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Community Paper

Transforming Infrastructure:
Frameworks for Bringing the Fourth Industrial Revolution to Infrastructure

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91-93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland
Tel.: +41 (0)22 869 1212
Fax: +41 (0)22 786 2744
Email: contact@weforum.org
www.weforum.org

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Executive summary

The technological advances of the Fourth Industrial Revolution have fundamentally altered society in ways both seen and unseen. This digital transformation has changed how people live and work, and everything in-between. One area of daily life, however, seems to be largely missing out on this revolution: infrastructure. It remains one of the least digitally transformed sectors of the economy. While individual examples of highly advanced infrastructure systems exist, the sector at large lags behind others in innovation, a fact made all the more apparent by infrastructure's ubiquity. When the World Economic Forum Global Future Council on Infrastructure gathered for its annual meeting in Dubai in November 2018, it sought to understand why.

As it began to think through solutions, the Council found a situation full of opportunity. Infrastructure is far from being a staid industry devoid of innovation – indeed, new technologies and ideas are flourishing. Integrating these innovations, which could change the way infrastructure is designed, developed and delivered, requires aligning stakeholders, implementing effective strategies and creating fertile enabling environments. This will allow existing innovation into the space and provide opportunities for new ideas.

The Council thus decided to create a guidebook, contained here, that explores major questions about how to bring the Fourth Industrial Revolution to infrastructure. The guidebook surveys some of the fundamental issues and provides robust frameworks that can help public- and private-sector decision-makers decide how to create the right enabling environments for their situations. It also contains case studies to help illustrate how public- and private-sector entities can work together to integrate exciting existing technologies into infrastructure and spur the creation of new innovations. Overall, the content illustrates three main imperatives:

1. **The importance of focusing on community outcomes, not physical assets:** It is tempting to define future infrastructure requirements in terms of specific assets: "this city needs light rail" or "we must expand our motorway" are some examples. Defining projects in terms of social outcomes, such as delivering affordable public mobility between specific points, leaves an opening for technological innovation to deliver those outcomes.
2. **The need to adopt a "flexible architecture" approach to infrastructure planning:** The technological transformation of infrastructure can be accelerated by recognizing that, while technology-driven disruption cannot be predicted, it can be allowed for and positively leveraged. Planning traditional infrastructure with a more flexible architecture is a way of achieving this; it allows for change and innovation at the edges while protecting and extending the life of core elements. It also permits the use of policy frameworks to allow new innovations to move from idea to commercial success.
3. **The necessity of recognizing and respecting infrastructure's "data layer":** As the world moves into an era of ubiquitous sensors and an ever-connected internet of things, infrastructure assets will become data assets. These technologies offer great potential to increase the social and economic value of infrastructure assets through predictive maintenance, real-time optimization and peak demand management. Much like traditional infrastructure assets such as airports, utilities and community facilities, these data pools will become highly valuable and highly sensitive assets, requiring owners with the right character operating under the right oversight.

For planners and policy-makers, there is potential for enhancing efficiency, value and user experience for the publics they serve. Infrastructure owners have the prospect of improving long-term viability, project development and asset management. Technology providers could develop new innovations, forging new partnerships and technologically transforming a new sector. Using this guidebook, decision-makers can begin the conversation on how technological innovation can be nurtured in infrastructure to continue to meet the challenges of the Fourth Industrial Revolution.

Introduction

The technological changes of the Fourth Industrial Revolution are transforming societies and remaking economies. Innovations, such as artificial intelligence (AI), 3D printing and augmented reality, are reshaping fields like healthcare, manufacturing and entertainment. The opportunities provided can improve life in both developed and developing economies and create a more sustainable and inclusively prosperous world.

But infrastructure, a crucial area of the economy, is still struggling to embrace the promise of this new technological era. Although infrastructure is critical for society, the integration of new technologies into infrastructure planning, development and delivery lags behind other sectors. The brave new world of innovation, changing the way the rest of society works, seems to be passing the sector by. Why is this? More importantly, how can the sector change this and improve the development and adoption of new technologies into existing and future infrastructure networks?

The frameworks and strategies contained in this guidebook attempt to provide solutions to some of these questions. By leveraging the expertise and experience of the public and private sectors, this guidebook can better prepare infrastructure planners, developers and operators for creating long-lasting, fruitful and profitable partnerships and strategies. Both of these can benefit the partners involved and society as a whole by providing better, more affordable and more sustainable infrastructure. The frameworks, presented over four questions, provide opportunities for the public and private sectors to act and can be applied across the infrastructure life cycle. Case studies then put some of these solutions into action. The questions and cases resulted from multisectoral, multistakeholder consultation and variously address driving, protecting and using innovation.

At the crossroads of technology and infrastructure: four questions

1: How can technological disruption in the white space of infrastructure be encouraged?

While new technology is fast-paced, highly active and continually evolving, infrastructure is a stable provider of supporting services, more focused on continuity, dependability and stability. Innovations need to be given the opportunity to prove their value, and infrastructure systems must be designed with an eye towards potential future developments. Finding ingress points for new technologies during the initial stages of planning, and maintaining the flexibility to adapt to unforeseen technological changes, are crucial tactics in the battle to transform infrastructure.

2: How does the public sector drive innovation in technology by creating frameworks that encourage exchange while protecting intellectual property?

Better methods of collaboration are needed to speed the development and adoption of innovative new technologies in infrastructure across all phases of development. In particular, access to data needs to be as open as possible to allow for testing new ideas and encouraging innovation. At the same time, protections for new ideas will be vital to sustaining the business models that emerge from new ideas.

3: How can data and analytics help to prioritize and optimize infrastructure decision-making?

When looking at the planning, maintenance and operative phases of infrastructure, the potential benefits of leveraging data analytics are significant. Proper data analytics can help increase value for money, improve system design quality and even help protect the environment, health and safety. Leveraging these benefits will be crucial in improving the decision-making for the strategic development of infrastructure systems.

4: How can viable commercial models be created via catalytic policy and regulatory frameworks?

The policy and regulatory environment must be modernized to create a flourishing ecosystem of infrastructure innovations. Regulatory goals that balance various societal needs and create a consensus appropriate for citizens, private companies and government entities must be better understood. Additionally, creating the right partnerships between the public and private sectors can produce effective policies and fully informed strategies. Only by taking an open, multistakeholder approach can new commercial models thrive while the public is protected.

Summary – and the future

These questions help identify how to unlock the benefits of combining the transformative power of emerging technologies with the wide societal reach of infrastructure. They are also meant to provide exemplary strategies for stakeholder groups to help prepare better, longer-lasting, more fruitful and more profitable partnerships that benefit society as a whole by providing the infrastructure the world needs.

The four questions are a starting point for more profound thought and provide an anchor for more in-depth conversations. This paper provides case studies on how to answer the questions and what good practices might entail to provide practical examples of the frameworks and strategies discussed. Infrastructure is at a crossroads: should it continue down the well-trodden path or move towards an exciting new horizon? This guidebook is meant to be the start of a push into the future, together.

The guidebook: four questions on technology and infrastructure

1. How can technological disruption in the white space of infrastructure be encouraged?

The transformative effects of technological change do not take hold in a vacuum – they need nurturing. Infrastructure systems are, by nature, built for the long term and rely on proven materials and methods. The development of assets as economically, socially and politically important as infrastructure prioritizes cost-effectiveness, safety, durability and reliability. Not surprisingly, the entities tasked with designing and delivering infrastructure can be hesitant to explore new ideas and technologies.

This does not mean that these ideas and technologies do not exist. Entrepreneurs are coming up with a wide array of innovative solutions to fix the shortcomings of infrastructure systems across the entire asset life cycle to fill infrastructure's "white space" – the areas of opportunity where unmet and unarticulated needs are uncovered to create innovation. How can this white space be filled with exciting new innovations? And how can systems be built that are designed for the long term yet can adapt to new technological realities? This section explores two areas: the redesigning of procurement methods and the future-proofing of infrastructure systems.

Procuring the future: Using procurement to introduce innovation

Innovating at the core

Infrastructure developers face a dilemma in bridging the gap between the technological advances that can modernize infrastructure at all stages and the status quo of current infrastructure development practices. Infrastructure delivery is already benefiting tangentially from technological advances. AI tools are reorganizing how traffic flows are measured and managed, and the demand for smart and smarter cities rightly dominates discussions about infrastructure technology priorities. In construction, technological advances can shorten completion times and lower costs, providing much-needed efficiency in project delivery.

These innovations, however, are primarily in the domains of urban planners and the engineering and construction industries. Core infrastructure will remain structurally resistant to the potentially dramatic benefits of technology unless the entire infrastructure procurement cycle is radically altered. Procurement is the core of the infrastructure community; it starts when planners finish and ends just before construction professionals take over. Procurement primarily revolves around finance – no blueprint can become a building without capital. This narrow yet critical space remains resistant to the technological revolution; indeed, it remains in the dark ages.

How can infrastructure finance become the door through which disruptively creative forces enter? First, consider how infrastructure is financed. Generally the financing comes directly out of the public coffers, whether with current or borrowed capital or with private capital in some version of what is usually called a public-private partnership (PPP). This financial underpinning, which is largely one of debt over equity, is quite the opposite of the financial underpinnings of disruptive technological innovation, which prizes equity over debt. A publicly financed project is likely to be little more than a construction project unless the government has invested in an incubator of technological solutions, which is an unlikely scenario. A PPP should be the model that allows technology entrepreneurs to unleash innovative forces. Sadly, this is not the case.

The reason for this is simple: the needs of capital markets combined with a tendency of government procurement processes to tread cautiously in delivering infrastructure assets. Capital markets require a tightly designed financial package, and most governments are averse to making commitments to private partners without a competitive process that can be evaluated with a defined metric. This means that even a PPP is only a small improvement from a purely public procurement in its openness to a disruptive delivery solution, with every detail baked in before the procurement is put out for bidding. The process has no place for innovators to take a look, let alone compete to win. Innovation is sidelined in the infrastructure space so that the potential future technological pioneers of infrastructure cannot prove their value.

To allow this system to carry on is to continue to deny the public the fundamental benefits that the Fourth Industrial Revolution can bring to daily life. Technological innovation can disrupt all aspects of procurement, including financial models. Yet infrastructure finance is stuck on the tax-or-toll axis, and infrastructure contracting models rely on bureaucratic planning departments. The PPP procurement process, as well as the larger process of providing for basic services, needs to be comprehensively reconfigured, even disrupted, to provide a door for innovators to enter and a way for them to profit. This is the primary motivator for the change that is remaking many other industries.

Open models for better results

How can this be done? Since the needs of capital cannot be altered any more than the laws of physics, the change must be in the resistance of government to private enterprise and profit. Governments must devise procurements in a way that welcomes innovators and protects and rewards their efforts and intellectual property (IP).

This likely means more open-ended procurements. In practice, it means moving beyond PPPs and designing models more akin to the way urban development agencies choose private real estate development partners for large projects – by designating development teams that will work to create a plan following a shorter selection round, with a preference for teams with strong technological partners. This can allow developers of new innovations to work with procurement officials to design financial models within the procurement programme that allow them to benefit while providing their innovative products and services.

Creating new procurement models will require wholesale changes in the laws, regulations and cultures of the procurement agencies in most countries. Nevertheless, unless agencies undertake this kind of full upending of infrastructure procurement, infrastructure will continue to lag behind the rest of the economy in reaping the benefits of the Fourth Industrial Revolution.

Every procurement does not need to be revised, however, for technology's innovative power to reform infrastructure development. Rather, this is more likely to occur in selected pilot programmes that demonstrate new pathways forward. As many countries face economic governance and capacity issues, these projects are likely to be first piloted in countries with strong economic governance and later replicated around the world.

Some will undoubtedly fail, as with any attempt at changing a staid status quo. This effort, however, can lead to new approaches in delivering solutions that current systems prevent and can bring about the digitally transformed infrastructure systems so badly needed around the world.

Future-proofing for the next revolution: Designing infrastructure systems for innovation resilience

A key factor in the slow pace of technological transformation among infrastructure developers is that the technology will be obsolete well before the infrastructure's useful life is exhausted. This mismatch discourages infrastructure planners from embracing innovation. How infrastructure investors approach the conflicting life cycles of infrastructure and technology will be crucial in determining whether or not the world receives the innovative infrastructure solutions it needs. The same issue exists in other business sectors, but planners there have developed models to mitigate obsolescence. This may hold some lessons for how infrastructure investors should approach the conflicting life cycles of infrastructure and technology.

Mitigating technology obsolescence in telecommunications

The Open Systems Interconnection (OSI) model is useful in showing how the telecommunications sector manages infrastructure costs and the technology life cycle. Used as the reference model since the 1970s, it describes telecommunications networks and has seven layers (Figure 1).

Figure 1: Open Systems Interconnection model

Layer	Simplified description	Propensity to change	Cost to change
7. Application	Opening and closing of communications between specific applications	Higher	Lower
6. Presentation	Definition of application-specific protocols	↑	↑
5. Session	Opening and closing of data sessions		
4. Transport	Reliability and quality of service		
3. Network	Data structure		
2. Data link	Connection of devices and correction of errors	↓	↓
1. Physical	Physical connection and raw data	Lower	Higher

Source: Authors based on information from Wikipedia.org, "OSI model", https://en.wikipedia.org/wiki/OSI_model

The model's design dictates that the elements most expensive to change, and least likely to change, are placed at the bottom of the model (layers 1 through 3), and the layers that change most frequently and require the most agility are placed at the top (layers 4 through 7). All layers depend on the layer below and enable the layer above. This model has several advantages:

- Ensures a long life of the most expensive physical aspects of network implementation (layer 1)
- Creates robust and enduring standards for communication and interoperability (layers 2-4)
- Enables flexible and agile development of new applications and use cases (layers 5-7)

The model ensures that major investments, such as the shift from copper to fibre (layer 1), will last their business case life and beyond, while the end-user applications and services (layer 7) are allowed to rapidly innovate without fear of obsoleting lower-level investments that require a long payback.

Applying the OSI model to infrastructure

This way of thinking is already in place in many infrastructure categories. For example, a proxy of the telecommunications OSI model can be applied to transportation (Figure 2).

Figure 2: Applying the OSI model to infrastructure

Layer	Description	Propensity to change	Cost to change
7. Vehicles	Vehicle choice and options (e.g. autopilot, GPS, Apple CarPlay)	**Higher**	**Lower**
6. Congestion management	Variable zones, time-based parking and traffic flow		
5. Traffic layout	Road choices – one way, bus lanes, commuter zones		
4. Training and standards	Licensing laws, alcohol limits		
3. National localization	Signage, language, revenue models		
2. International localization	Left or right side of road, indicator stalk left or right		
1. Global standards	Pedal layout, red = stop, green = go	**Lower**	**Higher**

Source: Authors

While not a formal transportation planning model, it is frequently implemented by planners around the world. This phenomenon illustrates how infrastructure planners can use similar thinking to plan how technology risk can be mitigated – i.e. invest in core assets that will endure and last the forecast life of the infrastructure, while creating optionality so that agile use cases can be implemented and changed out over time.

Technology – innovation vs disruption

This thinking fails, however, when innovation at an upper layer has an unexpected effect on a lower layer that breaks the business case/expected returns of the layers at the bottom of the model (layers 1-4).

Transportation is again a useful example where the fundamentals of the internal combustion engine and road systems have been in place and largely unchanged for almost 120 years. However, a number of recent, complex disruptions at the top of the model, including electric vehicles, autonomous vehicles, mobility as a service and shared mobility, are challenging transportation planners' ability to forecast effective capital deployment.

The distinction between technology innovation and technology disruption is an important one. While innovation can be gradual, incremental and predictable, disruption is forceful, rapid and unpredictable and is confronting transportation planners across several fronts (Figure 3).

Figure 3: Disruption across infrastructure layers

Layer	Electric vehicles (EVs)	Shared mobility	Autonomous vehicles (AVs)
7. Vehicles		– Reduced private ownership	– Reduced private ownership
6. Congestion management	– EV parking and charging	– Drop off and pick up zones	– New traffic patterns
5. Traffic layout	– EV lanes	– Road utilization – Congestion changes – Public transport demand	– AV lanes – Road utilization – Congestion changes – Public transport demand – Smart parking requirements
4. Training and standards	– Pedestrian safety	– Pedestrian safety – Regulation – Reduced licensing demand – Drink-driving changes	– Pedestrian safety – Regulation
3. National localization	– Revenue reduction	– Revenue reduction – Transport ghettos	– Reduced revenue – Transport ghettos
2. International localization	– Charging methodology		
1. Global standards	– Safety standards		– Liability and insurance – Safety standards

Source: Authors

These disruptors combine to create a challenging environment for planning and implementation. For example: globally, transport planning agencies are pursuing the development of multiyear, multibillion-dollar light rail programmes with expected lifespans of up to 35 years. In the same planning horizon, most automotive manufacturers will have launched advanced autonomous vehicles (e.g. without a steering wheel or pedals) that will disrupt private and public transportation systems.

Given the disruption created by autonomous vehicles and shared mobility, and the ambiguity of when they will arrive at scale, transport planners need to adopt a planning strategy to solve short-term needs while remaining agile for future transportation models.

Adapting infrastructure planning to embrace disruption
Planners may get a line of sight into how they could future-proof long-term transport investment by using a model that identifies core aspects of infrastructure systems – based on long-term inflexible, medium-term flexible and short-term agile categories – and aligns these against transport needs and disruptors. It will also give planners insight into what areas of the transport plan will require the most frequent review against disruption risk. Adopting models like these can help ensure that an infrastructure asset's useful life is also a life well used.

2. How does the public sector drive innovation in technology by creating frameworks that encourage exchange while protecting intellectual property?

Commercial innovation – the successful creation of products, services, processes and business models – is a critical component of economic growth and social progress. The capacity of competitive markets to seek innovative opportunities, prove their value and enable their diffusion into the public sphere can change entire economies. Introducing new or improved solutions can generate value and increase productivity across sectors and value chains. Great ideas, however, can come from many different places and result from individual efforts as well as collaboration across groups; this is as true of infrastructure as it is of any other sector.

Still, for innovation to flourish, those with the right scientific, technological and other professional skills not only need the freedom to experiment and collaborate, but also the security of knowing their hard work is recognized and their ideas protected. If infrastructure systems are to undertake fundamental changes, they need the underpinning of frameworks that allow for exchanging ideas and protecting the fruits of those innovations. This section will discuss how to understand and promote the best ways to encourage and enhance collaboration and share ownership and risk within both the public and private sectors and to embed frameworks designed to support implementation.

Encouraging collaboration, protecting ideas

Increasing access to open data
A prime example of an area ripe for a bridge between methods of exchange and strategies for protecting IP is in the use of public-sector data for driving private-sector innovation. The public sector often has a treasure trove of valuable data that can be used to improve the design, development and delivery of infrastructure. Traditionally, however, public-sector policy-makers have adopted laws and regulations that require the public sector to own any publicly funded innovation. These laws and regulations also typically do not allow for private-sector access to data that may support innovation, even if that data is not part of the innovation itself.

The rationale is often that the public sector should own any resulting intellectual property rights (IPRs), including decision-making power over access by competitors, if its funding underwrote the innovation. Additionally, the public sector has generally operated under the mindset that its data should not be given out to the private sector. This attitude reinforces the misconception that being the sole recipient of data that has IPRs confers a competitive advantage to its owner, leading many organizations, both public and private, to protect their data vigorously. These policies have largely chilled innovation and progress, with the private sector looking for alternative ways or venues to pursue research and development (R&D) where the climate is more favourable.

In recognizing the potential of innovation from shared data, however, the public sector is now leading the charge in promoting open-data approaches, providing the private sector access to its proprietary data to spur innovation. Such approaches increase the pool of private-sector organizations able to use this data, particularly individuals and smaller companies, boosting competition and increasing choice for consumers.

Together, the public and private sectors share responsibility and interest in partnering for development. Governments need to commit to funding and implementing long-term policies and frameworks that will facilitate collaboration, allow access to their own IPRs and proprietary data, attract and maximize investment and drive innovation. The growing focus of public bodies to provide creative ways of permitting open access to data and publicly funded IP will help foster greater innovation (given that more internally focused public entities experience slower development, higher costs and difficulty in securing new investment). For the private sector, a shift to closer engagement makes business sense, with evidence emerging that such partnerships accelerate innovation and increase competitiveness.

Protecting ideas

While improving the private sector's ability to access public-sector data and knowledge is crucial to accelerating innovation, particularly in such an incredibly public-facing sector like infrastructure, robust IPRs for private-sector innovations are also important. Innovation often leads to the creation of IP and IPRs, which give individuals and organizations a vehicle to obtain the required funding to develop innovative ideas and bring them to market for the benefit of all. Many private innovations currently being designed build on volumes of relevant data, in which the public sector may have IPRs. Thus, collaboration between the public and private sectors is essential to encourage innovation and ensure that new ideas can be tested and protected effectively to sustain profitable business models.

IPRs for innovations are typically unpatentable ideas, trade secrets (that may or may not be patentable) and patentable inventions, the latter being the most utilitarian in encouraging innovation. Patentable inventions begin with an idea that can be brand new, or a novel combination of existing solutions. Having ideas is not enough, however; creators must also understand how to implement their ideas, and the implementation concept must be reasonably understood by others. The explanation of how to implement the idea, demonstrated either through a model or a sufficient description, confirms an invention's patentability. Proof of viability is often necessary even with a sufficient description. Thus, the need to access public sector data that supports the invention, even if that data is not part of it, may be essential.

But patentability is only the beginning. The path from patentability to commercial viability can be long, expensive and risky. Significant funds may be needed to take a patentable invention from early development to commercial deployment. To secure funding, potential investors must be convinced that the sums required can be accessed and can be recouped profitably. Investors will not invest without access to necessary public-sector data or IPRs (or both) to protect the recovery of investment in the commercial development of new technologies. The risk is that competitors could simply undercut the inventor as soon as they get to market, copying the new product or service and selling it at a reduced, profitable price because they do not have to cover the same upfront development costs.

Therefore, to reassure the market and encourage investment in robust research, innovation and creative work, the private sector needs access to public-sector data and the creation of IPR monopolies. The public sector's role is to strike a balance between competition and innovation in its frameworks, supporting the development of new ideas and solutions while also facilitating creative models for open data and IPRs for owners.

Innovate in practice — the Bayh-Dole Act

Over recent decades, the US federal government has had to reassess its policies to prevent R&D efforts in the biotech and high-tech sectors from moving offshore due to a lack of unencumbered public funding. Beginning in the 1980s, the government introduced critical policy changes, such as R&D tax credits; increased funding for national research centres; passed laws favourable to private-sector development; and enforced IPRs to reverse the exodus of creative minds and new technologies.

Within this successful framework, the Bayh-Dole Act was one of the major laws fuelling domestic development through a proliferation of PPPs. Passed in 1980, the Bayh-Dole Act allows academic institutions and the private sector to own the inventions and innovations they make with federal funding, thereby encouraging public-private sector cooperation rather than competition. Additionally, prior to the Bayh-Dole Act, very few academic and research institutions had technology licensing expertise. Now, most universities that do R&D also have a significant technology licensing focus. The Bayh-Dole Act formula for private ownership of publicly funded IPR development has been adopted internationally.

Think globally

Just as established techniques can enhance the IP portfolios of enterprises, proactive governmental policies are increasingly recognized as able to strengthen the human capital and IP portfolios of nations. For example, Russia and the United States signed a bilateral treaty several years ago for universities in the United States (i.e. University of California Los Angeles [UCLA], Purdue University and the University of Maryland) to provide assistance to Russian universities in erecting their own university technology licensing programme and to help draft Russian laws to promote new technology start-ups, private equity ownership and the sourcing of private investment.

Innovation is a global endeavour that transcends borders. Recognizing commercial realities, countries must establish frameworks for new technologies that will grow a local economy and address its most critical challenges, while also balancing open markets and fair competition with appropriate access to public data, IPRs, IPR protections and enforcement.

Playing the role, enabling innovation

The public sector has different policy levers to use covering the political, financial, organizational and technical elements to help drive innovation. The levers constitute eight roles that entities can adopt proactively to establish the most effective frameworks possible:

1. **Provider**: Create methodologies, laws and policies for private-sector access to public-sector data and databases that may be necessary or desirable for developing related innovations, even if the data itself is not part of the innovation.
2. **Funder**: Increase funding for private-sector experimentation and development with co-ownership or private-sector proprietary access to any IPRs (such as the Bayh-Dole model). Recent public-sector support for this also includes encouraging IP development by permitting the private sector to retain the IPR. In return, the public entity receives a discount for using the IP.
3. **Market creator**: Push legislators to reduce barriers to entrepreneurship and calibrate regulation to the appropriate contexts. Numerous statutory and regulatory barriers discourage or prevent entrepreneurs from bringing innovations into new markets. As the demand for new technologies grows, policy-makers must rethink status-quo funding formulas and IPR ownership requirements.
4. **Facilitator**: Drive governance reform and create common metrics for accountability and the adoption of common standards and assessments. Traditional methods of organizing, financing and governing innovation initiatives can impede their conception and implementation. Reform is needed to enable more of the public sector to experiment (for example, via living labs and accelerators). System-interoperability standards and data standards may also need public-sector backing to gain traction.
5. **Disseminator**: Promote formal and informal networks of businesses, academia and entrepreneurs. Professional networks help diffuse innovations. In a more fluidly networked world, policy-makers and entrepreneurs should be able to converse in real time about what works, what doesn't work and the real challenges of implementation.
6. **Technology supporter**: Enhance technical assistance between the public and private sectors, with up-to-the-minute communication, data and feedback loops, to radically reshape innovation development. The technical assistance function should be a two-way communication channel between sectors, spurring action in response.
7. **Researcher**: Public-sector programmes intended to promote external innovation may increase awareness and public support, but they need the right people, expertise and resources to be truly effective. These programmes can suffer from a lack of clarity about what innovation means, how to assess its effects and how to bring successful models to scale. Running internal programmes for public-sector employees can be a powerful tool for generating good ideas. It also helps ensure scrutiny for policies and practices that may no longer be relevant. Challenges include providing enough time, expertise and funding to process and develop ideas.
8. **Organizer**: Public-sector bodies can create dedicated teams (across multiple public-sector organizations) that are responsible for innovation. Such teams work to stimulate innovative thinking across government. A team works to bring user-focused innovation into the parent entities by observing the effects of their policies and programmes on employees, businesses, consumers and markets. The team may also host projects that run in collaboration with universities and the private sector.

Regulators who strive to maintain a balance between encouraging innovation, protecting citizens and addressing the potential unintended consequences of disruption face significant challenges. Therefore, discussions on IP policy and the frameworks for innovation can sometimes become controversial. Policy-makers and public-sector champions can support collaborative innovation through various roles that help to develop frameworks based on categories of activities that go well beyond the traditional policy levers, driving innovation to secure economic success and social progress.

3. How can data and analytics help to prioritize and optimize infrastructure decision-making?

The global need for greater investment in infrastructure is felt in both abstract statistics and people's daily experiences. Increasing global urbanization – 68% of all people are projected to live in cities by 2050, up from 55% in 2018[1] – will further exacerbate the growing infrastructure gap. Dense urban areas will continue to face challenges as they seek to augment existing infrastructure systems and build new ones.

Compounding these issues is the lack of a way to solve all the world's infrastructure problems simultaneously. Projects will need to be prioritized, and systems designed, based on a wide array of consumer needs and provider ability. Increasingly, data provides opportunities to inform infrastructure decision-making and provide the tools for planners to deliver better and more flexible solutions. This section explores how to improve the capacity to use data and analytics in infrastructure decision-making.

Data and digital transformations

Addressing the growing infrastructure gap is complex: the infrastructure of tomorrow not only involves building wholly new and stand-alone systems but also designing systems built upon existing infrastructure. These can be expansions, enhancements and renewals requiring further considerations and decisions on integration, interoperability and complete or partial decommissioning.

According to a 2015 study by McKinsey & Company, the US economy as a whole is realizing only 18% of its digital potential.[2] The study revealed that the non-infrastructure sectors, such as information and communications technology (ICT), media, finance and insurance, demonstrated relatively high degrees of digitization and were ranked among the top five, while the infrastructure-related sectors were ranked lower, with oil and gas ranked seventh and construction and agriculture ranked in the lowest group.

Like many other sectors, infrastructure is struggling to extract value from a deluge of data and to translate it into better decision-making. Harnessing data requires a range of new skills and capabilities, with many organizations facing technological hurdles in integrating large, isolated and disparate data sets. Furthermore, the ongoing challenge of maintaining data integrity and protecting personal privacy remains front of mind for key decision-makers.

This does not mean, however, that the technology to improve the planning, development, delivery and operation of infrastructure does not exist. In fact, a host of exciting innovations are already occurring at all stages of the infrastructure life cycle: data analytics approaches involving "digital twins", building information management, and real-time analyses of demand and asset operational performance show promising signs of driving fundamental changes. Nevertheless, and based on emerging trends and conversations with industry leaders, three key barriers exist to the widespread adoption of technology and data analytics in infrastructure decision-making:

– **Lack of an empowering and enabling environment:** A general lack of familiarity and comfort with more technologically or data-driven approaches, particularly among senior industry leaders, is a major contributor to this problem. A risk-averse environment that makes it incredibly difficult to change traditional approaches exacerbates these issues, especially within government entities.
– **Constrained approach to infrastructure decision-making:** The value of data and data analytics is often not considered from a full life-cycle perspective, but is generally limited to the life-cycle stage at the time of decision-making.
– **Cybersecurity and data privacy:** Cyberthreats to critical infrastructure contribute to the lack of technological advances.

Despite significant gaps in the adoption of technology and the use of data and analytics in infrastructure decision-making, infrastructure organizations increasingly realize the benefits of leveraging data and analytics and have a renewed focused on investing efforts in response. Credible and compelling examples exist of data-backed decision-making leading to desired outcomes, but such cases are still the exception and are certainly not widespread. Furthermore, many decisions are still made without fully considering the infrastructure life cycle or the changing needs of developers and consumers. Few organizations have enterprise-wide decision-making approaches informed by a comprehensive organization-wide data analytics approach, and few have the depth and breadth of data skills required.

Promising examples and significant value from better use of data help to support infrastructure decision-making. To create successful decision-making apparatuses, however, support is required from the following:

– **Leaders** – They need to be educated on the possibilities of advanced data analytics and the value it can create. Executives and middle managers cannot lead without a basic understanding of how leveraging value-adding data analytics use cases in their organizations can deliver value.
– **An empowering and enabling environment** – Leadership from governments is crucial in creating environments where innovation can flourish but sensitive data is protected.
– **Internal capabilities** – Companies are increasingly integrating disparate data sets (i.e. physical, spatial and financial) into real-time analytics models and platforms for sophisticated decision-making. As more companies demonstrate the benefits of doing so, infrastructure organizations should commit to building internal capabilities and capacity to integrate available data models and to enable new decision-making approaches supported by comprehensive and advanced analytics.
– **Effective data governance and data security** – Frameworks for these are needed to ensure a line of sight between the overall vision (national and/or corporate) and underlying practices to achieve the vision.

Given the magnitude of the global need, the complexity of the challenges and the insufficiency of resources to "build our way out" of problems, the opportunities available through data and analytics provide governments and businesses with promising opportunities to support enhanced infrastructure decisions and outcomes.

4. How can viable commercial models be created via catalytic policy and regulatory frameworks?

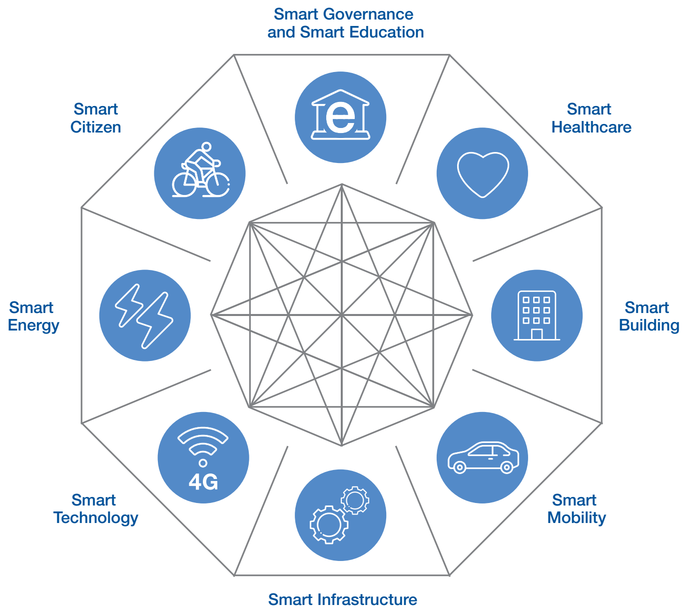
Digital transformation in infrastructure is people-driven, as communities are the ultimate users and beneficiaries. Citizens who demand better of their government are often the catalyst for change. Government entities that are proactive in instituting change, however, and particularly in the Fourth Industrial Revolution, can reap the social and economic benefits of a rapidly digitizing world. The role of policy and regulatory frameworks in creating viable commercial models while balancing the needs of society, including citizens, private companies and government entities, is vital. This section discusses ways to create these frameworks to enhance innovators' ability to design and apply new solutions and create better infrastructure systems.

Integrating technology to build modern cities

The ability to create viable commercial frameworks often depends on the ability to understand cross-systemic issues, especially considering the development of infrastructure. Understanding these complexities is particularly important in urban areas, with their many crisscrossing infrastructure systems. Burgeoning "smart cities" are often living laboratories for these catalytic policy and regulatory frameworks, and provide examples of how to successfully orient policy to achieve wider goals.

The United Nations estimates that 68% of the world's population will live in urban areas by 2050 (vs 55% in 2018).[3] Such rapid urbanization exacerbates challenges like traffic congestion, pollution, waste management and water scarcity, among others. Many governments have chosen to confront these challenges by focusing on creating smart cities. A smart city is innovative and uses information, ICT and other means to improve the quality of life, efficiency of urban operations and services, and urban competitiveness (Figure 4). This helps to ensure it meets the economic, social and environmental needs of present and future generations.[4]

Figure 4: Smart city concept and the advantages of deploying technology



Advantages of deploying technology
Government – Data analysis for identifying key concern areas and undertaking precise actions – Efficient planning and execution
Private sector/businesses – Development of innovative business products and services, creating enormous revenue potential – Opportunity to partner with the government
Urban residents – Ultimate beneficiaries with access to cost-efficient services – Greater citizen engagement leading to citizen-centric solutions – Employment opportunities and promotion of entrepreneurship

Source: Authors based on Frost & Sullivan and Caisse de dépôt et placement du Québec information

Technology touches every aspect of a smart city and integrates all stakeholders. A range of devices, such as smartphones, radio frequency identification (RFID)-enabled devices and smart cards, as well as GPS systems and real-time monitoring, are used to input and measure data that is analysed to develop solutions (Figure 5).

Figure 5: IT applications in smart cities

Smart transportation	Smart energy	Smart water	Smart buildings
An intelligent transportation monitoring system uses big data analytics to determine traffic patterns and ensure smooth flow of traffic by adjusting traffic lights and signals. For example, Dubai is planning to invest $161 million to avoid congestion build ups and detect accidents.	Smart energy deploys big data analytics to provide insights about energy consumption trends and ensure efficient management of the grid. For example, Edinburgh is deploying smart streetlight controls in 64,000 lights across the city – reducing energy consumption and quickly rectifying faults.	Smart water solutions are aimed at monitoring quality of water supply with the help of sensors and automated control systems. Further, water quality monitoring can help in detecting pollutants. For example, to improve the water supply efficiency, Saudi Arabia plans to install 2 million water meters across the country.	Smart buildings are fitted with sensors that can help in reducing energy use and ensure timely repair and maintenance. For example, air-conditioning and lighting requirements can be optimized in real time.

Source: Authors based on Macrosource Media Pty Ltd, Smart cities market report, March 2019

Incorporating technology, however, poses additional challenges for planners. Cybersecurity breaches, privacy concerns and the level of inclusion are all factors to address in smart city design. Thus, implementing smart cities requires a well-defined regulatory and policy framework uniting a diverse system of stakeholders that ensures transparency and accountability.

Frameworks for smart cities in India

Almost one-third (31%) of India's 1.3 billion people live in urban areas.[5] This population is expected to double by 2050, with another 416 million people – or more than the present population of the United States – calling Indian cities home.[6] To address persistent problems in India's growing cities, the Government of India launched the Smart Cities Mission (SCM) in 2015 (Figure 6). SCM expects to develop 100 smart cities in five years. While the government did not define the term "smart city", key features include efficient transportation, energy-efficient buildings and robust digital connectivity, as well as adequate water and electricity supplies, sound governance and affordable housing.

The 100 cities were selected through a first-of-its-kind competitive process (Figure 7), with each city presenting a smart city concept and vision suited to its local context. The strategic components of the SCM included the following:

- Area-based development to transform existing areas (via retrofitting and redevelopment) or new areas (greenfield development) to accommodate the expanding population in urban areas
- Pan-city initiatives that cover large parts of the city

Figure 6: Analysing the Smart Cities Mission policy framework

- SCM promoted city-specific local solutions prepared in consultation with the city residents to meet the nation's diversity challenge.
- While SCM promoted citizen participation, it was limited to digital literates, potentially skewing opinions.
- Cybersecurity remains a challenge due to limited consideration given to it during various phases of smart city development.
- Separate SPV for implementation of smart city projects created a unified boundary for smooth execution. However, relationship and hierarchy between SPV and municipality remains ambiguous.

Source: Authors based on Caisse de dépôt et placement du Québec information

Figure 7: SCM – smart cities evaluation and selection

State level	**Intra-state city challenge**	**Evaluation criteria**	– Existing service levels: 25% – Institutional system and capacities: 15% – Self-financing: 30% – Past track record: 30%	This first-time intra-state challenge encouraged competitive federalism within the context of shared national objectives.
City level	**Smart city proposal**	City-level criteria (30%)	**Evaluation criteria** – Vision and goals: 5% – Strategic plan: 10% – Citizen engagement: 10% – Baseline, KPIs, etc.: 5%	With 16% weightage of citizen-level engagement, the SCM was a citizen-driven event, while technology was a secondary contributor with 10% weightage to "smartness" of proposal.
		ABD (55%)	– "Smartness" of proposal: 7% – Citizen engagement: 5% – Results orientation: 15% – Process followed: 3% – Implementation framework: 25%	
		Pan-city solution (15%)	– "Smartness" of proposal: 3% – Citizen engagement: 1% – Results orientation: 5% – Process followed: 1% – Implementation framework: 5%	

Note: ABD = area-based development; KPI = key performance indicator
Source: Authors based on Government of India, Ministry of Housing and Urban Affairs, "Criteria for selection of potential smart cities announced" [press release], 25 June 2015, https://pib.gov.in/newsite/PrintRelease.aspx?relid=122782; India Smart City Mission, "The Smart City Challenge Stage 2", (undated), http://mohua.gov.in/pdf/58fd958bc7ed75821af4818704SCP_Template.pdf

Special purpose vehicles (SPVs), responsible for the management of smart city projects, were proposed to carry out implementation at the city level. The SCM currently stands at over $29 billion, with 45% of the funds provided by the central and state governments.[7] The remaining funds will be raised through market-based sources of capital.

The programme has led to the development of models as diverse as Indian cities themselves. While deploying and adopting technology remains a challenge, political will and active citizen participation enable smart city development. Innovative business models that support private-sector participation and a conducive regulatory environment ensure hassle-free implementation. Almost all cities have planned a central command-and-control centre to monitor and manage services for issues such as managing traffic, waste and citizen feedback.

Smart cities demonstrate that infrastructure projects do not follow a one-size-fits-all approach. When such cities design their smart city strategies, contrast is clearly visible between brownfield cities, which require an attitude shift among their residents, and greenfield cities, which can use innovative technologies as they build from scratch (Figure 8). A comprehensive framework is thus required that incorporates stakeholder opinions, clearly defines their roles and responsibilities and provides flexibility to develop new commercial models. This framework also creates more avenues for close collaboration among various players in the quadruple-helix model, namely government, industry, academia and civil society.

Figure 8: Smart cities in India

City overview	Innovation	Key takeaways
	Brownfield cities	
Indore (Madhya Pradesh): India's cleanest city – Population: 2.5 Mn – Area-based development: 3 sq km, Redevelopment: 0.21 sq km – Project cost: INR 51 Bn	– Indore's success is attributed to its effective citizen behaviour change envisioned by the Municipality. Such change was executed by comprehensive awareness campaigns, supported by levying of strict spot fines. – Indore integrated ICT with its waste management system, deploying GPS receivers for real-time monitoring and launching app for citizen feedback.	– Indore's cleanliness profile was transformed by combination of political will and citizen cooperation. – Tangible impact was also achieved by an innovative service fee model.
Pune (Maharashtra) – Population: 3 Mn – Project cost: ~INR 30 Bn	– Pune has launched a Lighthouse programme that focuses on digital literacy of underprivileged youth. It involved setting up of community hubs in slums for skill training in digital technologies.	– Digital transformation requires both people and technology. Pune has recognized that digital literacy is an important component for success of smart cities.
	Greenfield cities	
Amaravati (Andhra Pradesh): First capital smart city	– The city will be born as "digital twin" i.e. everything that happens in the city will be 'scenarioized in advance' to optimize outcomes. Among other innovations, it is planning cloud-connected rapid transit systems, real-time governance centre, energy efficient buildings, etc.	– Amaravati is the first entire city to incorporate best-in-class innovative technologies as it is built from scratch.
Gujarat International Finance Tec-City (Gujarat): India's first operational smart city – Project area: 3.6 sq km – The city has a strategic location	– GIFT city is being designed as a global financial and IT hub with futuristic infrastructure, such as a city-wide underground Utility Tunnel, District Cooling System (centralized cooling system for the city) and Automated Waste Collection System (India's first).	– GIFT City offers a competitive tax regime (SEZ benefits, IFSC benefits, etc.), improving the ease of doing business. – There is ~30-40% reduction in operational costs due to shared infrastructure and limited human intervention for its operation.

Note: Mn = million; Bn = billion; INR = Indian rupee; SEZ = special economic zone; IFSC = Indian Financial System Code.
Sources: Indore Municipal Corporation, "Indore – Smart City", presentation; Urban Hub, "Pune – one of India's best smart cities leads with citizen engagement and top technology"; Hindustan Times, "Pune's new lighthouse guides turbulent youth to make smart choices"; Pune Municipal Corporation, "Light House Project"; Cision PR Newswire, "Cityzenith's SmartWorld Pro™ Digital Twin Software Platform Selected for New Capital City in India"; Gujarat International Finance Tec-City Company, "India's First Operational Smart City & International Financial Services Centre".[8]

Case studies: addressing the four questions

1. Technological disruption in the white space of infrastructure

Systemic future-proofing: The Zhuzhou light rail

Light rapid transit is predicated on building fixed rail infrastructure with fixed commuter platforms. Planners typically choose from one of a handful of known locomotion methods, such as diesel, overhead pantograph or third rail, and the choice may be limited by compliance with bylaws that restrict diesel or overhead lines. In greenfield projects, the siting of rail corridors and platforms are major project elements. These choices and restrictions run counter to flexible planning as they force major system choices and, consequently, the bulk of capital spending to the model's bottom layer. Therefore, the ability to adapt to future disruption requires rethinking and redeveloping the rail infrastructure.

In Zhuzhou, China, transport planners are experimenting with a disruptive approach to light rail transit (LRT) and rethinking how to address the most inflexible parts of a transport programme. Rather than accepting the assumption that light rapid transit requires tracks, fixed electrification and dedicated platforms, China is experimenting with flexible "trains" that run on roads and use emerging battery technology for electrification. This combination both removes the need for fixed tracks and platforms and allows for flexible rerouting of trains to adapt to changes in commuter demand. To make this work, other long-standing elements of the transport system require rethinking and adaptation – for example, control of intersections, coexistence of private vehicles and rapid transit, location of bus stops and light rapid transit platforms, pedestrian safety and congestion planning – but these elements move higher up the model and therefore have greater inherent flexibility. Also, where land is available, such as beside motorways or alongside rail corridors, dedicated LRT "roads" could be built at much lower cost than traditional rail tracks.

The thinking behind the OSI model can be used to illustrate how the Zhuzhou light rail trial mitigates some of the inflexibility of traditional LRT systems (Figure 9).

Figure 9: OSI model applied to the Zhuzhou light rail

Ease to change	Cost to change	Traditional light rapid transit	Zhuzou light rapid transit trial
High	Low		– Platform location – Right of ways (new) – Prioritized LRT lanes (new) – Effect on traffic
Medium	Medium		– LRT locomotion choice – LRT carriage choice
Low	High	– Platform location – Effect on traffic – LRT locomotion choice – LRT carriage choice – Level crossings (removed) – Easements and tracks (removed)	– Recharging infrastructure (new)

Source: Authors

Under the Zhuzhou light rapid transit approach, the most expensive and inflexible LRT elements (easements, tracks and level crossings) have been removed and other elements (locomotion, carriages and platforms) have been moved up the model. In addition, while locomotion and carriages are still expensive, the Zhuzhou model has introduced routing and demand flexibility into the transport system. This forward-looking system design built the expectation of change into the LRT programme from the beginning, allowing it to benefit from a rapidly changing mobility system.

Procurement models for disruption: The Michael Tippett School

Context and background

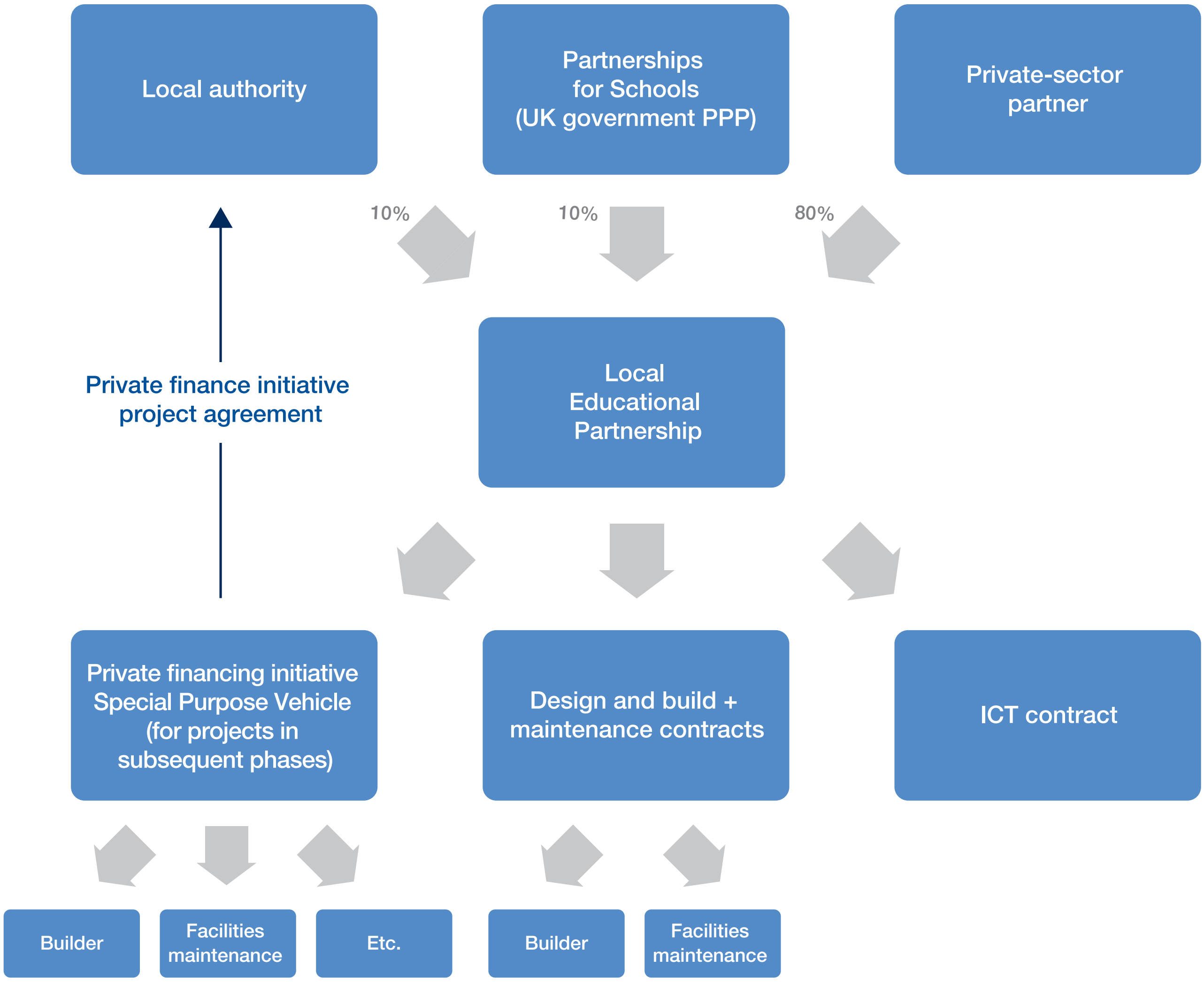
In the early 2000s, the UK government recognized that all 3,500 of its secondary schools needed some form of refurbishment or replacement. School structures were outdated and learning environments had failed to keep pace with technological changes transforming classrooms in other parts of the world. The government decided to implement a massive refurbishment and replacement programme to bring modern classrooms to English pupils. To fund this enormous undertaking, the government devised a programme leveraging the Strategic Partnering model to create more localized, open and strategic procurement processes for developing and achieving strategic goals rather than defined outputs. This model encouraged faster builds, improved input and calibration over the life cycle of a project, and created an enabling environment for using new materials, techniques and technologies before it ended in 2010.

Building Schools for the Future programme

The UK Department for Children, Schools and Families launched the Building Schools for the Future (BSF) programme in 2003 with the goal of replacing or refurbishing all of England's secondary schools over several phases. It was the largest single capital investment programme in 50 years. Aimed at providing improved learning environments for England's 3.3 million secondary school students, the goal was not only to invest in infrastructure but also to raise attainment and achievement by providing modern, ICT-enabled learning spaces. BSF was intended to address the entire procurement process covering financing, construction, refurbishment, management and service provision for schools.[9]

Under the programme, a local authority would enter into a joint venture, dubbed a local educational partnership (LEP), with Partnerships for Schools, a UK government PPP and a private-sector partner (Figure 10). The private-sector partner would be scored in a bidding process on past work as well as the submission of sample projects that met the needs of the various facility types the LEP was designed to deliver. The LEP would then contact potential subcontracting partners to tender for various aspects of the project, from designing and building the schools to delivering facilities management and maintenance and providing ICT services. The LEP would also be given exclusivity over subsequent projects and partnering services. To ensure value for money, continuous improvement targets would be set that the LEP would have to meet or face losing its rights of exclusivity.

Figure 10: Building Schools for the Future – local educational partnership structure



Source: Authors based on Byles, T. and Wilson, C. (2008). an introduction to Building Schools for the Future. Public Private Partnership Programme 2008, UK Department for Children Schools and Families, https://webarchive.nationalarchives.gov.uk/20100208213450/http://www.partnershipsforschools.org.uk/documents/BSF_Guidance_Documents/BSF%20Introductory%20Guide%202008.pdf

The process allows for more locally focused and open procurement of projects and services. This is not only more cost-effective than a fully refined PPP agreement, but also allows for innovative techniques and technologies to be introduced during the project development and post-construction provision of services, thanks to the flexibility provided by the BSF structure and, particularly, by the LEPs.

The Michael Tippett School

The Michael Tippett School in Lambeth Borough was the first school in London, and the first special needs facility, to be completed under the BSF programme. The borough needed a new school for 80 special needs students aged 11 to 18. The building had to be completed on an accelerated timeline because it was meant to house students from two separate schools, one of which had to be closed for the new school to be built.

Using the flexibility afforded under the BSF programme, and considering how quickly the project needed to be completed, the Lambeth Borough Council (the local authority) forwent the customary bidding process and selected an architectural firm based on the strength of its competitive interview. Once the design brief was prepared, it was put out for a two-stage tender which included two other schools that had already been designed by architects directly selected by the council. While the schools were let as three separate contracts, the Council awarded them to a single contractor to increase management efficiency and decrease cost. The design also required meeting specific guidelines for headroom, light and adaptability for lunch. The selected design team not only used sustainable material for the structural frame, but also worked closely with the school to use new building techniques at the right stages of the project to keep the building schedule on track.

In the end, the Michael Tippett School was recognized as one of the flagship projects of the BSF programme and won numerous design awards. It not only provided a sorely needed educational asset on time and on budget, but also gave the local authority the flexibility to work strategically and use innovative techniques and materials.

2. Public-sector innovation in technology via creation of frameworks

Creating partnerships for progress: Dynamic in-road charging infrastructure for electric vehicles

The global focus on tackling climate change – its effects on the environment and society more broadly – is at an all-time high, with countries around the world increasingly acknowledging the need to shift from a fossil fuel-driven economy to one driven by more sustainable, renewable energy sources. Transportation – the ability to move people, goods and services – drives the world's economy. Across established modes of road transportation, however, most private and public vehicles are still petrol- and diesel-powered, contributing to air pollution and negative environmental effects. Currently, transportation accounts for over 50% of air pollution and 71% of petroleum use in the United States.[10]

The infrastructure challenge

However, change is coming, with a primary focus on electricity. With the goal to reduce carbon emissions, municipal leaders worldwide are pledging to partially, if not fully, replace city fleets of fossil fuel-powered mass transit with e-buses over the next decades. Several cities, such as Mexico City and Philadelphia, have started pilot tests, as have national and regional transportation departments. Shenzhen (China) recently converted its entire public bus fleet to electric vehicles, and Chile has designed a national programme that aims to make 40% of private vehicles and 100% of public transportation vehicles powered by electricity.[11] At the same time, vehicle manufacturers have pledged to convert their fossil fuel-based fleets to electric power within the next 10 years.

The success of such moves depends heavily on the ability of cities and organizations to rapidly and effectively deploy technological advances. This comes with one persistent barrier, however: the lack of existing infrastructure to support widespread electrification, and the significant technological, financial, legal and institutional challenges that come with developing and deploying it. For example, when cities consider adopting electric vehicles for mass transit, they need to understand the power grid upgrades and charging infrastructure required. Electric vehicle infrastructure technology must become cost-effective to drive the adoption of electric vehicle use and innovation in other modes of transportation.

Dynamic collaboration

A transformative approach is needed to deliver a transportation energy platform that can heal the climate. This transformation begins with strengthening partnerships with academia, government agencies and the private sector to produce new static and dynamic wireless power transfer solutions for electric vehicles, concentrating initially on larger vehicles, such as freight trucks and transit buses.

The Sustainable Electrification of Transportation (SELECT) centre has been leading the way in developing wireless charging solutions at the Utah State University Electric Vehicle and Roadway (EVR) test track in the United States. SELECT has a fully operational in-pavement charging system that provides power to vehicles operating on the track. A consortium of 13 universities based at Utah State University, SELECT has researched and developed new dynamic wireless power technologies with the assistance of government funding under the Bayh-Dole Act; the Act is a US law that allows academic institutions and the private sector to own the inventions and innovations they make with federal funding. Provided by the National Science Foundation and other government entities, the initial funding has ensured the SELECT consortium can develop these new technologies and take them to market unimpeded by commercialization.

Many of the world's largest infrastructure developers have been collaborating with SELECT and Utah State University to further develop and deploy this technology in partnership with their existing clients. This has included supporting further government grant applications to continue the research. Also governed by the Bayh-Dole Act, these additional grants provide for SELECT's continued control of the IP related to the developing technology.

A wealth of opportunities

Cooperation allows for new technologies to be developed and tested for eventual inclusion in future transportation systems. Engineering and construction firm AECOM offers one example. The firm's transportation practice provides a large and robust client base for deploying new technologies, increasing electric vehicle adoption and fleet conversion. AECOM is working via these partnerships to ensure its infrastructure solution is compatible with existing wireless technology to enable future manufactured vehicles that are charging platform-agnostic – static or dynamic. Through partnerships with clients, communities, academia, and the public and private sectors, the world can accelerate the transformation of transportation infrastructure.

Partnering for environmental clean-up: The case of per- and polyfluoroalkyl substances (PFAS)

PFAS and the environment

A diverse group of synthetic chemicals, per- and polyfluoroalkyl substances (PFAS) have grown in use since the 1950s. They are widely found in consumer products, such as non-stick cookware, pizza boxes and stain-resistant fabrics, as well as commercial and industrial products and processes like fire-retardant foams, and are used in industries from construction to aviation to oil and gas. PFAS manufacturing and processing facilities, facilities using PFAS in production of other products, and airports and military installations contribute to their proliferation. In recent years, PFAS have made their way into landfills, wastewater treatment plants, biosolids and groundwater from fire response sites, industrial sites and consumer products, with ever-increasing concentrations in air, soil and water.

Due to their widespread use and persistence in the environment, a significant number of people worldwide have been exposed to PFAS. There is concern globally about the potential effect of PFAS on humans and the environment, as well as PFAS's ability to move through different environments. Because human exposure can lead to adverse health effects, health considerations mandate the remediation of PFAS from the environment.

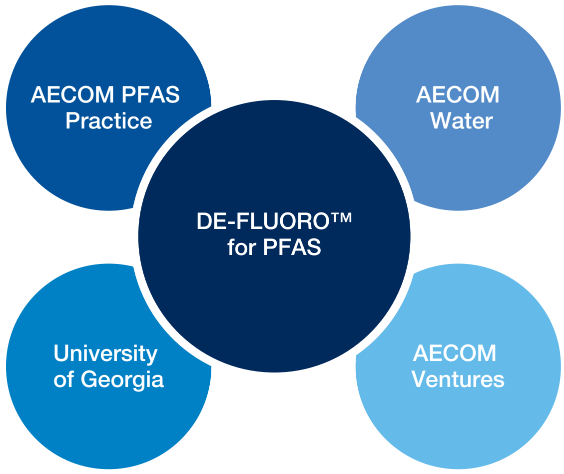
PFAS are hard to decompose and, due to their chemical structure, are heat-, water- and oil-resistant. Their engineered properties mean that conventional technologies are inadequate to remediate the substances.

No full-scale treatment systems are in place to destroy PFAS. Commercially available treatment technologies transfer PFAS from water and concentrate it in filtration systems and other waste streams, requiring disposal management. This PFAS-laden waste is dealt with off-site, retaining legacy and associated liability. The total market for PFAS destruction is estimated to be greater than $5.5 billion, including a recent estimate by the US Department of Defense alone of over $2 billion[12] and the 3M settlement of nearly $1 billion in Minnesota (USA).[13]

Using frameworks for public-private innovation

Recently, researchers at the University of Georgia (UGA) in the United States invented new technology for the electrochemical degradation of the carbon-fluorine (C-F) bond that is integral to the PFAS chemical structure. This development was underwritten with funding from government sources and is covered by the Bayh-Dole Act. Believing this technology to be applicable for PFAS destruction on-site, experts from AECOM invented a PFAS destruction process dubbed DE-FLUORO (Figure 11), which couples a combination of existing solutions, such as ion exchange resins or reverse osmosis, with the UGA technology to destroy PFAS without the unwanted and harmful waste streams. On-site destruction is more cost-effective given expected quantities of affected materials and the distance to suitable disposal facilities. Furthermore, certain jurisdictions (e.g. Australia) restrict or prohibit cross-border transport of PFAS waste. AECOM saw wide application for its new PFAS destruction process for its clients, many of whom are government entities and include wastewater treatment facilities.

Figure 11: DE-FLUORO Development Partners



Source: Authors adapted from AECOM, "AECOM'S Promising New PFAS Treatment Technology DE-FLUORO™ Shows Complete Destruction of PFAS"

Bringing technology to market

AECOM and UGA have actively engaged and partnered with federal and state agencies and other industry leaders to work towards commercial deployment of their combined technologies, in order to protect human health and limit human exposure to potentially harmful levels of PFAS in the environment.

AECOM recently completed a robust demonstration project to treat eight real-world PFAS-impacted liquids. The treatment is compact, highly efficient, cost-effective and mobile. AECOM executed a three-month trial at its laboratory facility in Australia, testing PFAS-impacted wastes from participating client sites. The trials used two models of its compact, bench-scale EO reactor. Full-scale on-site reactors will include smaller, mobile skid-mounted units as well as larger, semi-permanent pad-mounted facilities. Globally, the team is also pilot-testing the technology at multiple US Department of Defense sites under grants awarded by the Strategic Environmental Research and Development Program and the US Air Force Broad Agency Announcements project. Using these sponsored efforts to continue developing the technology, AECOM and its partners will soon be able to bring this technology to market.

3. Data analytics for prioritizing and optimizing decision-making

Data analytics for planning: Indian power generation and the transmission planning model

Context and background

The integration of renewable energy production and storage systems into the power sector is becoming an increasingly important business imperative for most economies, including India's. This is largely driven by policies created to meet local and international commitments to address the growing threat of climate change.

Renewable energy systems, however, require integration into wider grids that include a mix of generation and distribution facilities located in widely varying proximity to end users. High-potential hydro areas are generally located far away from the load centres, while solar panels may be installed on the rooftop of a customer's home. Coal mines are often in remote locations and the coal requires transportation to a power plant before use. Due to such diversified grid operations, generation and transmission planning models need to evolve. Data analytics plays a big role in planning, modelling and assisting with decision-making in the Indian power sector due to the complex market structure, spatial and temporal uncertainties in demand, the need to integrate new renewable power systems and the changing conduct of market players.

Several key business and operational drivers must be considered when planning a grid for this new energy mix:

- Cost-efficiencies of storage technologies and distributed generation
- Integration of renewable energy sources
- Transmission infrastructure
- Legal and regulatory frameworks
- Market uncertainties

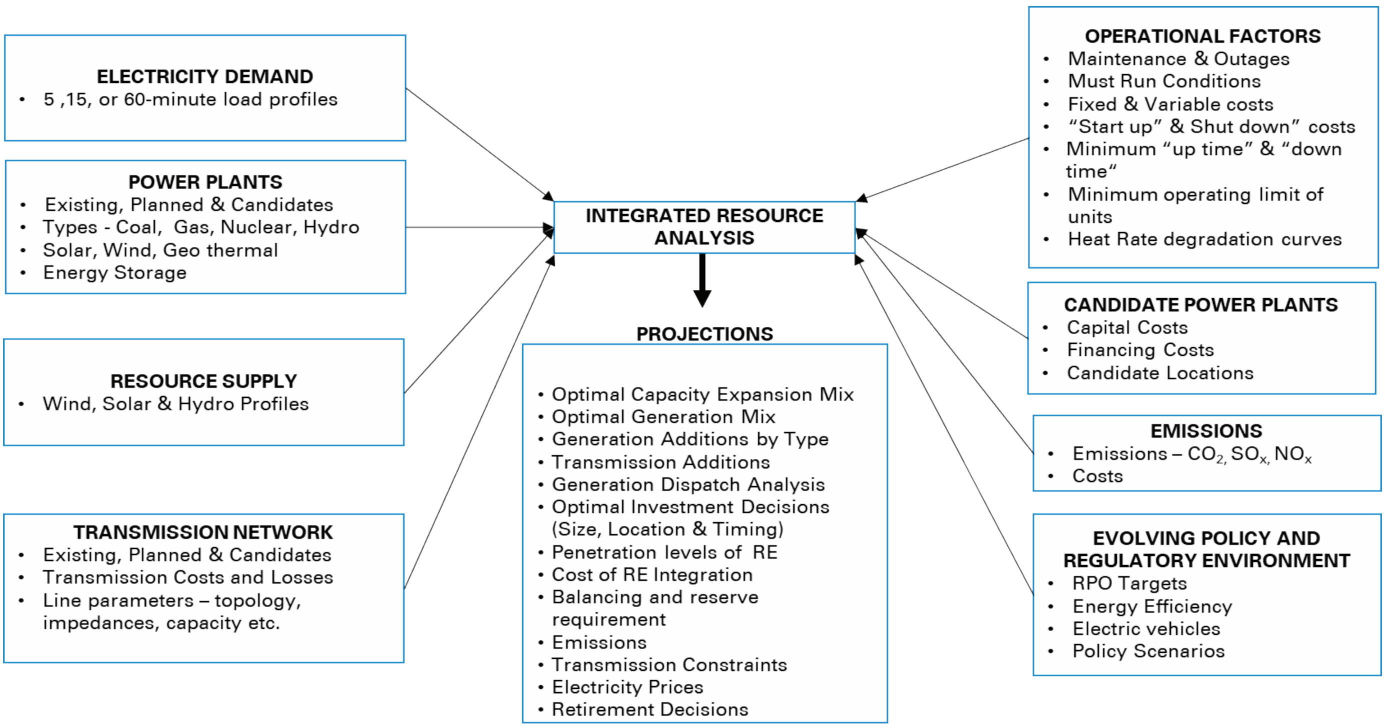
The complexity of assessing these factors in the short and long term requires sophisticated data analytics and optimization techniques.

The solution

Distribution utilities need to acquire adequate generation contracts and attendant transmission systems to reliably serve demand. These utilities must also ensure flexibility in designing the power generation and distribution systems. For solving the long-term investment problem, the planning division must take short-term operational timescale issues into account. A unit commitment model is used to address operational timescale problems and considers technical characteristics of generation units and storage systems as well as transmission constraints. Such a model, when extended to a longer time horizon, provides for long-term generation and transmission planning.

The capacity planning solution (CAPLAN) uses optimization techniques, such as mixed integer linear programming, to arrive at the optimal infrastructure planning scenario. Various considerations go into the planning model and the outcomes from the planning (Figure 12).

Figure 12: CAPLAN planning model



Note: RE = renewable energy; RPO = renewable purchase obligations.
Source: Provided to the World Economic Forum by KPMG

Most of the data required, which needs to be collected and fed into the model, is typically available at state utilities (distribution, transmission and generation). Some input data, if not already available, is added as a one-time exercise (e.g. long-term demand projections).

Results and outcome

The long-term planning model gives the optimal locations for the new transmission lines, generation units and battery storage units along with the optimal timeline for establishing the assets. Moreover, it provides optimal scheduling for generation units. The model also provides a multiparadigm solution for the power sector that is generally absent in current models. The model considered can yield a significant improvement, as the earlier models dealt only with load duration curves. Integration of battery storage and the consideration of installing new generation units are unique to this model.

Optimization models help the planning division to make effective long-term decisions while considering short-term effects. They also help the distribution utilities manage the power shortages in the short and long run. The integration of battery storage in the model is required to provide balancing mechanisms while the system integrates large-scale renewable generation capacity, and thus eases efforts towards environmental protection.

The model's outcome leads to efficient planning for the installation of new transmission, storage and generation assets. The outcome results in significant cost savings for the public and private entities due to the efficiency and effectiveness of the predictive modelling solution. It also provides industries the ability to expand in a more sustainable environment.

Where is it currently?

The CAPLAN model is being developed for the Central Electricity Authority, the preeminent power-sector planning body in India, for:

1. Deciding the right type of generation capacity needed (renewable, storage, etc.)
2. Planning for the right balancing mechanisms required to manage variability in demand and generation
3. Planning for transmission infrastructure

Relevance to other organizations and sectors

Data-driven planning empowers the decision-maker in arriving at an optimal solution while allowing for flexibility in the face of uncertainty. A similar model can be used for investment planning in any networked industry (transportation, supply chain and logistics) and other utility industries, such as water and gas.

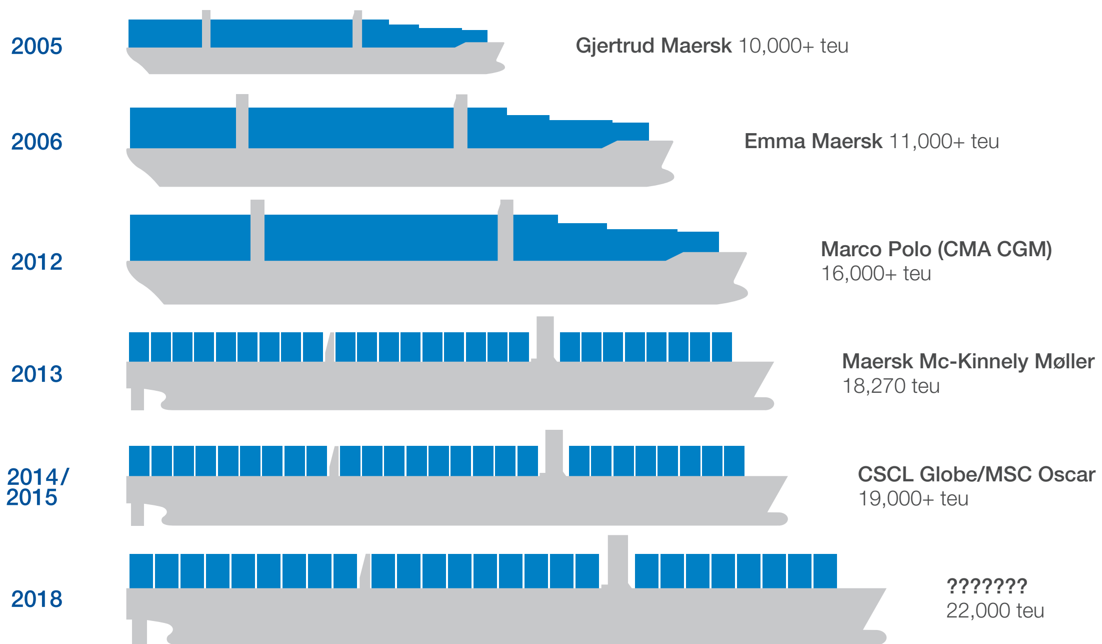
Data analytics for operation: Port of Brisbane's nonlinear channel optimization simulator system

Context and background

The Port of Brisbane (PoB) is one of Australia's fastest-growing container ports, handling about $50 billion in trade annually.[14] Owned by Caisse de dépôt et placement du Québec, IFM Investors, QIC Global Infrastructure and Tawreed Investments, the port is responsible for the sustainable development and maintenance of its 90 km navigation channel connecting the port to the ocean. Driven by a global trend towards larger container ships (Figure 13) pursuing per-unit cost savings, demand for channel capacity is rising. To cater for larger ships, PoB assessed the following options to deepen the channel:

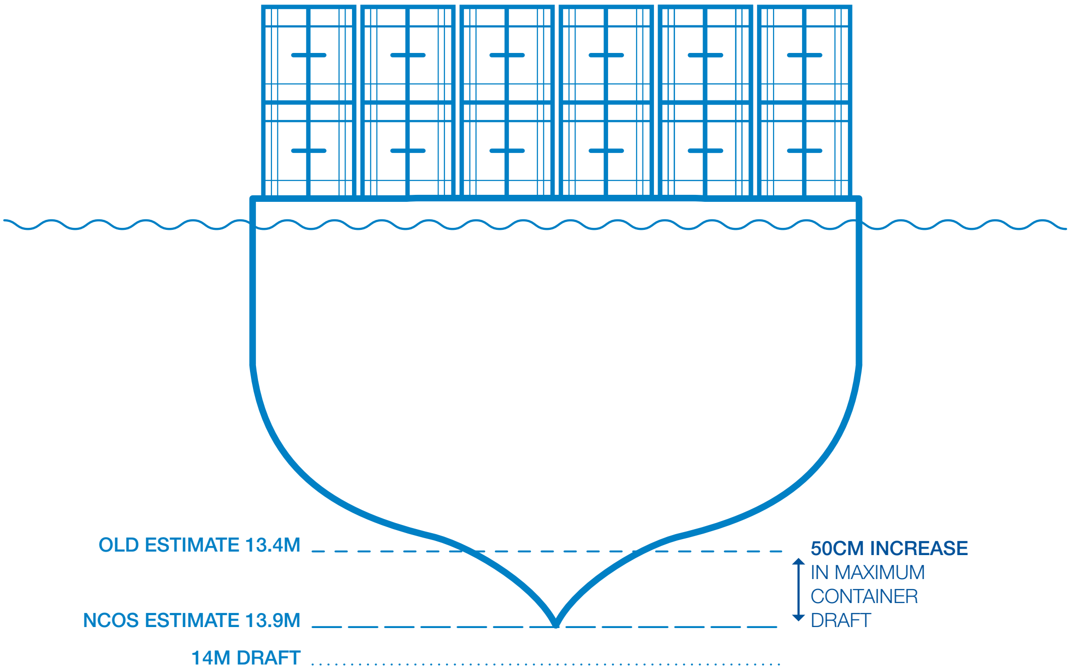
- Traditional dredging (which can be expensive and environmentally sensitive)
- Nonlinear Channel Optimisation Simulator (NICOS) Online: an innovative solution to extract more capacity, operational safety and flexibility without dredging (Figure 14)

Figure 13: Approximate ship capacity data



Note: teu = twenty-foot equivalent unit.
Source: World Shipping Council, "Container Ship Design" (Allianz Global Corporate & Specialty, Approximate ship capacity data: Container-transportation.com), http://www.worldshipping.org/about-the-industry/liner-ships/container-ship-design

Figure 14: Increased channel capacity at Port of Brisbane via data-driven solution



Source: Provided to the World Economic Forum by IFM Investors

The solution: NCOS Online

PoB commissioned DHI Australia, an international software development and engineering consulting firm specializing in hydraulic and hydrological modelling software, to develop NCOS Online, a cloud-based technology solution that incorporates real-time environmental and weather data, vessel specifications and transit information. PoB's navigation channel was used as a "living laboratory" during the product development process that examined how inbound and outbound vessels are subject to significant temporal and spatial variability in tidal levels, currents, waves and winds as they navigate the channel. NCOS Online uses big data to make millions of calculations a second to accurately ensure optimal and safe sailing conditions for larger ships, based on forecast channel depth requirements. This significantly increases operational flexibility and safety for shipping customers and reduces dredging requirements.

Results and outcome

In use at PoB since August 2017, NCOS Online has enabled several improvements in port operations. Channel capacity was increased with no dredging, deferring major capital expenditures and ensuring port access for vessels up to 9,500 twenty-foot equivalent units that visited over the past two years.[15] The loaded draft increased for bulk cargo vessels (i.e. the depth of water a ship can safely travel though when it is carrying goods and passengers, among others, without the ship sinking). NCOS Online continues to provide PoB with ongoing operational benefits, such as optimized dredging costs via deferred major capital works that maximize existing channel capacity; improved risk management through optimized operational safety in navigational channels and at berth; and enhanced decision-making and planning via integrated numerical modelling approaches that facilitate efficient planning of future port expansion activities.

Relevance to other organizations and sectors

NCOS Online has been built in a user-friendly, intuitive web environment and can be deployed at other ports, with technical support from DHI. Ports around the world have forward capital dredging programmes that can cost hundreds of millions of dollars, without the sophisticated tools to optimize their existing channel depths. These costs are ultimately passed on to channel users, increasing supply chain costs. NCOS Online is also a platform that facilitates improved engagement between all key stakeholders (i.e. the port, Harbour Master and shipping customers) in managing supply chain constraints. As a result, port users benefit from more efficient navigation, movement windows and lower costs.

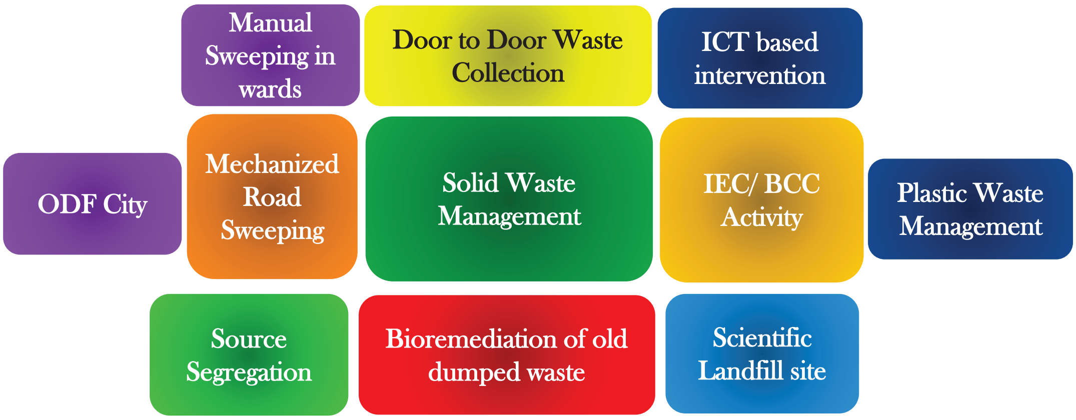
4. Viable commercial models via catalytic policy and regulatory frameworks

Smart(er) city policy frameworks: Indore's successful waste management

Collective efforts for singular results

Indore, the largest city in the Indian state of Madhya Pradesh, transformed its waste management via political will, enthusiastic public participation and hard work by the municipal government (Figure 15). Initiated as a pilot project in 2016, the city's waste management[16] programme was implemented with the help of private partners to make Indore a garbage bin-free city. Citizens segregate their waste and pay a user fee[17] that helps recover operational and maintenance costs for the programme.

Figure 15: Indore – solid waste management components



Source: Indore Municipal Corporation, Swachh Bharat Mission. "India's Cleanest City – Indore", presentation in "Note on Capacity Building Workshop at Indore", 8 June 2017, http://sac.ap.gov.in/sac/UserInterface/Downlaods/compressed_1504666485.pdf

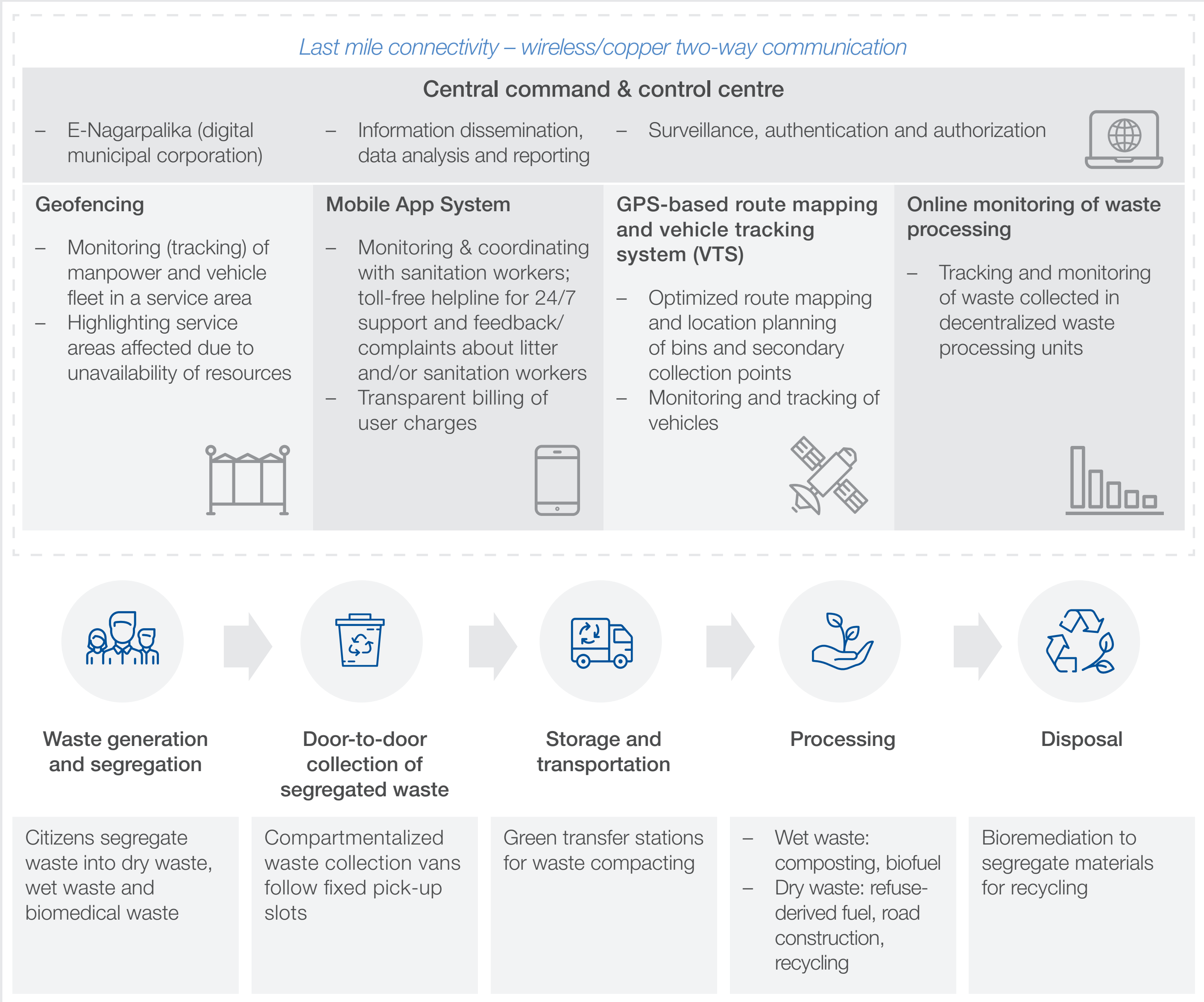
Waste segregation is a crucial initial step in the proper functioning of the programme. The success Indore experienced at this step was largely because of active citizen engagement spurred by innovative educational campaigns and the support of non-governmental organizations. Waste segregation is regularly monitored, and spot fines are imposed for violations and littering. Segregated waste is collected according to a predetermined schedule and transported to green transfer stations, where it is compacted and sent for further processing.

Waste processing is done through a combination of decentralized and centralized solutions. Wet waste is processed to make compost and bio-fuel (which is used to power public transport) using bio-methanation. Dry waste is sent to a material recovery facility for waste sorting and shredding of plastic, followed by palletization or compression. Additionally, reverse vending machines have been set up at roughly 10 public places for the on-site conversion of plastic bottles to flakes. Such plastic is then used for road construction (flexible pavements) or sent to cement plants as refuse-derived fuel and for recycling. Legacy waste at the landfill has been bioremediated[18] to transform the dumpsite into a recreational golf course.

Indore Municipal Corporation also implemented the Indore Intelligent City Management System (IICMS) as part of its smart city initiative. Intelligent solid waste management, a subset of the IICMS, is an ICT-enabled system for planning, managing, monitoring and improving the system's waste management services (Figure 16). The central command and control centre monitors the entire waste management system, acts as a digital municipal corporation and disseminates information, analyses data and does reporting. It also monitors vehicle movement in real time and resolves any concerns. A mobile application connects citizens for data crowdsourcing and transparent billing, and for compiling information on primary and secondary waste collection.

Sanitation workers, known as *safai mitras*, have a biometric attendance system linked to their Aadhaar, a voluntary government ID number. Recently, GPS-enabled wrist watches have been introduced to track efficiency in addition to recording attendance. This is buttressed by geographic information system (GIS)-based asset management, which is designed to manipulate, visualize, capture, analyse and store geographical data, tracking the status of waste bins, vehicles, personnel and more. Waste transportation vehicles are monitored using a GPS-based vehicle tracking system (VTS). At transfer stations, a GPS-enabled camera also monitors vehicle movement. The VTS helps in route planning, route optimization and fleet management, and is also integrated with the weighbridge (scales used to weigh a vehicle and its contents) at processing facilities for monitoring and recording purposes. These efforts by citizens, workers and the government have produced results noticed nationwide. In 2019, the Union Ministry of Housing and Urban Affairs named Indore India's cleanest city for the third consecutive year.[19]

Figure 16: Intelligent solid waste management system – Indore smart city proposal



Source: Authors based on information from Indore Municipal Corporation, “Indore – Smart City”, presentation, http://smartcities.gov.in/upload/uploadfiles/files/Indore_SmartCity.pdf

Support at all levels

Indore's waste management model is supported by the Government of India's flagship initiatives of Smart Cities Mission (for technology integration) and Swachh Bharat Mission (or "Clean India Mission", for waste management and sanitation) (Figure 17). Swachh Bharat Mission promotes basic hygiene and sanitation, an integral component of a smart city. Along with fund allocation, both initiatives set a national-level vision and targets and help plan national transformative projects.

Figure 17: Flagship initiatives for Indore's waste management model

Smart Cities Mission	Swachh Bharat Mission
– Setting national-level vision and targets for transformative urban solutions – Capacity building of implementing agencies to develop innovative solutions for specific context – Adopting technology in infrastructure through sensitizing and involving citizens – Providing financial support for implementing innovative solutions	

Solid waste management rules 2016
– Using regulatory framework for implementing waste management initiatives – Defining roles and responsibilities of different stakeholders – Setting standards and outlining monitoring mechanisms

Source: Authors based on information from Caisse de dépôt et placement du Québec

Both initiatives also focus on citizen participation and behavioural change, thereby enabling technology adoption. Waste management in India (and thus, Indore) comes under the purview of Solid Waste Management (SWM) Rules 2016. These define the roles and responsibilities of different stakeholders, namely for citizens to mandatorily undertake source segregation and for municipal corporations to collect, transport, process and dispose waste. According to SWM Rules 2016, municipal corporations can charge a fee or "user charge" for providing waste management services and can implement a "spot fine" for littering and not segregating waste. The Indore Municipal Corporation uses this fee to ensure financial sustainability of waste management activities and to monitor effective behavioural change.

The Smart Cities Mission and Swachh Bharat Mission complement Indore's inclusive waste management approach while SWM Rules 2016 helps ensure accountability among stakeholders. Moreover, the exuberant pride among citizens helps with keeping the city clean, winning accolades and improving the quality of life, thus setting an example for over 600 municipalities in India.

Proactive government partners: Bangladesh's Solar Home System programme

Context and background

In 2003, Bangladesh was the world's eighth-most-populous country, with nearly 134 million people and growing. The gross domestic product (GDP) growth rate of 4.7% lagged behind that of its regional neighbours, with India and China growing at 7.9% and 10%, respectively.[20] The previous year, Bangladesh had ranked 138th on the Human Development Index, barely escaping the lowest tier.[21] Economic growth was badly needed to improve the standard of living. A major hindrance to growing the Bangladeshi economy, however, was the lack of reliable electricity supply. Even in urban areas, only 79.7% of residents had access to electricity. In rural areas, this number fell to 26.7%, a particularly large hurdle with nearly three-quarters of the population residing in rural areas.[22]

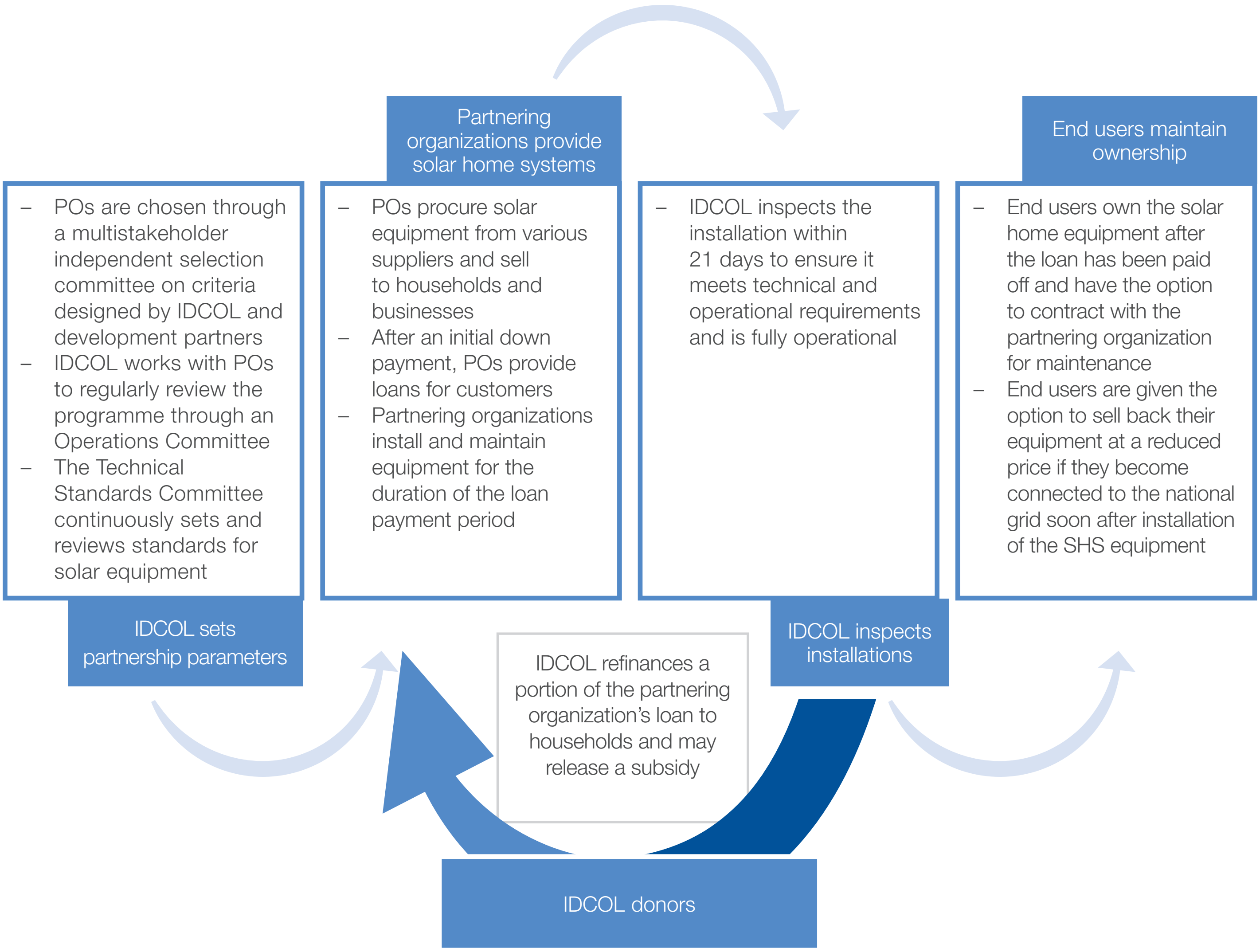
It had become increasingly clear that relying solely on the expansion of the current electric grid would not be sufficient if Bangladesh were to provide power to all its citizens. The Government of Bangladesh, declaring in its 2002 National Energy Policy a commitment to "bring the entire country under electrification by the year 2020", created the Solar Home System (SHS) programme to build a distributed solar energy grid for bringing cost-effective and reliable energy to communities across rural Bangladesh.

Solar Home System and the Infrastructure Development Company Ltd

In 2003, the Infrastructure Development Company Ltd (IDCOL), with assistance from the World Bank, launched the Solar Home System programme. IDCOL was established in 1997 by the Government of Bangladesh as a non-bank financial institution focused on bridging the financing gap for developing medium- to large-scale infrastructure and renewable energy projects in Bangladesh. While the Ministry of Finance owns IDCOL, it is managed by an eight-member independent Board of Directors with representation from both the public and private sectors.

IDCOL's strategy is to provide a combination of loans and grants to partner organizations (POs) that include development partners, solar home system suppliers and microfinancing institutions (MFIs). Those partner organizations then pass along the financing means to the end users and collect the loan in instalments. They also install, maintain and educate end users on the solar equipment. The inclusion of MFIs was particularly important as they have deep networks and strong, trusted relationships in Bangladesh. In addition, IDCOL's willingness to work with organizations of all sizes meant the initiative could penetrate deeply (Figure 18).

Figure 18: Solar Home System programme model



Source: Authors based on information from Meyer, T.-P., "Solar Home Systems in Bangladesh", Global Delivery Initiative, 2015, German Development Cooperation: KfW., http://www.globaldeliveryinitiative.org/library/case-studies/solar-home-systems-bangladesh

The POs procure the solar home systems from various suppliers and sell them to households and small businesses on microcredit terms. For households, this includes a down payment of 10-15% and 2-3 years of payments at market interest rates (generally between 12% and 15%). After the POs install the products, IDCOL verifies the installation – initially on all installations, now on a sample basis – within 21 days based on specifications and certifications prepared by IDCOL's Technical Standards Committee. Following verification, 60-80% of the credit extended by the PO to households is eligible for refinancing at a 6-8% prevailing market rate with a 5-7 year repayment period.[23] Subsidies were originally included to make units more affordable, but they have mostly been eliminated as economies of scale and technological improvements reduced the price of solar panels and rural income increased over time.[24]

The monetary incentives, namely subsidies and financial instruments, were meant to keep the price of using solar equipment at or below the price of kerosene, the fuel of choice for many of those disconnected from the electric grid. The technical requirements ensured proper functionality and built trust with end users that reduced the perception of risk on what was seen as relatively new technology.

Systems came in different sizes based on customers' willingness to pay, and offerings have increased as technology has changed. After the loan is repaid, the end user becomes the owner of the solar home system and the POs continue to provide maintenance and service. A buy-back guarantee allows end users to return the systems for a depreciated price if their homes become connected to the electric grid within a year of purchase, but many customers choose to continue using solar panels as they are often more reliable than the grid.

A rural power revolution

The programme is widely regarded as a success. In 2003, the year the SHS programme launched, about 12,000 solar home systems had been installed around the country. IDCOL set a goal to install 50,000 systems by 2008, a target achieved three years ahead of schedule while spending $2 million less than anticipated. By 2011, 1 million systems had been installed, and by April 2014, 3 million (representing 130 megawatts of renewable energy serving 15 million people).[25] IDCOL set of a target of 6 million for 2017. By mid-2014, the SHS was providing electricity to 50,000 new households every month.

The effects have been felt across Bangladeshi society. Nearly all components of the solar home systems are made in Bangladesh, supporting 114,000 jobs as of 2013 (the sixth-largest renewable energy-related workforce in the world, according to the International Renewable Energy Agency). Savings from using the system led to increased spending on food and other household goods, increased evening study hours for children and decreased respiratory disease in women by 1.2%, while increasing their mobility and entrepreneurship opportunities.[26]

The programme has been an important factor in increasing rural electrification, which jumped from 26.7% in 2003 to 81.3% in 2017, and a likely factor in increasing annual GDP growth for Bangladesh from 4.7% in 2003 to 7.9% in 2018.[27]

Conclusion

While this effort has been judged a success, factors specific to Bangladesh help make it efficacious. The country is densely populated, with 1,240 people per km^2 as opposed to 148 people per km^2 in China and 36 per km^2 in the United States. This improved the ability to create economies of scale, while rising incomes made solar equipment more affordable. Additionally, Bangladesh has a highly developed system of microfinance institutions that could act as partnering organizations.

The key to this programme's success, however, was effective policy and regulation by a government entity, in this case IDCOL. Early during the push to expand disaggregated solar power access in Bangladesh, finding partners who were willing to extend debt was difficult as they feared becoming entangled in "nonproductive loans". The alternative funding source offered by IDCOL was crucial to reassuring skittish partners.

Additionally, the capacity building efforts and technical support increased public trust in the project and thus facilitated adoption. Because IDCOL proved itself to be a willing and reliable partner, it has since been able to secure support beyond its initial partnership with the World Bank to include the Global Partnership for Output-Based Aid, Asian Development Bank, Islamic Development Bank, Japan International Cooperation Agency, KfW, GIZ and USAID. IDCOL's cooperative model allowed the SHS programme to scale, providing millions with power, creating a new domestic renewable energy industry and raising the standard of living for rural Bangladeshis, all while protecting the environment.

Conclusion

The challenges of bringing the Fourth Industrial Revolution to infrastructure and precipitating infrastructure's industry transformation can seem daunting. These challenges are felt both by those endeavouring to finance, plan, design, build, operate and maintain infrastructure, as well as by the end users who depend on high-quality infrastructure for their prosperity and well-being. As this guidebook has striven to demonstrate, however, exciting solutions exist that can change how the infrastructure that underpins global society is built. The four questions asked in this guidebook, the frameworks presented in each and the case studies that conclude this paper are not meant to be the definitive guide to solving infrastructure's innovation gap. Silver bullets rarely exist for issues that affect society in such a fundamental way.

This guidebook and the case studies are meant to help frame the conversation and spark a broader discussion on how to transform infrastructure. By moving the conversation beyond individual technologies, and by exploring systemic strategies and implications for enabling innovation and adoption of new technologies in infrastructure, the Global Future Council on Infrastructure hopes that this guidebook can support decision-makers as they look to successfully navigate the world in the Fourth Industrial Revolution.

The Council, as well as the World Economic Forum Platform for Shaping the Future of Cities, Infrastructure and Urban Services, will continue to explore these topics, highlighting more of the frameworks and case studies that can both spur innovation in the space and accelerate the adoption of existing, exciting technologies. Sustained multistakeholder partnership is crucial for advancing the technological transformation of infrastructure, ensuring that the Fourth Industrial Revolution's benefits in life are as ubiquitous as the infrastructure people use every day.

Contributors

Global Future Council on Infrastructure

Council Co-Chairs

Rashad Kaldany, Partner; Chief Investment Officer, BlueOrange Capital, USA

Anita Marangoly George, Executive Vice-President, Growth Markets, Caisse de dépôt et placement du Québec, Canada

Council Members

Sujoy Bose, Managing Director and Chief Executive Officer, National Investment and Infrastructure Fund (NIIF), India

Sylvia Coutinho, Chairman, UBS, Brazil

Clemente del Valle, Director, Center for Financial Markets and Sustainable Infrastructure, Universidad de los Andes, Colombia

Alain Ebobisse, Chief Executive Officer, Africa50, Morocco

Fu Jun, Academic Dean and Professor, Institute of South-South Cooperation and Development, Peking University, People's Republic of China

Pierre Guislain, Vice-President, Private Sector, Infrastructure and Industrialization, African Development Bank Group (AfDB), Abidjan

Vicky Kefalas, Head, Investments and Development Projects Group, Strategic Planning and Investments, Consolidated Contractors Company (CCC), Greece

Mounia Khelifi Touhami, Senior Adviser, Infrastructure and Real Assets, Boston Consulting Group, USA

Leslie Warren Maasdorp, Vice-President; Chief Financial Officer, New Development Bank, People's Republic of China

Saadia Madsbjerg, Managing Director, Rockefeller Foundation, USA

Jean-Patrick Marquet, Core Expert, Working Group on Sustainable Development Goal Compliance, United Nations Economic Commission for Europe (UNECE), Geneva

Joel Moser, Professor of International and Public Affairs, Columbia University, USA

Nadia Musallam, Assistant Undersecretary for Support Services, Ministry of Infrastructure Development, United Arab Emirates

Emmanuelle Nasse Bridier, Independent Adviser, France

Paul Newfield, Chief Investment Officer, H.R.L. Morrison & Co, New Zealand

Lara Poloni, Chief Executive, Europe, Middle East, India and Africa, AECOM, USA

Annalisa Prizzon, Senior Research Fellow, Overseas Development Institute, United Kingdom

Jordan Schwartz, Director, Infrastructure Finance, PPPs and Guarantees, World Bank, Washington DC

Keisuke Sakamoto, Director, Public-Private Partnership/ Private Finance Initiative (PPP/PFI) Promotion Office, Cabinet Office of Japan, Japan

Richard Threlfall, Global Head, Infrastructure, KPMG, Netherlands

Council Fellow

Clemens Kielhauser, Postdoctoral Researcher; Lecturer, Infrastructure Management, ETH Zurich, Switzerland

World Economic Forum

Council Manager

Joseph Losavio, Specialist, Cities, Infrastructure and Urban Services

Other contributors

Adrian Box, Partner, Infrastructure and Projects Group, KPMG

Ralph Brayham, Head, InfraTech, H.R.L. Morrison & Co

JoAnna Esty, Senior Vice-President, Strategy, AECOM

Kavisha Khandelwal, Consultant, Caisse de dépôt et placement du Québec

Salar Shemirani, Manager, Global Infrastructure, KPMG

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744

contact@weforum.org
www.weforum.org