might evolve over a 20-to-30-year period. Using demand elasticity and price elasticity estimates taken from other countries is often the closest proxy available, but the possibility of introducing some statistical bias is evident. We may be able to quantify the uncertainty in the demand elasticity estimate but be unaware of a critical omitted variable.

A deeper problem for forecasters is the need to forecast phenomena not yet experienced or not widely experienced. Uptake of technologies only minimally present globally, let alone in the studied country, presents forecasting challenges. For example, deployment of a mini grid, using solar photovoltaic (PV) power and battery storage, is a package of technologies for which traditional quantitative models will have weak data. Mini grids with PV and batteries are one promising means of providing electricity access to some of the 1.1 billion people currently without access. Though mini grids (using diesel generators) are present in many countries, they are still a blip on total electricity supply, and their deployment has been uneven both geographically and over time. Moreover, while solar PV is not a new technology per se, it has become economic only in recent years and hence its deployment in many areas is still novel, certainly in mini grids, which more commonly rely on diesel generators. The cost and deployment of battery backup power is on a similar trajectory to solar PV, but trailing by several years, hence its presence is even more unusual. The costs and performance characteristics of the technologies are still evolving rapidly. Lastly, new financing models and new policy incentives are emerging to deploy mini grids, and hence the first-year costs and payback periods for mini grids are inherently uncertain. Combining these uncertainties with, say, the uncertainties regarding timing of transmission extension to remote villages, makes modeling electricity demand growth in developing countries especially fraught.

There is a third dimension of uncertainty at play, which stems from the combination of truly novel technologies and their 2nd- and 3rd-order effects. For example, with so little data on deployment of all-electric vehicles (EVs), we do not yet know the 3rd-order effects of how charging patterns will affect grid reliability or peak demands. Or for example, with no commercial, fully autonomous vehicles (AVs), we cannot yet confidently say how they will affect vehicle-kilometers-traveled (VKT) or urban traffic congestion. Nor, as a 3rd-order effect, do we know what either EVs or AVs might do to the housing and labor markets. The costs and performance characteristics of the novel technologies can be estimated, though with low confidence, but the 2nd- and 3rd-order uncertainties can barely be parameterized. This deeper uncertainty is labeled "Knightian Uncertainty"[1] by economists, as a way to distinguish quantifiable from non-quantifiable uncertainty. In infrastructure planning, given the long-lived nature of assets such as power plants, transmission lines, railways, water delivery systems, etc., Knightian uncertainty can lead to institutional paralysis (e.g., why spend money when the outcome is so uncertain) or poor decision making (e.g., why pay attention to something so uncertain).

In infrastructure planning, deep uncertainty can lead to institutional paralysis or poor decision making.

Knightian uncertainty is most often recognized in hindsight, in the case of “Black Swan” events. Black Swans are very low probability and high impact events which, according to Nassim Taleb, we are essentially incapable of foreseeing. Taleb argues that Black Swan events are typically improperly rationalized after the fact, i.e., arguments are made that they “could” have been predicted had relevant data been accounted for. Critically, Taleb argues that statistical and parametric analysis lull us into a false sense of security, in believing that we have accounted for risk, when in fact Black Swan events - because they are unprecedented - fall outside modeled distributions. We do not know what we do not know. Taleb argues that since we lack the ability to predict Black Swans, we should instead build our institutions to be Black-Swan proof, making them resistant and resilient to shocks, and minimizing the incentives to build hard-to-unwind and hard-to-rebuild assets.

In order to help World Bank client countries plan infrastructure that is robust to these multiple levels of uncertainty, we designed three scenarios. Our approach to scenario building (described in more detail below) is slightly unorthodox, and the scenarios as constructed are meant to be used as guides and tools, rather than off-the-shelf products. At their core, the scenarios present alternative futures that are distinguished by their levels of technology deployment and adoption - but *not* by the success of technology R&D. Fundamentally, we assume that the technology deployment and adoption levels are the result largely - though not exclusively - of actions taken (or inaction, or actions blocked) by governments and incumbent institutions.

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[1] Named after Frank Knight, an economist who studied risk and uncertainty.

Fundamentally, we assume that the technology deployment and adoption levels are the result largely - though not exclusively - of actions taken (or inaction, or actions blocked) by governments and incumbent institutions.

However, it is crucial to acknowledge that a framing solely on one, proximate cause is inherently limited. As Derbyshire and Wright[2] point out, this form of "intuitive logics"-based scenario construction can give the "misimpression that each end-state of a scenario has only a single set of antecedent causes."[3] In their language, the "efficient cause" method of scenario construction (focusing on the single set of antecedents) narrows futures thinking instead of broadening it. They suggest consideration of three other forms of causation, including:

- "material causes" - how the state of things might lead to a step change or tipping point;
- "formal causes," encompassing
  - how actors intend actions to have effect, including e.g., the transportation plan of a municipal government, and
  - how actors' behavioral patterns typically play out, e.g., the tendency of monopolies to resist change; and
- "final cause" - how motivated behaviors can influence outcomes, e.g., an incumbent firm using political influence to protect its own interest.

Our scenario construction exercise accounted for all four of these categories of causes. Following Derbyshire and Wright, our workshop focused on "identifying the forces (i) that can cause step-change transformation, (ii) whose formal design can either facilitate or restrict change, and (iii) where actor motivations and actions can either facilitate or restrict change."[4]

Purpose of the Scenarios

The scenarios are meant to accomplish multiple, complementary purposes. First and foremost, they are meant to help governments and planning authorities in World Bank client countries address uncertainty in infrastructure planning. The scenarios are somewhat extreme versions of how futures might play out, and are not meant to be fully descriptive. Rather, they are meant to focus attention on choices that can be made (intentionally or not) and what the impacts and ramifications of those choices might be. The scenarios are not purely descriptive, in that the actions of institutions (public and private) certainly affect the outcomes, some of which are more desirable than others; but nor are they purely normative, because - like descriptive scenarios - they describe processes of change that are common in many countries. Thus, the scenarios are meant to be a tool to help client countries examine how suited and prepared they are for taking advantage of technological disruptions. By tailoring the scenarios to country-specific

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[2] Derbyshire, James and Wright, George, "Augmenting the intuitive logics scenario planning method for a more comprehensive analysis of causation," International Journal of Forecasting 33 (2017): 254–266.
[3] Ibid.
[4] Op Cit, Derbyshire and Wright.

circumstances, governments can build an analytic mechanism which is at once both a mirror and a telescope; this is us, and this is what we might be.

Brief Descriptions of the Scenarios

The three scenarios, “Leapfrog,” “Lopsided” and “Lock-in,” are described below, first generally, and then in detail in the appendix to the paper. The primary feature distinguishing the three scenarios is not the success of technology research and development (R&D), but rather its deployment in developing countries.

The premise that distinguishes the scenarios is the ability and success of governments, planning authorities, and regulatory authorities to fulfill their enabling and distributive functions. By enabling function, we mean the ability to put in place enabling measures (e.g. backbone infrastructure, regulatory frameworks) and remove or minimize barriers. By distributive functions, we mean measures that ensure that the spread of new technologies is not limited to the wealthy and does not result in a decrease in opportunities and access for the rest of the population.

The primary feature distinguishing the three scenarios is not the success of technology research and development (R&D), but rather its deployment in developing countries.
The premise that distinguishes the scenarios is the ability and success of governments, planning authorities, and regulatory authorities to fulfill their enabling and distributive functions.

In other words, the key difference across the scenarios is how well governments, incumbent institutions and regulatory agencies manage the perennial challenge of balancing the needs of protecting and improving social welfare and reducing inequities with enabling radical, systemic change and ensuring it leads to progress. R&D success is necessary, but by itself is an insufficient condition to achieve transformation.

In addition to the sector-specific technologies or business models, such as mini grids for the power sector, or Mobility as a Service (MaaS) for the transport sector, there are several technologies which enable the disruptions and transformations. Those technologies are described and discussed below.

Enabling Technologies

Regarding technology, we assume the following holds across the three scenarios:

- Artificial intelligence (AI) and machine learning technologies continue to scale rapidly, permitting optimization of operations in virtually all industries and walks of life.
- Robotic function has increased dramatically, in perception and cognition (ability to understand and react to the surrounding environment), ambulation, motion and fine motor movements (ability to physically interact with the environment) and inter-agent coordination (ability to coordinate complex tasks across multiple robots).
- Sensors are available to be used in all devices.

- 5G or better communications are widely commercially available.
- Low earth orbit satellites are widely deployed and, together with 5G, enable a true internet of things (IOT) economy.
- Advanced manufacturing techniques, such as additive manufacturing (AKA 3D printing, or 3DP), have altered how things are built, how efficiently they use energy, and even how those equipment and structures communicate.
- Tools like augmented reality, natural language processing, and delivery drones have begun to change the geography of production.
- Connected, fully autonomous vehicles (AVs) are readily commercially available.
- Electric vehicles (EVs) are widely mass produced.
- Ride sharing/ Mobility as a Service (MaaS) apps are common.
- Batteries for EVs are significantly less expensive and longer lasting than today.
- Batteries for grid storage are much cheaper and longer-lasting than current technology.
- Other energy storage technologies have advanced by virtue of R&D and/or business models and found economic use cases leading to further deployment. These include pumped storage (where the hydro resource and topography exist, but where financing, heretofore, has not), molten salts for thermal storage, flywheels, compressed air, and other novel ideas.
- Water utilities can benefit from advances in chemistry, filtration, UV purification, and contaminant detection and sensing.
- Blockchain is widely employed, enabling coordination among disparate and diffuse actors, without a central, coordinating body.

How Enabling Technologies May Affect Infrastructure or Infrastructure Needs

In the following sections we present examples of how enabling technologies might affect infrastructure and service delivery.

How Industrial Internet of Things (IIOT) and Machine Learning Might Affect Power Grids

We anticipate that services delivery can become much more efficient via digitally connected systems, or a robust IIOT. The IIOT will depend on sensors, which are increasingly cheap to manufacture, and increasingly easier to embed into a product's original design, e.g., via 3D printing the circuitry into a part. The sensors will rely on an advanced communications infrastructure, which will combine 5G technology and Low Earth Orbit (LEO) satellites. 5G and LEO will combine for extremely low latency communications between devices, and for some use cases, extremely large amounts of data transfer.

For example, in electric power, sensors within components of a wind power plant might relay information to a control system, which would optimize the turbine blade pitch and yaw; that same control system may also connect the multiple turbines in the wind park, optimizing each one in concert with the others, to maximize the total output of the park. The wind park, in turn, will communicate with other power plants and substations, as well as with the grid operator. The grid control system will take into account real time conditions that affect the locational marginal price (changing costs to operate and changing congestion costs). The substations may communicate with control systems on the distribution end, sending signals about pricing to end use customers’ devices, which might modulate and moderate their power demands accordingly, e.g., by sending price signals to a building’s air conditioning system.

The same set of devices may also play a role in optimizing the pricing and charging of electric vehicles; or whether a building stores the power it generates from a solar array in an on-site battery, or sends the power to the grid; or whether a power plant may be about to experience a fault and should instead cycle down into a preventative maintenance mode, and so forth.

Further, the same types of sensors and optimizations could function on a mini grid, perhaps even with more value, since a mini grid’s operation typically has fewer degrees of freedom than a central grid. The algorithms might help the mini grid operators coordinate with the central grid (in cases where a connection is possible), to decide if the mini grid should supply power to help a central grid return from a forced outage and blackout or if the mini-grid should remain “islanded.” Moreover, all the data being collected and acted upon may be input into a system of ever-improving machine-learning algorithms, so that the performance of the equipment and the grid and mini grid get increasingly better.

The sum effect could be fewer outages, more reliability, less equipment wear and tear, cheaper pricing, fewer pollutants, and any number of outcomes that result from better and more efficient operation.

How Batteries, AI & Additive Manufacturing Might Affect Transportation

We anticipate that battery technology continues to evolve at a very rapid pace, and that costs continue to drop. At some point, commodity prices will create a “floor” for how low prices can go, but we expect that a combination of new chemistries (i.e., beyond Lithium Ion), continued economies of scale (more giga-factories) and “learning by doing,” as well as continued competitive forces will keep prices on a downward trajectory for quite some time. Moreover, we anticipate that new chemistries and new means of manufacture will optimize some batteries for very long discharge periods over long life times (i.e., 8 hours of storage with thousands of cycles over a 25-year lifetime), and optimize other batteries for vehicle operation (i.e., many stops and starts, and quick recharging).

We further anticipate that artificial intelligence and machine learning will continue its progress, such that fully autonomous vehicles (level 5) will be commercially available in a few years. AI will also enable fully pilotless drones, and efficient ground and urban air traffic control systems to manage the flow of vehicles. (5G will also facilitate vehicle-to-vehicle communication and vehicle-to-traffic controller communication.)

Finally, we anticipate that additive manufacturing (3D printing, 3DP) will continue to progress and commercialize. The current R&D paths for finding faster production and larger component size 3DP will be successful. 3DP will enable light-weighting of vehicles (and hence extend the effective miles per charge from car and drone batteries) and enable novel vehicle designs that would otherwise not be possible to manufacture.

The combination of these technologies has the potential to reshape transportation systems and their infrastructure, for example:

A system of autonomous vehicles (AVs), coordinating with each other and with a traffic controller algorithm, has the potential to dramatically reduce traffic time, traffic accidents and vehicular pollution (from more efficient driving and less stoppage). Alternatively, in a poorly managed system, AVs might increase sprawl by minimizing the opportunity cost of driving, thus encouraging people to live farther away from their work.

Relatedly, dropping battery costs and increasing demand for electric vehicles (EVs) have already prompted several car makers to produce more hybrid, plug-in hybrid (PHEV) and fully electric battery (BEV) vehicles. Many AVs will be BEVs, as the computing power needed to control an internal combustion system is greater. PHEVs and BEVs could add strain on power grids if rates are not carefully designed and if the vehicles do not have optimizing algorithms to make charging decisions. Charging infrastructure (grid or off-grid) will be needed.

Economists like to describe “technological spillovers,” and the same factors leading to AVs and EVs will help the drone market. Some workshop participants were skeptical that aviation authorities would allow much passenger transport, but there was more optimism about package delivery drones. Infrastructure for receiving packages from drones will be needed in buildings, or potentially “drone depots,” but roadway traffic may abate as fewer delivery trucks and motor-scooters will be employed.

Even absent flying cars, as ride sharing grows in popularity, cities may see a decrease in total number of vehicles on the road, thereby decreasing car ownership, as well as the need for parking spaces and parking structures. There is still disagreement about whether ride sharing would increase total vehicle kilometers traveled (VKT), but consensus that planning and regulations can mitigate that potential effect. With fewer vehicles, there are implications for roadway lanes and overall widths. Mobility as a Service (MaaS) is an extreme form of ride sharing, in which all forms of transportation - car, bicycle, scooter, rideshare, bus, rail - are all interlinked by app. The app’s logic will be powered by machine learning algorithms and improve with use. Without an interwoven transportation system such as MaaS, public transit may be more likely to suffer as car-sharing and AVs penetrate. But with MaaS, well planned transit systems may thrive, as the “last mile” problem may be solved, and as utilization of existing lines can grow. In particular, non-BRT buses may be most vulnerable to disruptive transportation technology, but if those buses use AI to incorporate adaptive and dynamic routing, and integrate with a MaaS platform, they could instead become valuable assets in the system.

The sum effect could be a more agile, efficient and environmentally friendly way of moving people and goods, but the outcomes are very dependent on planning and regional coordination.

How IIOT & AI, and Chemistry and Biology Advances Might Affect Water Management

We anticipate that several of the same technology advances that will enable disruptions in the power and transportation sectors will also affect the water sector, both at the water resources management level, and at the distribution level. Data analytics spanning the entirety of water system operations are becoming more common, increasing efficiency and leading to operational improvements. A wholly different, but complementary, set of scientific breakthroughs will affect water purification and sanitation. The techniques will make centralized systems better and more effective, but will also enable decentralized, and disruptive innovations. Many of these technologies and techniques have already started deploying.

For example, in water resource management:

- Drones, satellites and remote sensing technologies are being combined, and used to complement (scarce) ground measurements, to more efficiently measure flow and map topography, to better plan for floods and drought.
- New, “softer” physical techniques such as dry dams and movable, inflatable dams are being considered for flood control, rather than traditional dams or berms and levees.
- New materials are being used for irrigation channels, to prevent and minimize leakage.
- Use of modeling has led to a revolution in “precision irrigation”.
- Drones and other remote sensing techniques are also being deployed for irrigation management.

The sum effect could be reduced flood and drought risk, reduced water usage in agriculture via precision water delivery, reduced water loss via improved irrigation, and in areas with depleted groundwater, reduced subsidence, and in estuarine areas, reduced salinity.

And for example, in water distribution systems:

- The use of satellite imagery has already been proven for leak detection.
- New hydraulic modeling algorithms enable lower pressures and, in turn, less system stress and energy consumption.
- Sensors with telemetry are already being deployed to monitor pressure and flow, minimizing losses and improving system maintenance.
- Miniaturized robots are being tested for deployment within pipes to identify leaks.
- Machine learning and “digital twins” are being used for system optimization, predictive analytics and preventative maintenance in pumping systems and distribution.
- New metering technology allows for better data analysis with lower labor costs, as well as better monitoring of the status of the meters’ conditions themselves.
- 3D printed water quality meters are being developed to measure pH and conductivity.
- *The sum effect could be reduction in leaks, breaks and “non-revenue” water, thereby improving the financial position of the water utilities and their ability to deliver services.*

And for example, in drinking water purification systems:

- Various new filtration techniques have been discovered in recent years. These include advances in materials and nanomaterials such as graphene, titanium dioxide and metal organic frameworks (MOFs, which have the largest internal surface area of any known substance).

- Other new purification systems based on biological techniques, such as biological filtration, algal filtration using euglena, and biomimetic system using aquaporins are being developed and deployed.
- Purification systems using UV rays and photocatalysts or using traditional methods but powered by solar PV and batteries are also being tested.

The sum effect of these technologies would be to reduce costs for utilities to purify the water in their central systems, but they would also reduce costs of purification in decentralized systems. With lower energy costs, lack of need for heavy chemical treatments, and modularity, desalination and water purification can become a viable option even in remote areas and on a small scale.

And, for example, in sewerage and treatment systems:

- New trencher systems are replacing traditional excavators to make pipe laying much quicker and cheaper, and with far less disruption to street traffic.
- New wastewater treatment sanitation techniques using ultrasound are being tested.
- New designs for wastewater treatment plants (WWTPs) are being designed to enable modularity and scalability.
- In some WWTPs, the sludge is being dried with solar power, and then made usable as a fuel for biopower electricity.
- In some cases, the nutrients from WWTP sludge are being used as fertilizer.
- Some buildings are being designed with dual wastewater systems - “gray” water and “brown” or “black” water - to minimize overtreatment of graywater and enable energy efficient and less costly water reclamation and reuse.
- Small and modular WWTPs are becoming increasingly economic, as the techniques for filtration and purification advance. “Lego”-like systems are being deployed, so as to maximize utilization and better manage CapEx.

Like the water purification technologies, the sum effect of the wastewater treatment advances would help not just centralized water utilities but also decentralized systems. Decentralized systems can be in remote areas, where laying miles of pipe would be very costly, or in dense, urban areas, where land resources are scarce.

Scenarios, in brief

LEAPFROG

- Technologies have advanced quickly and some exponentially, and cost and business models made them widely attractive.
- Policies, social habits and institutions adapted well and in timely manner, enabling the technologies to diffuse quickly and in an equitable fashion across all segments of society.
- Data collection and use is a core part of infrastructure planning.
- Data infrastructure, such as laying fiber, building towers and satellite connections, using data to improve planning and to facilitate new business models has been, and is, a core of planning.

LOPSIDED

- Technologies advanced quickly and some exponentially, and cost and business models made them attractive.
- Policy design did not allow for equitable use of the technologies.
- Social habits of the wealthy in developing countries mimicked and mimic those in developed countries, public institutions generally fought and fight change, and some policies with competing aims remain in place.
- Technologies diffused quickly, but only in selected areas and even then, only for a portion of the population, resulting in social exclusion and a two-tier world of have and have nots with respect to modern systems.
- Proactive use of data is largely the domain of the private sector, with sporadic use by public agencies, and little public-private coordination.
- Adequate data infrastructure exists only in pockets and is more often dictated by narrow private concerns than by public policy.

LOCK-IN

- Technologies have advanced but barriers to adoption and challenges to business models make them attractive in developing countries only in rare cases.
- Policies and social habits did change or adapt as new techs were introduced, some institutions fought change, and policies with competing aims remain in place.
- Technologies diffused in developed countries, but developing and emerging countries saw widespread use of older investment patterns.
- Data collection and data use continues to be an afterthought in planning.
- Building data infrastructure is not part of normal planning.

Table 1. General technology deployment levels by scenario

	Leapfrog	**Lopsided**	**Lock-in**
Power	IOT-based digital grid Acceleration of grid-scale renewable energy and battery storage Construction and incorporation of some EV charging stations Rapid diffusion of microgrids	Investment in digital only in privately-owned capacity More renewables, but not well integrated Private microgrids for fleet EV charging Microgrids for gated communities	Lack of investment in digital smarts and communications infra. More renewable capacity, but poor grid integration Grids too weak to support much EV Very few microgrids
Indicative stat:	*Electricity access improved by ~95% versus 2018 base*	*Electricity access improved by ~65% versus 2018 base*	*Electricity access improved by ~75% versus 2018 base*
Transport	Shared, Autonomous EVs (SAEVs) have become the norm for millenials Single passenger cars are a rare luxury Wide diffusion of mobility as a service (MaaS) Common package delivery drones; occasional, autonomous flying cars	Limited penetration of AV/EVs Limited implementation of physical infrastructure New techs most common for the wealthy, new neighborhoods Resistance by incumbents to TNCs & ride sharing	Requisite physical & communication infrastructure has not fully arrived Resistance by incumbents to TNCs & ride sharing Grids not capable of handling loads from electric vehicles AVs create new problems for “drivered” cars
Indicative stat:	*50% of cars on the road are SAEVs*	*Passenger VKT for the wealthiest is up by 20-30%*	*No more than 5% of cars are SAEVs*
Water	Water mgt agencies cooperate within & across boundaries Wide collection & use of data use data for resource and system mgt Non-revenue water is reduced substantially Mix of new connections to the main system & distributed systems	Cooperation in closely politically aligned areas Advanced flookd control in areas with industrial operations or wealth , Private water utilities incorporate digital strategies to reduce non-revenue water Wealthy nbhds built with local water reclamation and purification	“Stove-piping” & little coordination of data Legacy data systems and untrained staff Little approval for spending on digital Few distributed systems exist Few “trenchers” … piping remains costly and disruptive
Indicative stat:	Safe water access improved by ~70% versus *2018 base*	Safe water access improved by ~40% versus *2018 base*	Safe water access improved by ~50% versus *2018 base*

Additional Detail on the Scenarios, Based on Workshop Discussion

Below are a series of comments we received during our workshop, which helped refine and flesh out our scenarios.

- Satellite and ground-based video will integrate seamlessly, which combined with AI, will enable interpretation of events in real time. Our ability to model the world - energy, transport, water and more will improve as AI grows more ubiquitous.
- There were several technologies we omitted but which participants felt would have an important effect on overall service demands. These include:
    - Biotech and the potential for longer, healthier lives, via CRISPR,[5] new ways of manufacturing artificial limbs and organs, and machine-human organ interfaces.
    - Agritech, including in-vitro meat, urban farming, and other techniques that could upend agrarian societies and supply chains
    - The potential for blockchain to reduce transaction costs across many markets, and for fintech to empower many in poverty to access new markets
    - Energy efficiency, which will continue both on the supply side in the form of more efficient energy and electricity production, and on the demand side in the form of more efficient buildings, equipment and devices

Methodology

In constructing our scenarios, we used three steps, including interviews with both open dialogue and more formal, expert elicitation, scenario “strawman” construction, and an interactive workshop with multiple experts.

Interviews

In the interview phase, we spoke with sector experts from various organizations within the World Bank (including IFC), and sector and technology experts at external organizations. We spoke with experts in artificial intelligence, advanced manufacturing, including additive manufacturing (AKA 3D printing), communications systems, water technology, battery technology, transportation and mobility, mini grids, electric vehicles, water resource management, water utility systems, and more. In all, we interviewed nearly 50 experts (a complete list is available at the end of this paper), some of whom were also at the workshop.

For both technology and sector experts, we typically included various open-ended questions as well as some narrower questions using techniques of formal expert elicitation. Our questions for technology experts revolved around the current state of the technologies and research pathways and goals. We asked about the likelihood of technological progress and barriers to the technical goals. To the extent we felt that these experts could discuss the technologies in a developing country context, we asked if there were reasons to believe that there might be

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[5] Clustered Regularly Interspaced Short Palindromic Repeats, a genome editing technology.

barriers in that context that were different from a developed country context. Our questions for sector experts focused on the current state of the energy, transport or water sectors in developing countries in which they had knowledge, barriers to better services provision, and their views on the potential for diffusion and deployment of disruptive technologies. In many cases, we asked interviewees to give qualitative probabilities on certain outcomes, including whether the outcome was:

- More or less likely than not
- Likely
- Very likely
- Extremely likely
- Near certain

In many cases, we asked interviewees to rethink their answers after a challenge, such as “how might a different outcome be reached?” or “what are the barriers to xyz outcome?” Lastly, for nearly every interviewee, we asked them to envision a developing country of their choice, in the year 2040, and describe it to us, particularly with respect to the built environment.

Our technology expert interviewees were generally extremely confident that by 2040, all the technologies we discussed would have developed substantially, that the current research problems would have been solved, and that the technologies would be widely commercially available. Our sector experts too, were generally confident that the disruptive technologies under discussion would be widely available, and also generally confident that there would be some deployment. The main area of uncertainty was the *degree* of deployment, and whether institutions in developing countries would adapt quickly, and whether customers would adopt widely.

The main area of uncertainty was the degree of deployment, and whether institutions in developing countries would adapt quickly, and whether customers would adopt widely.

Scenario Straw Person Construction

In the second phase of scenario building, we took what we learned from the interviews, and using five principles for scenario construction (detailed below), crafted three scenarios. Given that our experts were generally optimistic about the availability of technology, we chose to build the scenarios around the key uncertainty of *deployment.* The primary factors distinguishing the scenarios was whether the technologies were deployed extensively and equitably. The scenarios shine a light on the enabling function of government - did it fulfill its responsibility to ensure that barriers to technology adoption are limited; and the distributive function of government - did it fulfill its responsibility to all its citizens, or just some.

The scenarios shine a light on the enabling function of government … and the distributive function of government.

So that the “efficient cause” is not the sole determinant of a future state, the scenarios also focus on the role that incumbent institutions play, such as transit authorities, power utilities, water utilities, etc.

We presented the scenarios to the workshop participants both in advance, in written form, and in presentation at thee workshop itself, as a strawman. That is, participants were invited to rethink the premise, rewrite a scenario or eliminate one altogether. There was in fact one suggestion to use only the “leapfrog,” but the broad consensus was to refine them, rather than replace any wholesale.

Principles for Scenario Construction

In addition to employing the four classes of causes for scenarios espoused by Derbyshire and Wright (efficient, material, formal and final causes), our strawman and final scenarios are built using five principles, driven by previous experience in scenario construction and use. These are:

1. Scenarios should be plausible. It is fun, and often tempting, to craft scenario worlds that are fantastical. Drawn from flights of fancy and science fiction, one can readily conjure worlds that are far different from our current one. However, scenarios have to be plausible and reality-based for them to have impact. Plausibility does not mean highly probable, nor does it mean an extension of business-as-usual (BAU) conditions. Rather, the condition of plausibility forces us to draw out story lines, to rely on knowledge and reasoned conjecture rather than purely on imagination, and critically, to not break the bounds of science. Critically, plausibility enables decision makers to place themselves in those future worlds and believe in their possibility.
2. Scenarios should stretch thinking far. Scenarios are only useful if they present material difference from the current state and suggest significantly different strategies. If all scenarios in one exercise only suggest slight changes from BAU, then the exercise is not useful and motivates neither change nor introspection. This rule and the previous one, taken together form a tension. Scenarios should stretch thinking to the bounds of plausibility.
3. Scenarios should be internally consistent. Each scenario within a set should describe a future whose constituent parts jibe with each other. This condition does not mean envisioning a homogenous world, but it implies a set of precursors and resulting phenomena or states that all flow from the same basic set of conditions. For example, we cannot envision a future in which there is lower demand for coal and in which coal prices are high, unless there is a further assumption about coal supply constraints. Or for example, we cannot envision a world in which electric vehicles are the dominant form of transportation without making assumptions that the battery supply chain will expand and develop. The scenarios must have an evident logic underlying them.
4. Following Einstein's rule on theorems, scenarios should be “as simple as possible, but no simpler.” That is to say that scenarios should not be unduly dense. They should be complete and “tangible,” but there is no need for precision in all details. At their core, scenarios represent uncertainty. One should not feel the need to paint extravagantly detailed descriptions of what the world might look like. Details that distinguish the

scenario from the present, or from other scenarios, are important. So too, are details that complete a picture of the whole. But details that serve mainly to create a denser description are of lesser value, and sometimes can over complicate the narrative, inviting users to nitpick.

5. Scenarios should be useful, usable and used. If scenarios are not integrated into planning exercises, then their construction is purely academic. Understanding the challenge of creating scenarios for each of the World Bank's client countries, we have tried to frame the scenarios in relatively broad terms. For the scenarios to be used, they need to be made slightly more usable - namely by refining some of the geographic details. What may be plausible for one country may be impossible for another, and what may be seem like an inconsistency from one country's perspective may describe another country's reality. We intend these scenarios to have a life beyond this report, but in a tailored form.

Our principles are similar to those outlined by two former Shell executives[6] in an article prepared for Harvard Business Review.[7] These include:

- Make It Plausible, Not Probable. "Plausible stories encourage judgment, not just attention to data and other information."
- Strike a Balance Between Relevant and Challenging. "Relevant can be too familiar, but challenging can go unheard."
- Tell Stories That Are Memorable Yet Disposable. A scenario's story and its name should be "sufficiently vivid and memorable ... A few words can evoke a world."
- Add Numbers to Narrative. "The persuasive power of scenarios in the world of business rests on an effective combination of narrative and numbers." Note that in this regard, our philosophy diverges somewhat from Shell's, for two reasons. Our scenarios complement the model-based analytics, rather than serve as a means for creating inputs to the model. Second, our uncertainties are aimed at disruptions that are definitionally hard or impossible to model well.
- Scenarios Open Doors. Shell utilized their scenarios as a way to engage with customers and stakeholders. The World Bank can utilize these scenarios in much the same way, with client country governments, planning authorities, private sector investors, NGOs, and so forth.

Scenario workshop

The workshop to flesh out the scenarios was held on April 24, in Washington, DC. There were more than 50 people in attendance, including several of our expert interviewees. The group included experts from the World Bank and IFC, the UN, OECD, universities, research laboratories, consultancies and corporations.

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[6] The Shell Corporation is often credited with being a pioneer in the use of scenario planning.

[7] Wilkonson, A. and Roland Kupers, "Living in the Futures," Harvard Business Review, May 2013. https://hbr.org/2013/05/living-in-the-futures

The workshop consisted of four main sessions, two with all gathered together, and two with breakout groups. The first session of the day, with all participants, included a review of the scenarios and an open discussion about their plausibility, consistency, and whether any of the scenarios should be dropped. During the first breakout, the participants were divided into three groups - one for each scenario - with a mix of expertise in each group. The morning groups were given the assignment of fleshing out the scenarios. Questions focused on the level of technology penetration (e.g., the level of electric vehicles versus internal combustion engines), the roles of market participants (e.g., whether utilities have different roles), the effect on service providers (e.g., are utilities in a better financial position), and the effect on service provision (e.g., do more people have electricity access than they otherwise would). The afternoon breakout groups split the participants into three new mixes, but again with each group focusing on one scenario. The afternoon question asked participants to focus on the transition to 2040, rather than the end state. Questions in this session focused on what actions were taken (e.g., what did grid operators do?), what policies or incentives were put in place and what barriers were erected or removed, whether service providers restructured or recast their roles, and whether new market actors emerged. Finally, the workshop's closing session of the day, with all participants, asked for Black Swan-like ideas, i.e., low probability and high-impact events. Participants were asked to explain how the events might occur and what effects they might have on a scenario, regardless of whether the hypothesized phenomena were related to energy, transport or water.

During the full process, from interviews through workshop, we also followed the scenario planning "Dos and Don'ts" of McKinsey Consulting.[8] For instance, to counter the problem of "availability bias," we interviewed experts within, and external to, the World Bank, across multiple disciplines and geographies. To address "probability neglect," or the phenomenon of focusing too much and too early on numerical precision, our interviews combined open ended questions with probabilistic ones, and our probabilities were described only qualitatively, e.g., "likely," "very likely," etc. We avoided "stability bias" - assuming the future will look like the past - both by including great change in one of our scenarios, and by focusing on the uncertainty identified by our experts, specifically deployment, not technology breakthrough. We dealt with the pitfall of overconfidence by formal expert elicitation techniques in our interviews - asking experts to reconsider their answers - and by shuffling our experts in different groupings and in different scenarios during our workshop. These shuffled groups of experts were also designed to encourage free and open debate.

Sector Discussion

Below are some of the ways in which the three sectors might unfold under the different scenarios. None of these is meant to be comprehensive. Readers and users should bear in mind that the scenarios are "cartoons," and the real world will be more complicated, likely blending elements of our different futures.

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[8] Erdmann, . Bernardo Sichel, and Luk Yeung. "Overcoming Obstacles to Effective Scenario Planning," McKinsey & Company, June 2015 https://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/overcoming-obstacles-to-effective-scenario-planning

Power Sector

Under the Leapfrog scenario, by 2040, the power grid has undergone four, simultaneous waves of transformation. These include: (1) incorporation of an “Internet of Things” (IOT) approach to grid management and operation; (2) acceleration of grid-scale renewable energy and battery storage; (3) construction and incorporation of EV charging stations; and (4) rapid diffusion of microgrids and minigrids. Continued CapEx cost declines on renewables and distributed energy, including batteries, coupled with advances in real-time two-way communication, have enabled a greener, more flexible and more distributed grid. Microgrids are a significant part of this ecosystem, while solar home systems are used in some remote communities as well. Public EV charging is coordinated with time-of-use rates, though most charging is done by fleet companies (public and private) in islanded mini-grids. The Leapfrog grid will not be solely distributed nor simply a more efficient version of centralized system, but will utilize elements from both, including hybrid systems where microgrids can connect to the central grid when mutually beneficial.

Solar with storage will play a very strong role in Leapfrog worlds, both reducing the operating costs of centralized grids, and enabling affordable and functioning distributed energy. Energy efficiency - particularly in buildings - is propelled by the availability and use of sensors, data systems, and advanced metering infrastructure (AMI) and other “smart grid”-type technologies. In addition, power distribution companies are rewarded for efficiency measures and so are incentivized to help their customers use less power.

Countries which already have significant transmission and distribution infrastructure will tend to build more centralized renewable power; other countries may build more distributed power. For power systems to integrate decentralized power with centralized power on a large scale, and in a way that is financially sustainable, new regulatory structures and business models must emerge.

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Under the Lopsided scenario, in 2040, some of the transformations visible under “Leapfrog” are present, but in select circumstances. Sensors are added to new equipment when built by private entities, but rarely to equipment owned by the state-owned or parastatal utilities. Believing that the benefits conferred by the additional sensors are only fully realized with wide deployment and over several years, the utilities generally did not commit to full deployment of grid modernization. While cheaper CapEx on wind, solar, and batteries have enabled the power grid to become greener, the technologies were largely added without upgrades to communications infrastructure or grid modernization software. O&M savings from reduced fuel costs have been used to shore up utility balance sheets, but not invested back into equipment or system upgrades. EV charging is mostly for private transportation companies operating private fleets. Microgrids developed by international IPPs have expanded, but are more common as a tool for providing wealthier enclaves reliable power than for bringing electricity to underserved communities. Utilities are not rewarded for energy efficiency measures, but ESCOs enter into contracts with large building owners, who have the capital to pay the initial equipment costs and building envelope upgrades. The effects of energy poverty are exacerbated because absent the ability to pay for efficiency measures, lower income consumers pay an even large portion of their income towards electricity.

Some participants posited that there could be alternate paths for a Lopsided power sector. In one path, off-grid solutions provide a lower level of service and reliability than the central utilities. The off-grid system might eventually connect to the main grid, and may also prosper on its own. In another path, mini grid and off-grid providers outcompete public utilities. Utilities, bereft of paying customers, fall into even worse financial shape and some poorer communities are left behind, as they can neither afford off-grid technologies nor can the utility afford to serve them.

Under the Lock-in scenario, in 2040, the power grid has gotten slightly greener, as more wind and utility scale renewable energy have been added to the generation mix, but these were added without upgrades to communications infrastructure or grid modernization software. As the mega-trend of urbanization continues, grids have been unable to keep pace with the strain on urban grids, and the intermittence renewables makes the grid more complicated to manage.
In this scenario, the traditional electric utilities remain in place, as regulation favors the incumbents. There is a general lack of proactivity in introducing innovations. However, despite their continuation as primary providers, the utilities would be worse off because of higher cost of operation; there would be less uptake of digitization and hence missed efficiencies. Energy efficiency is not incentivized and utilities, seeing it as a means to reduce their revenue, use political power to hamper private ESCOs. Moreover, under lock-in, utilities will not sufficiently account for climate risks, thereby producing new stranded assets, e.g., large hydro plants. Grid reliability will be strained because of growing demands coupled with older grid management practices and technology.

Transport Sector

Under the Leapfrog scenario, in 2040, the transportation revolutions that now appear in their infancy are fully mature across the world, including in developing countries. Technologies such as autonomous vehicles and fully electric vehicles are the norm. Rider models such as rideshare and Mobility as a Service (MaaS) are commonplace and car ownership is on the decline. Shared, Autonomous EVs (SAEVs) have become the norm for millennials, car ownership declines, and single passenger cars become a rare luxury. Status is conferred by the “class” of the ride share, with status-seekers choosing only the “1st class” options. Moreover, technologies once thought the realm of science fiction are now relatively common sightings, including drones delivering packages, and in some areas with sophisticated aviation authorities, autonomous flying cars ferrying passengers. However, Leapfrog does not necessarily mean abandonment of existing, useful technologies and modes, for example public transport like bus rapid transit (BRT) will still exist, and “regular” bus service might have fewer buses operating with AI-enabled dynamic routing. Cities will still have traffic, but congestion pricing, sidewalk parking pricing and limits on garages will encourage people to ride share or use transit.

The transport sector in the “Lopsided” scenario, in 2040, witnesses some penetration of AV/EVs, and some “drivered” EVs, but very few ride sharing services, and hence the technologies are largely the domain of the wealthy, in particular in separated new cities or neighborhoods specifically designed for AVs but not accessible to the poorest. MaaS services do not gain popularity because transit authorities and taxi operators see them as challenging their incumbency. With limited implementation of physical infrastructure, and with barely any change to transit operating philosophies, the technologies’ potential is hard to realize. In some cases, sprawl will be a determining factor for MaaS, such that MaaS might be available in the city and near-in peri-urban areas, but not farther out, but without solving last-mile problems, MaaS would not always be a useful alternative. The Lopsided world’s transport would see the greatest divergence in terms of modes available and technologies utilized.

In the Lock-in scenario, the transport sector looks more like 2018 than the other two scenarios. While autonomous technology is fully developed, and while EVs are available at prices equal to internal combustion engines (ICEs) in most of the world, the physical and communication infrastructure needed to support those technologies has not fully arrived in developing countries. Moreover, a combination of resistance by transit agencies and taxi/ livery/ jitney drivers has conspired to block ride sharing companies from competing, while at the same time, the allure of car-ownership has not diminished. Grids are not capable of handing the additional loads from electric vehicles; charging stations are sparse; and communication infrastructure is not built to enable smart charging, so grids are strained in areas where the charges are present. Moreover, since communication infrastructure is not built out, shared AVs have less full functionality. Roads are not built or rebuilt with AVs in mind. The AVs that exist are not regulated nor encouraged, and the haphazard traffic conditions in cities hamper AVs from proper functioning, while creating new problems for “drivered” cars. Subsidies to public transportation systems - bus and urban rail - grow and become a bigger burden on government budgets, but transport companies have not markedly improved their service or the efficiency of their offerings; they have not kept pace with increasing demands or sprawl. The modernization of transportation infrastructure has been deferred or done at a very incremental pace. Sprawl itself has become a more difficult problem because of a lack of planning and proper regulation and incentives.

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Water Sector

Under the “Leapfrog” scenario in 2040, water resource management agencies cooperate within boundaries, and to the extent politically possible, across boundaries. Water resource management agencies take advantage of the widespread availability of satellites and drones to collect, process and use data, including for flood control, irrigation management, etc. New, energy efficient techniques for desalination - both at a large, centralized scale and in smaller, decentralized systems have greatly increased availability and access.

Water utilities are better able to manage their own system by incorporating digital water strategies, such as in-pipe sensors for leaks and pressure changes, as well as new chemical sensors for contamination. Non-revenue water is reduced substantially, allowing utilities to re-invest money into capital upgrades and maintenance. Communities that in 2018 lack adequate, safe water are served by a mix of new connections to the main system and a new generation of distributed water purification and treatment systems. New neighborhoods in megacities and new water distribution systems in previously unserved areas are often built with separate plumbing for drinking water and separate disposal systems for gray and brown water. New connections to the mains are done with trenchers rather than the disruptive excavators.

Under the “Lopsided” scenario in 2040, water resource management agencies cooperate only in closely politically aligned areas, and where neighboring managers have long-established relationships and best-practice sharing traditions. In watersheds where floods and drought affect industrial operations or where there is some concentration of wealth, water management agencies take advantage of the availability of data.

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Some wealthier regions in water scarce regions have adopted new desalination technologies, and some wealthy communities have adopted new, small-scale desalination; but lack of incentive for targeted water utility spending, and lack of long-term planning generally conspire to limit investment in new desalination technology.

Private utilities incorporate digital water strategies and reduce their non-revenue water, allowing them to re-invest money into capital upgrades and maintenance. In publicly-owned and operated systems, budgets and politics conspire to underinvest in data. Wealthy communities are built with plumbing systems necessary for local water reclamation and purification. Some communities that in 2018 lack adequate access to water are served by new connections to the main system or remain underserved.

Under the “Lock-in” scenario, water management agencies and utilities are often stove-piped with little coordination of data or efforts. Water resource agencies use satellites and drones to collect data, but data processing is often burdened by legacy data systems, and data remains in the hands of governments. Irrigation systems are not modernized. Lack of awareness of new technologies and lack of incentive for water resource spending means that investment in desalination is done only in emergency years. The availability of clean water is not as improved in Lock-in as in other scenarios, and water resource conflicts increase as population growth outpaces supply advances.

Water utilities which manage small systems see no benefit in data collection needed for digital water, and water utilities in large systems cannot afford the investment, which they believe only pays off with network effects. Non-revenue water is reduced by traditional leak repair. Some communities that in 2018 lack adequate, safe water are served by new connections to the main system, but few distributed systems exist, because utilities maintain a need for economies of scale, and builders and planners lack incentive for new types of plumbing architecture. Trenchers are often too expensive to purchase. Lack of proper pricing for water services weakens utilities' financial positions and accelerates the "death spiral" for some utilities.

General Discussion Themes

Impacts of Scenarios on Market Actors

How would market actors evolve under these three scenarios? Workshop participants and interviewees discussed what market actors might be or look like under the three scenarios. Below are some highlights.

Under Lock-in

One of the defining traits of Lock-in is the lack of innovation in service provision. A significant driver of that result is that the large power and water utilities, and major public transport will not be well placed to innovate, and hence will remain largely the same. Being not well placed to innovate could be due to lack of institutional capacity, lack of political will, bureaucratic design that precludes innovation (organizational lock-in), regulatory capture, or any combination of those factors.

In many cases, utilities will still be reliant on subsidization, which will weigh on service delivery and performance. Currently in developing countries, many services are not properly priced, and utilities regularly run deficits. Utilities (especially parastatal utilities) are reliant on subsidies to cover minimal operating expenses. Without the means to innovate nor the incentive to do so, many utilities are likely to remain dependent on subsidies.

Climate impacts will be difficult for utilities to absorb. For example, exacerbated flooding and storms may damage infrastructure beyond ability to repair. In newly drought-prone areas, some dams (for power or agricultural use) may become stranded assets, as may thermal power plants reliant on large water withdrawals. Utilities that cannot innovate their way out of difficulties, much less innovate to avoid them, and utilities whose subsidy-dependent budgets have no room for emergency expenses, will be hardest hit by climate catastrophes.

Governments will be more entrenched, and there will be more social unrest. Societies that stifle innovation sometimes also stifle social progress. While it might be tenuous to assign direct causality of social unrest to technological lock-in, the traits of governments that either cannot "get out of their own way," or intentionally protect incumbents are similar to those whose citizenry feel underrepresented or disenfranchised. The traits of these governments will include a lack of professional capacity among civil servants and high levels of risk aversion. The risk-averse governments and regulators will produce new regulations, but they will largely support business as usual practices and small, incremental changes.

Under Leapfrog

Unlike the utilities in Lock-in, the Leapfrogging utilities will have innovation as core to their mission. Utilities will have offices dedicated to socially positive innovation and programs constantly experimenting, because they will be incentivized to improve service delivery. Given the current state of utilities and the inability of many customers to pay for services, subsidization will not likely be wholly eliminated, but utilities' more efficient operations and larger customer bases will make utilities less dependent on subsidies.

Utilities will be in a "coopetition" with smaller, independent service providers like micro grid operators, transportation network companies (TNCs), and distributed water companies. The independent companies will play important roles by pursuing new business models and pushing the boundaries of innovations, serving customers with needs that require more tailored offerings than public utilities may be able to offer, but also sharing data and coordinating on service provision.

The more complex service landscape will engender more complex regulatory structures – and the best governments will deal with those not by building up in Lock-in, but by "building out" small teams for the new structures. The flexibility engendered will foster innovative approaches and facilitate handling of black swan events. The traditional problems of stove piping and silo-ing still occur, and in fact may be made somewhat more commonplace by virtue of smaller organizational units, but the damage done by silo-ing is mitigated against by an innovative culture. More important, a Leapfrogging government has coordinated planning as a central operating principal, hence inter- and intra-unit communication is high, and overall goal alignment is a common theme.

Under Lopsided

In a Lopsided world, utilities and public agencies must compete with new entrants offering alternative, and sometime better, services, although ill-equipped to do so. Regulations may not have kept new entrants from the market, but neither has organizational culture evolved to prepare utilities for their new realities. As such, the public companies are in worse shape. Their resources are stretched more thinly, they lose paying customers to new entrants, and the quality of their services diminishes. The Lopsided utility is in the throes of the "death spiral"—the reinforcing feedback cycle where the allure of better alternatives draws customers away, making the quality of publicly provided service worse, or cost more, which in turn reinforces the appeal of the alternative.

However, while the utilities are in a death spiral, the new entrants do not necessarily thrive. The Lopsided world has the additional, pernicious effect of protecting the incumbents, and upholding or erecting institutional barriers. Thus, the new entrants do not benefit from economies of scale; they do not benefit from density of market population; and they do not benefit from policies or programs that support their innovations.

The new entrants maintain their own data but are unable to reap the rewards of network effects of data, because the served population is balkanized, and because data sharing and cooperation are not woven into the fabric of service delivery. Neither are best practices shared with public institutions, hence the possibility of "spillover effect" is muted at best. The absence of benchmarking means that while some companies and some public institutions do better than others, there is increased disparity in the level and quality of service provision. The diverging states and qualities of public and private services heightens inequality and worsens social tensions; governments react to the increasing pressures either by doubling down on their protection of incumbents, or by inefficient allocation of resources, further exacerbating market interventions.

Role of Government as Enabling and Distributive … What Actions or Inactions Lead to Lock-in or Leapfrog

One of the central differentiating features of the three scenarios is the extent to which governments performs their roles as enabling, i.e., are policies designed to help or hinder innovations that improve service levels, and distributive, i.e., are policies designed to ensure that multiple segments of society reap the rewards of innovation. A question raised as part of that theme is how countries can avoid Lock-in, or how they might get derailed into Lopsided. Some institutional "behavioral markers" of the scenarios were identified in these discussions and are noted below. It is important to recognize that multiple combinations of these behaviors can lead to Lock-in or Lopsided.

Multiple combinations of institutional behaviors can lead to Lock-in or Lopsided.

There was some consensus that Lopsided is the most "natural" state, and perhaps the one that all sectors and development paths tend towards. There was also discussion that in real life, full consistency is unlikely, and that "Lopsidedness" can occur at various scales – continent, country, city, neighborhood – and even some facets of a given sector may be lopsided, some lock-in.

- In the transport sector, a lack of regulation disincentivizing sprawl could lead to Lock-in.
- The lack of coordinated regional urban planning and transportation planning would lead to worse public transportation systems and more sprawl, which would be part pf a Lock-in and Leapfrog scenario
- Public transit agencies are not taking advantage of technologies in Lopsided, but private companies are, and are successful at delivering services to a small segment of the population
- Access to data would remain in private hands without public benefit and without government encouraging integrated use of the data could lead to Lock-in or Lopsided
- Increasingly greater subsidies will create more societal burden, which would encourage Lopsided-type actions by the wealthy
- Lack of process for citizen representation could lead to Lopsidedness
- Poor planning capacity in general, particularly a focus only on the short term, could lead to Lock-in in multiple sectors
- Lopsidedness could result from poor planning practices for energy, water and transportation systems, including:
    - Lack of benchmarking
    - Lack of data transparency and availability
    - Overly rigid decision-making process
    - Lack of coordination between market actors, including government, utilities, corporates
- Policy making too focused on the technologies themselves, rather than the outcomes they might deliver could lead to Lopsided

- Price discrimination based on ability to pay – e.g. products with a spectrum of functionalities (e.g. mobile phones – flip phones vs. smartphones) could lead to Lopsided
- Public institutions falling prey to corruption and "regulatory capture" can lead to Lopsidedness and Lock-In
- Lack of commitment to reform can lead to Lock-in or Lopsided
- In the power sector, the public utility grid under-delivering will lead to the increased adoption of decentralized technology by the wealthy in a Lopsided scenario
- Special interests clinging to subsidization could lead to lopsidedness, if it creates uneven or poor service quality
- Deliberate constraints placed on "transportation network company" (TNC. e.g., Uber) services, along with regulation that prohibits adoption of new technology could lead to Lock-in
- Protectionist trade policies imposed on imported goods, i.e., local content rules or tariffs, can have unintended effects, e.g. on the adoption of renewable energy technologies, leading to Lock-in
- A refusal to align with international standards (e.g., intellectual property, web hosting protocols) based on state protection of industries could lead to Lock-in
- Lack of visionary leadership and the transient nature of government officials, and/or inadequately compensated and incentivized public-sector officials, could hamper dramatic technology strategies and lead to Lock-In
- Lack of truly competitive bidding and procurement policies could box out innovations, leading to Lock-in
- Lack of flexibility in design of governmental oversight bodies or policies, could lead to Lock-In
- Lack of finance availability for new solutions or for decentralized/smaller solutions
- A failure to price in positive externalities, e.g. the availability of clean water supply could lead to a Lock-in "death spiral." Insufficient revenue will lead to poor service, stagnation and inefficiency, and more subsidies.
- Failure to communicate early and often about new technologies will make their adoption more difficult, and hamstring their ability to succeed, leading to Lock-in.

Centralization versus Decentralization

One of the commonalities in the disruptions in the three sectors is the tradeoff between centralization and decentralization. Centralized systems are often thought to have the inherent advantage of economies of scale. With the ability to socialize fixed costs over a large number of users or customers, and the capital flexibility ability to amortize costs over longer lifetimes, centralized systems can be more efficient. Moreover, centralized systems, because they serve many customers and many segments of society, they are theoretically better able to engage in longer-term and broader-based planning; they should be more able to address inequities; and they should be more able to execute socially-desirable strategies.

However, as it evidenced by many public utilities in virtually all developing countries, large organizations with centralized service delivery suffer from multiple problems leading to inefficiency. These include stove-piped planning, underfunding, rent-seeking interests, cumbersome bureaucracy, uneven political power leading to inequities or simply poor choices, and, very often the need to cross subsidize service delivery such that some customers are underserved and some are overcharged.

Decentralized service delivery models often have some advantages that large, centralized organizations are unable to reach. These include nimbleness in decision making and implementation, fewer hurdles in adopting new technologies or business models, the ability to more specifically target products to individuals or customer groups, minimal political patronage as a barrier towards service optimization and, crucially, are often privatized and hence do not bear the costs of operating with larger responsibility.

Centralized systems are often thought to have the inherent advantage of economies of scale … but suffer from multiple problems leading to inefficiency. Decentralized service providers have the advantage of nimbleness in decision making and implementation … but the transaction costs of multiple, individual projects can break some companies.

Nevertheless, decentralized offerings have their own hurdles. Often, smaller scale projects are not attractive to financiers, and the transaction costs of multiple, individual projects can break some companies. Aggregation of multiple projects is sometimes an option, but then the sequencing of the projects itself becomes a “chokepoint” for deal flow. Lack of name recognition may hamper adoption, and lack of political power may slow acceptance.

The trade-offs are common, and each sector in the scenarios includes the push-pull between centralization and decentralization. It is most obvious in power, where decentralized solutions such as solar home systems and mini grids or microgrids are increasingly appealing, and are disrupting traditional service delivery models in many areas. In water delivery, newer technologies are enabling the dynamic, with the improving economics of decentralized water purification and treatment making them increasingly possible. And lastly, in transportation, the tension between the “Uberization” of transport versus central systems is in full swing in many municipalities around the globe. Our workshop participants by and large felt that all systems could - and perhaps should - evolve to a state whereby the centralized and decentralized systems complement each other. Decentralized systems are more likely to be able to quickly deliver service to those without, simply because putting in transmission, or sewerage or even new bus lines, let alone new rail, is a time-consuming process. But if managed and planned properly, centralized and decentralized systems should not only co-exist, but serve to bolster each other, and improve overall service levels.

Flexibility

One of the themes that surfaced multiple times in our workshop discussions was flexibility. This theme arose in multiple contexts, including institutional flexibility, regulatory flexibility, and flexibility of the infrastructure itself.

Institutional flexibility

Institutional flexibility is the quality that allows governments to enable new innovations in an equitable way and that allows incumbent firms to adapt. Institutional flexibility can be borne of a focus on the goals of service delivery rather than proxy metrics of success. I.e., focusing on people with electricity or new customers per year or kwh/ customer, rather than miles of transmission or electrified villages. Or, e.g., focusing on number of people moved per day or VKT/ day, rather than roads built or number of bus routes. Focusing on delivery of service enables a mindset change because it aligns the institution’s goals with the customer goals, and hence any new business model that achieves those goals, even if it means a total re-rendering of institutional operations, would be welcome.

Institutional flexibility can also be facilitated by smaller operating units. Smaller units accomplish two things at once. First, they maximize nimbleness in decision making. Second, they minimize the creation of bureaucratic fiefdoms and opportunities for politically motivated decisions. Institutional flexibility allows for creation of new authorities to serve new needs and address new markets, thereby encouraging innovation, while at the same time facilitating the dismantling of outdated offices.

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Regulatory flexibility

Regulatory flexibility is the quality of laws, incentives, policies and regulations that enable multiple means of meeting a societal need. For example, laws that mandate a level of water quality as opposed to specifying a treatment chemical, or incentives that encourage improved access to reliable electricity, as opposed to paying for transmission or a particular prime-mover, or for example, regulations that allow competition in serving commuters, under a safety and privacy standard, rather than a blanket prohibition or a blanket permission of TNCs.

Infrastructure flexibility

In addition to discussion around institutional and regulatory flexibility, there was some discussion about the need for infrastructure flexibility. One symptom of Lock-in is having financed long-lived infrastructure which has become obsolete; infrastructure flexibility then can take on different meanings. On the one hand, it can mean favoring projects that are shorter lived, so as to avoid Lock-in and obsolescence. At first blush, this could mean disregarding what might otherwise be valuable projects. However, depending on the project and sector, and innovation of the project managers, it might incentivize new methods for building the same type of project. Could projects we normally think of as requiring a 30-year financial life be redesigned to pay back in 15 years? Alternatively, infrastructure flexibility might also encourage a more modular or “lego-like” approach to infrastructure building. This method may have a longer time to “ultimate” completion, but could also result in faster delivery of service to some customers, might invite greater private financing, as risks would be lowered, and would mitigate against

Lock-in. Lastly, some workshop participants described flexibility of the infrastructure itself. For example, instead of designing infrastructure to last 60 years, design it to last 20-30, so that more rapid turnover of the capital stock becomes a natural cycle. Or, for example, design infrastructure for expansion and/or repurpose and re-use. If a country's analysis shows that, for the next 10 years, a light rail is the optimal form of transportation, what are the design elements that could quickly repurpose the right of way for BRT or autonomous/ electric vehicles?

Silos vs. Integration in Planning and Service Delivery

A theme that emerged recurrently during the interviews and workshops was the paramount importance of coordinated planning. This discussion took many forms. Coordinated planning was used as one way to minimize the chance of Lock-in and Lopsided in transportation. Coordinated planning and integration of agencies was used to prevent "silo-ing" within organizations and across them, for example, transport agencies should not assume an increasingly dense urban core while water agencies assume no in-migration. Coordination was heralded as a way to ensure that power system goals and transport goals with respect to electric vehicles are in sync. And finally, Integration in planning was also discussed in funding mechanisms - across and within MDBs, to help ensure that goals are not at cross purposes.

Equity vs. Rapid Deployment

One discussion that surfaced on several occasions was the tension between encouraging rapid deployment of innovation versus ensuring that innovations are equitable. This issue is related to the core of how governments perform their enabling and distributive functions, except in this case the equity concerns are for those getting disrupted. For example, when TNCs enter a city (whether drivered or driverless), governments must weigh the benefits of rapidly adding more transportation options with the costs of putting taxi drivers' employment at risk. Similarly, one of the broader conversations currently taking place across many domains is the tension between open data standards and data protection. In the name of maximizing the power of "big data," the more that is shared, the better, but that may infringe on data privacy protections that customers may expect or may be guaranteed. As Joseph Schumpter noted, creative destruction is the essence of an innovation economy, and hence governments must always allow some degree of destruction for innovation to progress.

High Impact, Low Probability Events

We asked workshop participants to identify "Black swan"-type events. Using Taleb's definition, a black swan cannot be identified in advance, nevertheless we asked for a list of high impact, low probability events. We include them here not to suggest that they are likey, but mainly to stimulate the imagination of users of these scenarios. While specific black swans may be unknowable in advance, their general character may be guessed at and their general effects can be predicted. Fashioning institutions and policies that are "black swan" proof, as Taleb suggested, may be easier with exercises of this type. It is important to note that (a) black swans need not be exclusively negative and (b), can appear in domains far outside a planner's view. Our workshop participants offered the following:

- Cyber-terrorism that threatens infrastructure systems and derails the “Leapfrog” innovations which rely on networks
- World War III or mass, regional warfare begins. Long simmering conflicts boil into full scale war, involving superpowers and proxies
- Nuclear fusion puzzles are solved, creating virtually unlimited carbon free energy. Massive infrastructure shifts follow
- Significant sea level rise causes flooding of major coastal population areas, leading to mass migration, and potential destabilizations and conflicts. Water resources and coastal infrastructure is heavily impacted
- Advanced personalized learning, powered by AI, enables individuals to learn much faster, absorb new skills with ease, and facilitates upward mobility and job seeking geographic mobility
- Advanced fusion of human and machine brains (digital implants, “cyborgs”), connected humans to the internet, enables massive cognitive abilities, but can lead to various dystopic scenarios
- Propulsion that is neither based on a chemical reaction nor magnetic force will make hyperloop viable
- Widespread political unrest driven by population growth, reduced access to clean water and fewer jobs due to automation
- Disease or plague with the deadliness of Ebola but with roots in a megacity

Appendix

Scenario Details: Technologies

AI and Digital technologies

1. Level 5 (fully) autonomous and connected vehicles (CV/AVs) are mass produced and readily commercially available
2. Autonomous delivery drones and flying cars are readily commercially available. These are also connected and capable of coordinated action. (There was not agreement among workshop participants over whether flying cars were realistic as a widespread technology, given the complexity of aviation management, but there was acknowledgement that they would be available. Skeptics on this issue agreed that in limited, very well-regulated areas, there might be limited deployment.)
3. Autonomous drones capable of operation in unfamiliar scenes are readily commercially available for water resource survey, traffic management, grid monitoring (vegetation, tampering, etc.)
4. AI-enabled robots are readily commercially available for a variety of repetitive, or dangerous or difficult tasks, from mining to warehouse operations to multiple, industrial-factory tasks, etc.
5. Augmented reality applications for productive are readily commercially available for remote work

6. Natural language processing has advanced to real time, multi-lingual simultaneous translation… combined with AR, the technology can create virtual, global workplaces

Sensors and communication technologies

7. Most consumer electronics and electric devices, and virtually all industrial machinery and equipment is built with sensor for Industrial Internet of Things (IIOT) connectivity and application, from power plants, water sanitation plants, to traffic lights and vehicles, to HVAC systems
8. Communication protocols that leverage bandwidth at speeds faster than 2018/2020 5G standards are available; 5G is the general minimum standard for true, real time IOT connectivity. (Given the population density and tower density needed to make 5G economic, 5G is not expected to be quickly deployed in rural areas.)
9. Low-earth orbit (LEO) communication satellites are commercially available, enabling extremely low latency two-way communications, at virtually every spot on the globe
10. LEO data collection satellites are common, allowing image collection and analysis if virtually the entire planet

Manufacturing technologies

11. Additive manufacturing (3DP) is able to produce stable components at 2-3X current size and 10X its current speed
12. Mass production using 3DP allows dramatic light-weighting of vehicles and aircraft
13. 3DP is commonly employed to enable novel designs to improve energy efficiency of power plants and building materials
14. 3DP is readily commercially available for use in remote areas such as mines, and in hard-to-service areas
15. 3DP of parts of embedded chips and circuits are in most equipment and available for easy physical update
16. Advanced mfg techniques are commonly used in tandem, including 3DP, digital-enabled rapid prototyping, robotics systems trained by reinforcement learning or similar AI, virtual reality and augmented reality (VR/AR), flexible line machinery, and fluid “platform-based” supply chains

Transportation

17. Electric Vehicles (EVs) are as available - or more available than - internal combustion engine (ICE) from all the major car manufacturers, globally
18. EV batteries are mass produced and sufficiently inexpensive to make EV cost fully on par with ICE cost
19. EV battery technology has evolved to a degree where driving range is equivalent to that of an ICE
20. Fully autonomous vehicles are readily available (see #1)
21. Much like pre-installed software on computers, cars can be sold as “MaaS-ready” with the ability to immediately integrate into a regional transportation network
22. Hydrogen vehicles are slightly more commonplace than in 2018

Energy supply and technologies

23. Grid batteries - Lithium ion or otherwise - easily achieve 8-hour storage over a 25-year lifetime, at costs that are ~25% lower than 2018 tech costs, and 12 hour storage is available for costs comparable to today's costs.
24. Other energy storage options have grown in popularity as their costs have declined and new business models and use cases have emerged. These include pumped storage where available but not yet deployed, but also technologies like molten salts, flywheels, compressed air, and other, newer technology options.
25. The combination of AI and predictive analytics, new materials and new 3DP components have made newly central power plants (fossil and renewable) significantly more efficient than in 2018
26. The combination of more efficient solar, longer lasting and cheaper batteries, increasingly powerful AI-based optimization algorithms, and increasingly inexpensive and efficient reciprocating engines, has made "hybrid" micro-grid-in-a-box offerings a commoditized product
27. Natural gas from shale continues to be cheap and abundant, and LNG demand globally has increased roughly by 50% from 2018
28. Steeply decreased coal use in the US & Europe, and coal use in China that peaked by 2030, has made the real price of coal in Africa and south Asia roughly the same as 2018 levels

Water management technologies

29. Satellites, autonomous drones and remote sensing, combined with predictive analytics have dramatically increased the potential for water resources management. Droughts can be predicted with high accuracy; irrigation leaks can be predicted and prevented upwards of ½ the time; floods can be predicted upwards of 75% of the time
30. "Lighter" flood control techniques and tools, such as dry dams and movable dams, are widely practiced in upper-middle income, flood prone countries like China, Brazil and Thailand
31. "Digital water utility" strategies, such as incorporating sensors into pipes to monitor for leaks, pressure changes and certain markers of contamination are readily available, and utilized commonly by developed countries' utilities. AI-based predictive analytics have made drinking water and wastewater treatment plants function more efficiently, including reducing energy costs, lowering equipment fouling, etc.
32. New buildings and neighborhoods in water-scarce and wealthier parts of the world, such as California, Israel, Gulf states, Chile, Spain, and parts of China, are commonly built with a separate plumbing system for drinking water, as well as separate systems for "gray" and "brown" water. Large buildings and newly build blocks or neighborhoods have local water reclamation and purification systems
33. Advances in detection methods, UV purification, chemistry and filtration system technology have lowered the energy costs and economies of scale for effective small-scale water purification and treatment
34. Advances in sensor technologies have enabled centralized management of decentralized systems

35. Trencher systems are used when budgeted for, as they require fewer hours of operation and are less disruptive to city streets and neighborhoods

Scenario details: Indicative technology levels provided to workshop participants

Below are technology levels that were included in materials given to workshop participants. These levels were meant to add more “flesh” and realism to the scenarios, but are not meant to be precise projections or forecasts. We encourage users of the scenarios to use these as starting points, debate and discuss the quantitative descriptions as indicative, but refine them to country-specific circumstance as appropriate.

One element worth noting is that in several cases, the outcomes are better in “Lock-in” versus “Lopsided,” which seemed counterintuitive to some of the workshop participants. Our rationale was that while the Lopsided scenario may have more penetration of new technologies, they penetrate in ways that serve primarily the interest of the wealthy, and to the detriment of others. In many service provision realms, be it energy or water or transport, or virtually any governmental function, there is some cross-subsidization. In “Lopsided,” we envision wealthy communities potentially dissociating from general service provision, and thereby eliminating a source of revenue and cross-subsidy. For example, wealthy, gated communities may opt for a mini grid and “defect” from the central grid, depriving the utility of its best paying customers.

- *Tech penetration:* Sensors are present in major equipment throughout the electricity value chain, from generation to distribution, including as retrofit on existing equipment.
- *Tech penetration:* Machine-learning algorithms are commonly utilized for equipment and grid predictive analytics
- *Tech impact:* Optimized power equipment has, on average, a 10% reduction in failure rates, though transformers have a 50% improvement in failures. O&M costs are reduced, on average by 15%.
- *Tech impact:* Heat rates at average (fossil) power plants improve 5-10% over 2018 levels; capacity factors at wind parks improve 5-10% over systems without AI-enabled analytics; utilization at grid connected solar photovoltaic (PV) arrays, coupled with large, inexpensive batteries, is optimized to smooth peaks and provide reliable power; batteries are also deployed at wind farms, thereby providing a composite of highly dispatchable solar & wind.
- *Tech penetration:* Renewable energy (x Hydro) expands dramatically, as costs continue to drop, and countries work to minimize fuel supply uncertainty and towards towards Paris Accord commitments
- *Tech*: Battery technology improves to the point where 8-hour storage in a 25-year battery is the norm.
- *Tech and service model:* Innovative electricity storage forms, such as linking chemical production to the grid, are part of the electric power ecosystem.
- *Tech penetration and infrastructure*: Since 50-70% of cars on the road are battery-electric vehicles (BEVs) - including some Plug-in Hybrid Electric Vehicles (PHEVs), EV charging stations are present at various points throughout the grid. (See transport section for more details.)
- *Service model penetration, tech infrastructure*: Private, off-grid or dedicated micro-grid charging stations, are used by most transport companies, including public transit and ride sharing companies. These can be owned and operated by independent power producers (IPPs) or a charging company, but are not available to the public. These stations supply 50-75% of the electricity for transportation.
- *Service model penetration, tech infrastructure:* Public (utility-owned or privately owned) charging stations for road-side charging are relatively scarce, as private car ownership is low, and day-time charging is pricey, controlled by Time-of-Use (TOU) rates and special rates for fast (level 3) charging. These stations supply 25-30% of electricity for transportation, are mostly on highways, or in urban areas far from the privately-owned stations. In some areas, the additional demand requires additional capacity, which is supported by the higher TOU/ fast charging rates.
- *Service model penetration, tech infrastructure:* Semi-public charging stations in office or apartment building garages account for 5-10% of electricity for EVs (for the 10-20% of cars that are “drivered” EVs, their electricity usage being less optimized, but lower on a daily basis than SAEVs). These are again subject to TOU rates, and the bulk of charging takes place overnight.

- *Service model penetration, tech infrastructure:* No more than 5% of charging is in private home garages, and these are charged largely in-home battery packs, using TOU pricing.
- *Tech infrastructure penetration*: Distributed energy resources (DERs) are a common part of the grid. These include combined heat and power (CHP) systems plus batteries for load smoothing at industrial facilities and building complexes; demand response systems for peak management, and battery-based, building-level distributed energy resource management systems (DERMS) for optimizing grid-to-building energy flows at commercial and industrial buildings. 50-75% of the smaller commercial buildings also have rooftop solar panels working in conjunction with the DERMS.
- *Tech infrastructure penetration*: DER penetration levels vary: For newly built industrial facilities with thermal load, 50-65% have CHP; 10-15% of pre-2018 industrial facilities have retrofit CHP. 30-50% of newly built apartment buildings have CHP; 5-10% of pre-2018 apartment buildings have retrofit CHP. 30-50% of new apartment buildings, and 50-75% of new office buildings have series of small batteries, meant to play the role that many diesel generators currently play.
- *Impact and tech infrastructure:* Access to electricity has improved by ~95% relative to the 2018 base, measured as a portion of the population (in 2018 and in 2040) without electricity. 5-10% of rural villages currently without electricity are utilizing solar home systems, supplemented with small batteries to provide 2-4 hours of home lighting or 1-2 hours of other electricity services during low/no-sunlight hours. 30-40% of areas currently without electricity are supplied by a minigrid, including remote rural areas, peri-urban areas existing in 2018 and new peri-urban areas. 50-60% of areas currently without electricity are supplied by connecting to the main grid, including remote rural areas, and new and existing peri-urban areas.

Electric Power, Lock-in, indicative reference points and assumptions

- *Tech penetration:* Sensors are present in some generation equipment, but can only be rationalized on select, new, major purchases, and is not retrofit on older plants or smaller equipment. As a result, network effects are not realized.
- *Tech penetration:* Machine-learning algorithms are utilized for new equipment, which runs better, but older equipment remains stuck in a cycle of failure and repair.
- *Tech impact:* Optimized power equipment has, on average, a 10% reduction in failure rates, but this equipment is rare. Operation & maintenance (O&M) costs are reduced, on average by 5%.
- *Tech impact and penetration:* Heat rates at new (fossil) power plants have improved 10% over 2018 levels, but most plants are at static levels of performance; most wind farms are newer, and thus have higher performance than 2018 technology, but cannot take advantage of system-wide optimization, and so contribution to grid overall reliability is constrained. PV arrays are common because of cost declines, but without grid-wide analytics and with batteries optimized for other uses, PV's increasing presence causes power and energy swings on the grid.
- *Tech impact and penetration*: Renewable energy (x Hydro) as a percent of total grid electricity ranges from 5-10% in most regions, with occasional outliers in both directions,

depending on wind and solar resources. Renewable *capacity* should produce more energy, but grid codes have not been optimized for renewables, and grid modernization efforts, along with communication infrastructure, has not gotten off the ground, hence capacity is curtailed or stranded, and total RE energy is far below potential.

- *Service model and tech performance:* Battery production and supply chain is designed and optimized for EVs, and the market for grid-scale storage options is not as robust, thus business models for grid storage in developing countries does not keep pace. Moreover, the strain on the battery life from the common and rapid power discharge from the power swings in developing grids, makes the batteries' life expectancy far lower than promised or expected. Rather than 8-hour batteries with 25-year lifetimes, the norm is 3-4 hours with 10-year lifetimes.
- *Tech penetration*: EV batteries are cheap and readily available, but grids are not capable of handing the additional loads from commercial electric vehicles; charging stations are sparse; and communication infrastructure is not built to enable smart charging, so grids are strained in areas where the charging stations are present, hence only some fleet vehicles are SAEV or drivered EVs. The classic "chicken and egg" problem of infrastructure utilization dominates, and only 5-10% of cars are BEVs and only 10-15% are PHEVs.
- *Service model penetration:* Very few Mobility as a Service (MaaS) plans are able to find a viable business model, and of those only a few employ EVs or SAEVs. Those that do, utilize private, off-grid or dedicated micro-grid charging stations. These stations supply 5-10% of the electricity for transportation.
- *Service model penetration:* Public (utility-owned or privately owned) charging stations for road-side charging are relatively scarce, because utilities worry that without proper TOU pricing and communications infrastructure, the stations will cause regular outages. Consumers are wary of the reliability of these stations. These stations supply 10-20% of electricity for transportation, are mostly on highways, or in urban areas far from the privately-owned stations. In some areas, the additional demand does indeed suggest a need for additional capacity, but financing the additional capacity faces the same constraints as other plants; there are no TOU prices.
- *Service model penetration:* Semi-public charging stations in office or apartment building garages account for 50-75% of electricity for EVs and PHEVs. These do not have TOU rates; instead, in addition to per Kwh charge, there is a fixed annual fee for use of the chargers at office buildings, and a rental cost for the use of the chargers in apartment buildings. The additional revenues collected by building owners mostly get subsumed into building operation, rather than subsidizing the power cost, and normal "principal-agent" problems persist. The bulk of charging takes place overnight at apartment buildings, simply because of the greater reliability of power.
- *Service model penetration:* No more than 5% of charging is in private home garages
- *Impact and tech infrastructure:* Access to electricity has improved by ~70-75% relative to the 2018 base, measured as a portion of the population (in 2018 and in 2040) without electricity. 5-10% of rural villages currently without electricity are utilizing solar home systems, supplemented with small batteries to provide 2-4 hours of home lighting or 1-2 hours of other electricity services during low/no-sunlight hours. 5-10% of areas currently

without electricity are supplied by a minigrid, including remote rural areas, peri-urban areas existing in 2018 and new peri-urban areas. 50-65% of areas currently without electricity are supplied by connecting to the main grid, including remote rural areas, and new and existing peri-urban areas.

Electric Power, Lopsided, indicative reference points and assumptions

- *Tech penetration:* Sensors are present in some generation equipment, typically only on major projects developed and owned by private developers. As a result, network effects are not realized.
- *Tech penetration:* Machine-learning algorithms are utilized for new equipment owned by IPPs, but other equipment remains stuck in a cycle of failure and repair - or disrepair, as the case may be.
- *Tech impact:* Heat rates at new (fossil) power plants have improved 10% over 2017 levels, but most plants are at static levels of performance; most wind farms are newer, and thus have higher performance than 2017/8 technology, but cannot take advantage of system-wide optimization, and so contribution to grid overall reliability is constrained. PV arrays are common because of cost declines, but without grid-wide analytics and with batteries optimized for other uses, PV's increasing presence causes power and energy swings on the grid. In general, new equipment is better, but overall grid performance is, if anything, worse.
- *Tech penetration and impact:* Renewable energy (x Hydro) as a percent of total grid electricity ranges from 10%-15% in most regions, with occasional outliers in both directions, depending on wind and solar resources. Renewable capacity *should* produce more energy, but grid codes have not been optimized for renewables, and grid modernization efforts, along with communication infrastructure, has not gotten off the ground, hence capacity is curtailed or stranded, and total RE energy is far below potential.
- *Tech performance, price and penetration:* Battery technology improves to the point where 8-hour storage in a 25-year battery is the norm. But costs have not come down, and thus are only occasionally deployed, since reliable electricity is not sufficiently rewarded by appropriate tariffs.
- *Tech performance, price and penetration:* EV batteries are readily available, but costs have not come down quite as drastically as had been hoped, and the grid is not reliable enough for widespread diffusion of public charging. As a result, EVs are not as widely diffused as in "Leapfrog." Roughly 30% of the cars are BEVs or PHEVs (including a small number of SAEVs), but almost all of these are either fleet vehicles or owned by the wealthiest drivers. Most EV charging stations are private.
- *Tech infrastructure:* Grids are not capable of handling the additional loads from electric vehicles; charging stations are sparse; and communication infrastructure is not built to enable smart charging, so grids are strained in the few areas where the stations are present. 5-10% of vehicles are SAEVs; an additional 5-10% are EVs, but they are mostly

fleet vehicles shuttling between gated communities and office parks, and rely on private micro-grids. Privately-owned EVs are generally PHEVs, charged at night, largely in apartment buildings.

- *Tech infrastructure and penetration:* 50-75% of hospital complexes and nearly all new industrial parks operate on a CHP-based mingrid, but nearly all of these are wholly of grid, and offer little or no grid services. The utilities lose some of their steadier energy revenue streams, and much of their demand charge revenue. Battery and thermal storage allows the systems to oversize economically.
- *Tech infrastructure and penetration:* Minigrids have also become increasingly popular in most gated communities of homeowners, reaching penetration of 50-65%. Wealthier residents are willing to pay more for their electricity and are less tolerant of unreliable power. Like the commercial and industrial complexes, these are mostly off-grid, CHP-based systems. The utility and regulators did not agree on a tariff structure that would have enabled microgrid communities to participate in energy markets, let alone ancillary services markets. Battery and thermal storage allows the systems to oversize economically. Utilities have not lost much of their served population, but have lost many of their most reliably paying customers.
- *Tech infrastructure and penetration:* Without some of their best customers, utilities have had an even harder time expanding the grid, and without appropriate measure to incentivize minigrids for underserved populations, only a small number have been built.
- *Tech impact and penetration*: Access to electricity has improved by ~65-70% relative to the 2018 base, measured as a portion of the population (in 2018 and in 2040) without electricity. 15-20% of rural villages currently without electricity are utilizing solar home systems, supplemented with small batteries to provide 2-4 hours of home lighting or 1-2 hours of other electricity services during low/no-sunlight hours. Roughly 5% of areas currently without electricity are supplied by a minigrid, mostly in remote rural areas. 40-50% of areas currently without electricity are supplied by connecting to the main grid, including remote rural areas, and new and existing peri-urban areas.

Transport Sector, Leapfrog, Indicative reference points and assumptions

- *Service model:* MaaS sees the same successes that BRT saw, with cities recognizing that integrated services form a more efficient way of moving people. The focus is on service rather than on cars, roads or number of buses.
- *Tech:* With increased light-weighting enabled by advances in additive manufacturing, which is now used commonly in mass production, cars, buses and trucks need less battery power to travel a given distance.
- *Tech penetration:* 50% of cars on the road are Shared, Autonomous, Electric Vehicles (SAEVs); 10-20% are “drivered” EVs, and the remainder are older cars from before 2020. There are virtually no new drivered ICEs.
- *Service model penetration:* 60-80% of passenger car vehicle kilometer traveled (VKT) is in some form ride shared vehicle.
- *Service model penetration:* “Traditional” transit VKT is down by 5-10%, but 50% of bus routes are now dynamic, meaning that utilization is up, and “micro transit” services for last mile connections are provided by a mix of public transit and private rideshare vans
- *Tech infrastructure:* Like BRT lanes, SAEV lanes are created, including for “micro transit.” SAEV lanes are created for: 80-100% of primary thoroughfares in cities; 50-75% of secondary streets in cities; 60-80% of suburban-urban commuting corridors; and 25-50% of intercity roads and highway miles.
- *Tech infrastructure:* Within cities, all new road construction and all repaving is done with an eye towards optimize for AVs and ride shares, including signage, lane lines, road dividers, marked sidewalks, and lane widening where needed.
- *Tech infrastructure:* Parking structures are minimized and parking prices/ road prices discourage single commuters and car owners, both on sidewalks and in office park garages. There are free or cheap parking lots in strategically placed locations, but available only to Shared EVs. These lots serve a dual function as they are operated by the same companies that own the private EV charging grids.
- *Tech infrastructure:* There are 75% fewer free parking spaces in cities in 2040 than in 2018. These spaces are identified via “smart city” communications infrastructure, so cars do not circle.
- *Tech penetration:* Package-carrying drones and people-carrying flying cars begin to penetrate, with well-planned and regulated flylanes, further alleviating ground traffic and pollution. 50-75% of small packages destined for office buildings and 20-30% of small packages destined for apartment building are delivered by drone, with a package-sorting robot on the receiving end.
- *Service model:* For the public EV charging stations that do exist, electric utilities welcome the EVs as a new revenue stream, including some dedicated minigrids that protect the main grid against demand surges, special TOU rates for charging, and smart charging for the AVs to optimize charge time and place.
- *Tech infrastructure:* Communication infrastructures are built out to support vehicle-to-vehicle (V2V) and vehicle-to-grid (V2G) communication.

Transport Sector, Lock-In, indicative reference points and assumptions

- *Tech penetration:* The wealthiest 1-2% have personal AVs, no more than 5% of cars are SAEV, 5% are drivered EVs, 20-25% % are HEV and PHEVs, and the remainder are drivered ICEs.
- *Service model:* Transportation Network Companies (TNCs, i.e., Uber, Lyft, Via, Didi, etc.) offer some additional options for few, but the incumbent transit agencies and taxi drivers oppose their growth on grounds of labor protection, and erect new regulatory obstacles.
- *Service model:* MaaS efforts fail because incumbents have no interest in integrating or because laws and policies are not tailored to allow MaaS.
- *Service model penetration:* Ride sharing continues to be seen as an option for people who cannot afford their own cars. Only 5-10% of trips are in TNCs.
- *Tech penetration:* Drone delivery of packages becomes popular, thus alleviating some road traffic, but the urban airspace is poorly regulated and quickly resembles the ground traffic. 75-100% of small packages destined for office buildings and 30-50% of small packages destined for apartment building are delivered by drone, with a package-sorting robot on the receiving end. Some packages beyond the drone weight limits are delivered as well, causing an occasional drone to crash, wreaking havoc in the air and on the ground.
- *Tech penetration:* Passenger-carrying flying cars are prohibited given safety concerns.
- *Service model:* Transit agencies don't face the competition they perceive from MaaS, but continue to be strained by growing urban populations.
- *Service model penetration:* 5-10% of passenger car VKT is in some form ride shared vehicle.
- *Service model and tech infrastructure:* "Traditional" transit VKT is static, but absence of communication infrastructure for dynamic routing and increased traffic makes the traditional buses less and less effective.
- *Tech infrastructure*: Parking structures continue to be built, and subsidized parking continues to be the norm at office buildings and downtowns.
- *Tech infrastructure:* Most EV charging is done in private apartment buildings. The ride share companies are discouraged, and do not build their own charging infrastructure. The few public charging stations that do exist are not optimized by smart communications, and hence usage tends to strain the grid.

Transport Sector, Lopsided, Indicative reference points and assumptions

- *Tech and service model penetration:* 5-10% of vehicles are SAEVs; an additional 5-10% are EVs, but they are mostly fleet vehicles, 20-25% are HEVs and PHEVs, and the remainder are ICEs.
- *Tech infrastructure:* SAEV lanes are implemented in limited areas, but because drivers don't see immediate benefits, are underutilized and lead to increased congestion on remaining lanes. SAEV lanes are created for: 10-20% of primary thoroughfares in cities; 5-10% of secondary streets in cities; 10-20% of suburban-urban commuting corridors; and no more than 5% of intercity roads and highway miles.
- *Service model penetration:* 5-10% of passenger car VKT is in some form ride shared vehicle.
- *Service model and tech infrastructure:* "Traditional" transit VKT is up, but absence of communication infrastructure for dynamic routing and increased traffic makes the

traditional buses less and less effective.

- *Tech penetration:* 80-100% of buses are EVs, because as fleet operators, the transit agencies recognize the reduced O&M costs quickly pay back the increased CapEx. The buses are drivered, the agencies not willing to put its drivers out of work.
- *Impact:* Overall passenger VKT is up, as cities begin to mimic the sprawl patterns of US cities.
- *Tech impact*: Passenger VKT for the wealthiest is up by 20-30%, both because they choose farther cities, and because they are the one demographic group to use AVs.
- *Tech infrastructure*: Parking structures continue to be built, and subsidized parking continues to be the norm at office buildings and downtowns.
- *Service model and tech*: Most of EVs deployed are for use for fleet vehicles such as delivery companies, taxi/livery/jitney, etc., whose CFOs recognize the advantage of significantly lower operating costs.
- *Tech infrastructure*: The EVs are recharged at fleet-owned, central locations, with electricity provided by private power purchases or private microgrids. Very limited EV charging infrastructure is built out, as utilities do not see the need for more supply since there is little increasing demand.
- *Service model and tech penetration*: The availability of AVs, particularly AV pods for mobile offices, gyms, salons, become popular with the very wealthy, who, while occupied, care less about road congestion. These account for 20-30% of AVs.
- *Service model and tech penetration:* To the degree there are AV rideshares, they mainly serve as “1st class” shuttles between the gated communities and office parks, making the existing SAEV lanes a subsidy for the wealthy, as their commutes are eased. Over time, wealthier families move farther away from city centers, since commuting times matter less. These account for 10-20% of AVs.
- *Service model and tech penetration:* Personal AVs owned by the wealthy account for the remaining bulk of (the small number) of AVs on the road.
- *Service model:* Since ridesharing is generally discouraged by incumbent transportation companies, the rideshare companies that do exist serve mainly the highest paying passenger as an “exclusive” service.
- *Tech penetration*: The availability of passenger-carrying flying cars exacerbates the trend of increasingly bifurcated transportation systems, with stations only in the wealthiest gated communities and office parks. 5-10% of commutes from those communities are by flying car.
- *Tech penetration*: Hyperloops are built between office parks in remote megacities, enabling rapid intercity transport for the business class. Under 5% of intercity trips are taken this way, but 15- 25% of weekday business trips are hyperlooped.

Water Sector, Leapfrog, Indicative reference points and assumptions

- *Tech and service model impact:* Because of coordinated water resource management and usage of satellites, autonomous drones and remote sensing, combined with predictive analytics, droughts are predicted with a high level of accuracy; irrigation leaks are predicted and prevented upwards of ½ the time; floods are predicted and managed upwards of 75% of the time
- *Tech penetration:* “Lighter” flood control techniques and tools, such as dry dams and movable dams, are the standard form of flood control
- *Tech impact:* “Digital water utility” strategies reduce non-revenue water by 50-75%, drinking water and wastewater treatment plants reduce energy costs by 10-15%, and equipment fouling is reduced by 75-95%.
- *Tech penetration*: 10-20% of all new buildings and 20-35% of new neighborhoods are built with a separate plumbing system for drinking water, as well as separate systems for “gray” and “brown” water. 35%-50% of new very large buildings and newly built communities have local water reclamation and purification systems.
- *Tech impact:* Advances in detection methods, UV purification, chemistry and filtration system technology have lowered the costs of effective small-scale water purification and treatment by 30-50%.
- *Tech impact:* Access to safe and adequate water has improved by ~90% relative to the 2018 base.

Water Sector, Lock-in, Indicative reference points and assumptions

- *Tech impact:* Droughts are predicted with slightly more accuracy than today; irrigation leaks are predicted and prevented upwards of ¼ the time; floods are predicted and managed upwards of 25% of the time
- *Tech penetration:* Movable dams are the standard form of flood control, but land rights make dry dams rare
- *Tech penetration and impact:* “Digital water utility” strategies are rarely deployed, and non-revenue water is reduced by only 5-10%, drinking water and wastewater treatment plants reduce energy costs by no more than 5%, and equipment fouling is reduced by 20-30%.
- *Tech penetration:* Very few of new buildings or new neighborhoods are built with separate plumbing systems for drinking water, “gray” and “brown” water. No more than 5% of new very large buildings and newly built communities have local water reclamation and purification systems.
- *Tech impact:* Access to safe and adequate water has improved by ~70% relative to the 2018 base.

Water Sector, Lopsided, Indicative reference points and assumptions

- *Tech impact:* Droughts are predicted with 50% more accuracy than today; irrigation leaks are predicted and prevented upwards of 35% of the time; floods are predicted and managed upwards of roughly 35% of the time
- *Tech penetration:* Movable dams are the standard form of flood control in resource management areas that have adopted best practices, but land rights make dry dams rare
- *Tech impact and penetration*: “Digital water utility” strategies are deployed predominantly by privately owned and operated utilities, and in those systems, non-revenue water is reduced 50-75%, drinking water and wastewater treatment plants reduce energy costs by 10-15%, and equipment fouling is reduced by 75-95%. But in publicly-owned systems there is only incremental improvement.
- *Tech penetration:* 50-75% of new buildings or new neighborhoods in wealthy, gated communities are built with separate plumbing systems for drinking water, “gray” and “brown” water. Those communities take advantage of new technologies for reclaiming and purifying water, and rely on the main water grid only for backup and pressure maintenance. Outside the gated communities, no more than 5% of new very large buildings and newly built communities have local water reclamation and purification systems.
- *Tech impact:* Access to safe and adequate water has improved by ~60% relative to the 2018 base.

Acknowledgments

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Expert Interviewees

1. Randy Altschuler, XOmetry (advanced manufacturing)
2. Gabriela Azuela, World Bank (electricity, distributed energy resources)
3. Deepali Bahl, IFC (disruptive technologies)
4. Josh Bloom, GE Digital (machine learning, Industrial IOT)
5. Clare Boland Ross, Rockefeller Foundation (mini grids)
6. Ricky Buch, GE Power (mini grids)
7. Carlos Campos, Suez Water Technologies and Solutions (water technologies)
8. Rebecca Ciez, Princeton University (batteries)
9. Rick Cutright, GE Global Research Center (batteries)
10. Glenn Daigger, One Water Solutions (water technologies)
11. Jon Exel, World Bank (mini grids)
12. Maxine Ghavi, ABB (electricity, mini grids)
13. Mark Hammond, Bons.ai (machine learning, Industrial IOT)
14. Bobbi Harris, Utilities Technology Council (communication infrastructure, water techs)

15. Nagaraja Rao Harshadeep, World Bank (water resource management, disruptive techs)
16. Wayne Holden, RTI International (disruptive tech)
17. Sandor Hollo, GE Global Research Center (additive manufacturing)
18. John Ikeda, World Bank (water)
19. Larsh Johnson, Stem (machine learning, energy storage, Industrial IOT)
20. Scott Kuznicki, Transpo Group (transportation)
21. Nico Larco, University of Oregon (transportation)
22. Elad Liebman, University of Texas at Austin (machine learning)
23. Peter Lilienthal, HOMER (mini grids)
24. Nancy Lozano, World Bank (urban planning)
25. Ayah Mahgoub, World Bank (urban planning)
26. Agatha Mattos, Aegea (water technologies)
27. Shomik Raj Mehndiratta, World Bank (transport, planning)
28. Mlungisi Mkhwanazi, Africa Utilities Technology Council (communications & power tech)
29. Robert Munro, Figure-Eight (machine learning, international development)
30. Catalina Ochoa, World Bank (transport)
31. Andy Palanisamy, Ford Motors (transport, mobility)
32. Achalesh Pandey, GE Global Research Center (machine learning, Industrial IOT)
33. Tatiana Peralta Quiros, World Bank (transport, data)
34. Marco Aurelio Pereira da Silva, Aegea (water technologies)
35. Karthik Ramani, Purdue University (advanced & additive manufacturing)
36. Andrew Salzberg, Uber (mobility, data)
37. Jennifer Sara, World Bank (water)
38. Aleix Serrat-Capdevila, World Bank (water resource management)
39. Dan Steingart, Princeton University (batteries)
40. Jessica Stephens, Africa Mini-grid Developers Association (mini grids)
41. Russell Sturm, IFC (off grid electricity, solar home systems)
42. Stratos Tavoulareas, IFC (energy, electricity)
43. Noosha Tayebi, World Bank (water)
44. Erika Velazquez, ABB (electricity, mini grids)
45. Christopher Williams, Virginia Tech (additive manufacturing)
46. Walker Wright, Engie (electricity, distributed energy)
47. Winston Yu, World Bank (water resources management)

Workshop Participants

1. Ashish Aneja, Suez (water technologies)
2. Nate Blair, NREL (power systems)
3. Sam Booth, NREL (mini grids)
4. Ricky Buch, GE (mini grids)
5. Michelle Carvalho, IADB
6. Duncan Cass-Beggs, OECD (strategic foresight)
7. Juan Chelby, UNEP (sustainable development)
8. Rebecca Ciez, Princeton (batteries)

9. Rick Cutright, GE (batteries)
10. Glen Daigger, One Water Solutions (water technologies)
11. Gabriela Elizondo, World Bank (distributed energy resources)
12. Darryl Farber, Pennsylvania State University (foresight, modeling)
13. Marianne Fay, World Bank (economics, sustainable development)
14. Charles Fox, World Bank (economics, sustainable development)
15. Stephane Hallegatte, World Bank (economics, sustainable development)
16. Bobbi Harris, Utility Technologies Council (communications tech, water tech)
17. Iain Henderson, UNEP (sustainable finance)
18. Douglas Herrick, OECD (environmental policy)
19. John Ikeda, World Bank (water technologies)
20. Abhas Jha, World Bank (urban infrastructure)
21. Holly Krambeck, World Bank (economics, transport)
22. Scott Kuznicki, Transpo Group (transport)
23. Shomik Lall, World Bank
24. Nico Larco, University of Oregon (transport)
25. Michael Leifman, Tenley Consulting (scenario planning, energy)
26. Elad Liebman, University of Texas at Austin (machine learning)
27. Peter Lilienthal, HOMER (mini grids)
28. Nancy Lozano Gracia, World Bank (urban planning)
29. Ayah Mahgoub, World Bank (urban planning)
30. Virginie Marchal, OECD (environmental policy)
31. Harsh Nagaraja Rao Harshadeep, World Bank (water resources, disruptive tech)
32. Joe Nanda, IFC (infrastructure investments)
33. Matthew Nejati, ABB (power systems, mini grids)
34. Claire Nicolas, World Bank (economics, sustainable development)
35. Catalina Ochoa, World Bank (transport, data)
36. Andy Palanisamy, Ford Motors (transport, mobility)
37. Tatiana Peralta, World Bank (transport)
38. Marco Pereira da Silva, Aegea (water technologies)
39. Felicity Perry, UNEP
40. David Pickeral, Independent consultant (transport, mobility)
41. Karthik Ramani, Purdue University (additive manufacturing)
42. Celine Ramstein, World Bank (climate change)
43. Julie Rozenberg, World Bank (economics, sustainable development)
44. Dana Rysankova, World Bank (off grid, mini grid)
45. Julia Staudt, OECD (strategic foresight)
46. Ben Stewart, World Bank (geographer, sustainable development)
47. Ancor Suarez, IDB (transport, infrastructure)
48. Mersedeh Tariverdi, World Bank (transport, data)
49. Winston Yu, World Bank (water resource management)
50. Simon Zadek, independent consultant (sustainability)