**The Role of Utilities in Developing Low Carbon, Electric Megacities**

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**Abstract**

The development of electric cities, with low carbon power supply, is a key strategy for reducing global greenhouse gas emissions. Here we analyze the role of electric utilities, who are important actors in catalyzing the transition to electric cites, drawing upon data for the world’s 27 megacities. Progress towards the ideal electric city is most advanced for Paris, Rio de Janeiro, Sao Paulo and Buenos Aires with respect to low carbon electricity; while Indian megacities have relatively high use of electricity as a percentage of total energy use. There is wide variety in the structure of markets for electricity provision in megacities, with a dominant, public utility being the most common model. We review literature on electricity sector business models and broadly propose future models dependent on the predominance of locally dispersed generation and the nature of the ownership of the electric grid within the city. Where a high proportion of electricity can be provided by locally distributed supply within a city, the role of utilities could predominantly become that of enabler of exchange with the grid, but new pricing structures are required. A further challenge for utilities in enabling the electric city is to provide a higher level of resilience to events that disrupt power supply.

**1.0 Introduction**

The development of *electric cities* using low carbon power is a key strategy for addressing the challenges of global climate change. Low carbon electrification entails replacing fossil-fuel powered engines and furnaces, etc., with electric devices such as electric vehicles and heat pumps powered from renewable resources. Electrification is central to many national visions for deep decarbonisation (Sustainable Development Solutions Network, 2014) and is seen as critical to avoiding average temperature rises in excess of 2 degrees Celsius (IEA, 2014; Kennedy and Corfee-Morlot, 2013) The potential to decarbonize high proportions (>60 to 80%) of the electric grid has been recognized, notably in China (ERI, 2015) and the United States (NREL, 2012). As centres of wealth, providing political and strategic leadership in reducing greenhouse gas (GHG) emissions, cities will be at the forefront of widespread electrification, with the electric utilities serving cities being key actors.

The combination of electric cities with decarbonized electricity can also more broadly promote green growth. Although energy conservation and efficiency measures should be encouraged, it is likely that cities, particularly those undergoing development, will consume higher quantities of electricity. There are strong links between urban economic growth and increasing per capita use of electricity (Liddle & Lung, Kennedy et al. 2015). Electrification combined with decarbonisation can be the central mechanisms for green growth in cities. Together they can achieve the goals of creating green jobs, healthy urban environments and prosperity, while decoupling economic growth from global environmental stresses (Hammer et al., 2011).

The vision of electric cities powered by low carbon electricity is a variant of the concept of *solar cities* (Winter, 1993; Beatley, 2007; Byrne et al., 2015), which are a form of eco-city or sustainable city. Winter (1993) wrestles with the question of how cities might develop under a second solar civilization, when solar energy (including wind, hydro) has again become the main source of energy supply for societies. He defines the solar city as “*an energetically self-contained settlement with solar irradiance as its main energy source and with no more than remainders of fossil or nuclear energy available as short-term alternatives.*” In such a city, solar energy would supply all of the heating and cooling needs of buildings, as well as transportation, industry, and all other energy requirements. Winter determined that 100% solar cities were not feasible with energy demand levels of the 1990s, and that power requirements would have to drop to 2 kW per capita. Encouraged by falling prices and increased efficiencies of PV cells, recent studies have quantified the rooftop PV potential for entire cities; estimates of the percentage of current electricity demands that could be met by rooftop PV within cities are, for example: New York City: 23%; San Francisco: 7.5%; Hong Kong: 14%; Turin 8%; and Seoul: ~30% (Bryne et al., 2015). These proportions can potentially alter with changes in demand and increases in the efficiency of PV. Solar energy can, of course, also be imported into cities. Indeed, the business models required for electric utilities to develop low carbon electric cities may change depending on the magnitudes of imported versus internally generated power, as we discuss later.

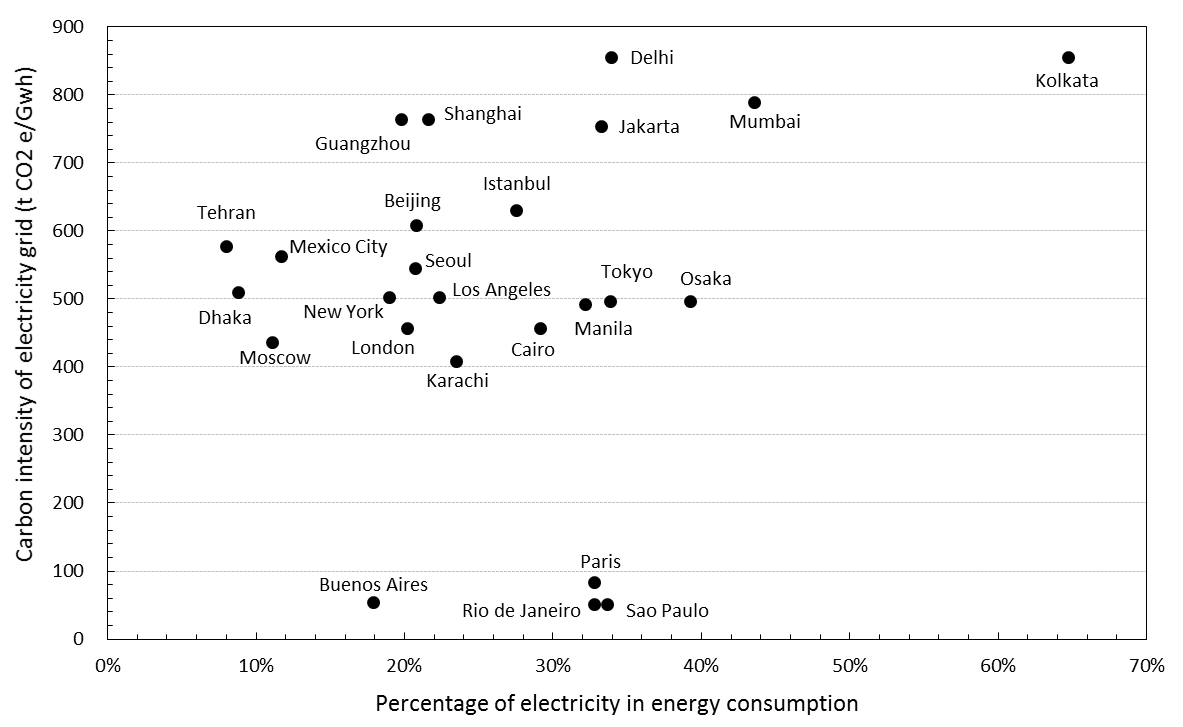
In this paper we examine the role of electric utilities in enabling a transition to electric cities with an emphasis on megacities. This is part of an overall project concerned with the sustainable development of the world’s megacities, i.e., metropolitan regions with over 10 million population. Our previous work has included review of the urban metabolism of megacities (Stewart et al. 214), study of the urban metabolism of the world’s 27 megacities as of 2010 (Kennedy et al. 2014a, 2015); and identification of the electric city as a key strategy for sustainable urban development (Stewart et al., 2015).

As the providers of electricity in cities, electric utilities clearly have an important role in the transition to electric cities. This transformative role is challenging, however, for several reasons. First, because decarbonisation involves technological change, with substantial amounts of distributed generation in many cases, then new business models may be necessary for the generation, distribution and co-ordination of electricity. Second, climate change is already occurring – and this puts additional pressures on utilities to provide reliable electricity services. If electricity is to provide an increasingly large share of the energy needs of a city, as is inherent with the electric city model, then this heightens the need to increase the resilience of electricity provision. We begin by assessing the status of megacities towards the goal on low-carbon electric cities, and describe the current market structure of electric utilities in megacities. Possible future models and the technological challenges of creating more resilient grids are then discussed.

**2.0 The Challenge for Megacities**

The challenge faced by the world’s megacities in developing as low carbon, electric cities is depicted by the scatter plot in Figure 1. The direction of sustainability shown by the arrow is towards a city with a high percentage of its energy needs being met by electricity with a low carbon intensity of supply. The ideal position is at the bottom-right corner of the figure, close to 100% energy supply from electricity and zero tonnes of CO2 emitted per Gigawatt-hour of electricity supplied (0 tCO2/GWh). A 100% reliance on energy from electricity need not be achieved if non-fossil fuel sources are used for other forms of energy use, e.g., solar or biomass heating. Having some sources of energy that are not electric might actually improve the resilience of the city, as discussed later. The megacities need to go through differing degrees of transformational change to become low carbon electric city as described here.

A group of three megacities: Paris, Rio de Janeiro and Sao Paulo stands apart from the other megacities as being closest to the ideal position at the bottom-right corner of the figure. These three megacities source approximately one-third of their energy use from low carbon electricity. Paris’ supply is primarily from nuclear power, while power in Rio and Sao Paulo is predominantly from hydropower. Buenos Aires has a similar level of carbon intensity for its electricity supply, but has a lower percentage of electricity in energy supply. Its higher percentage use of other energy sources in comparison to Rio and Sao Paulo can be explained in part by its colder climate. Buenos Aires uses relatively more of its energy for heating and industrial processes and has more heating-degree days (see Figure S4 in Kennedy et al. 2015).



**Figure 1:** Comparative status of global megacities with respect to electrification and decarbonisation.

The Indian megacities of Kolkata and Mumbai have the highest percentage use of electricity in their energy use. These cities are actually amongst the lowest in terms of absolute energy requirements, due to their high population densities and warm climates. They have very low levels of heating and industrial fuel use and relatively low levels of transportation energy use; hence electricity dominates. Both megacities, however, have highly carbon intensive electricity supplies, dominated by coal power. Kolkata and Mumbai - and to a lesser extent Delhi and Jakarta – are well progressed towards the status of electric cities, but need to decarbonize.

Amongst the wealthier megacities, Osaka (39%) and Tokyo (34%) have the highest levels of electricity use as a percentage of total energy use. (Paris, discussed above is at 33%). The Japanese megacities are thus closer to the model of electric cities than other wealthy megacities of London, New York, LA, Moscow and Seoul. All of these wealthier megacities (aside from Paris) have electricity supplies of mid-range carbon intensity (of the order 500 tCO2/GWh). Most of these wealthy megacities need higher rates of electrification and decarbonisation.

The megacities that are furthest from the ideal state of low-carbon electric cities are Shanghai, Guangzhou, Tehran, Mexico City and Dhaka. The first two use electricity to meet only around 20% of their needs and are serviced with electricity of a high carbon intensity – predominantly from coal. Tehran, Mexico City and Dhaka do at least have carbon intensities below the approximate threshold of 600 tCO2/GWh, at which electrification generally begins to reduce life-cycle GHG emissions compared to fossil fuel alternatives (Kennedy 2015; Kennedy et al. 2014b). The percentage of electricity use in these three cities is, however, particularly low at less than 12%. Clearly these five megacities - indeed most of the megacities - lie very far from the ideal low carbon electric city.

**3.0 Market Structure in Megacities**

In our study of the metabolism of megacities (Kennedy et al. 2014) we also collected information on the structure of electrical utilities, including details on the numbers of distributors and generators, and types of ownership. Technically the results shown in Table 1 are for the geographical study areas for which urban metabolism data was collected, as described in the Supplementary Information to Kennedy et al. (2015). The most commonly observed structure was that with one or two power suppliers and one or two distributors (Table 1 a). This occurs with nine of the twenty-two megacities for which we were able to collect information. For some of these nine, there may just be a single vertically integrated company providing both power supply and distribution. The other thirteen megacities are served by multiple distributors (e.g., Istanbul, London, Moscow, Guangzhou and Shanghai) or multiple power generators (e.g., Sao Paulo, Delhi, and Shenzhen) or multiple of both (e.g., Mumbai, Buenos Aires, Los Angeles and Cairo). The existence of multiple distributors or power suppliers in a megacity may be a result of efforts to introduce market competition or simply be reflective of the sheer size of megacities, which often cross over multiple jurisdictional boundaries.

More information on the nature of competition in megacities is given by the data on ownership (Table 1b). The most common ownership model, occurring in eleven megacities, has complete public ownership of both power generation and distribution. In seven of these cases: Paris, Mexico City, Tehran, Jakarta, Dhaka, Seoul and Beijing, there are also just one or two companies involved with generation and distribution. Conversely, in London and Sao Paulo, both power generation and distribution are fully under private ownership. The market structure, however, is different in these two megacities. London has over 5 suppliers with 1-2 distributors, while Sao Paulo has 1-2 suppliers with 3-5 distributors. There are no cases where generation is fully privately owned and distribution fully public, nor vice versa. There are several megacities, however, where a mix of public and private companies participate in power generation and/or distribution; these are Delhi, Shenzhen, Istanbul, Los Angeles, Mumbai, Karachi, Rio, Buenos Aires. Overall, Table 1 a) and b) reveals that while a dominant, public utility is the most common model, there is wide variety in the structure of markets for electricity provision in megacities.

|  |  |  |  |
| --- | --- | --- | --- |
| # of suppliers | # of distributors | | |
| 1 - 2 | 3 – 5 | > 5 |
| 1 – 2 | Paris  Mexico City  Rio  Tehran  Jakarta  Karachi  Dhaka  Seoul  Beijing | Sao Paulo  Delhi | Shenzhen |
| 3- 5 | Istanbul | Mumbai |  |
| > 5 | London  Moscow  Guangzhou  Shanghai | Buenos Aires | Los Angeles  Cairo (?) |

Table 1 a) Structure of electrical utilities in megacities: number of companies providing electricity distribution and number of power generators (excluding New York, Tokyo, Osaka, Lagos, and Kolkata)

|  |  |  |  |
| --- | --- | --- | --- |
| Ownership of suppliers | Ownership of distributors | | |
| Public | Mixed | Private |
| Public | Paris  Moscow  Mexico City  Cairo  Tehran  Jakarta  Dhaka  Seoul  Guangzhou  Shanghai  Beijing | Delhi  Shenzhen |  |
| Mixed | Istanbul | Los Angeles  Mumbai  Karachi | Rio  Buenos Aires |
| Private |  |  | London  Sao Paulo |

Table 1 b) Structure of electrical utilities in megacities: public and private ownership of electricity distribution and generation.

**4.0 Review of the Electricity Sector Business Model**

In order for megacities to transition towards low carbon, electric cities, it may in some cases be necessary to consider alternative forms of business models for the electricity sector. Before broadly sketching out what these possible new business models might resemble, we consider why they may be needed. In recent years, several observers, as well as the industry itself, have called for new business models in the electricity sector so as to enable new technologies (for example: Fox-Penner, 2010; Tomain, 2011; Edison Elec. Institute, 2013). Here we review studies by Sioshansi (2012) and Boyd (2014) that have examined the reasons why new business models may be required.

Sioshansi (2012) provides several reasons for rethinking electricity sector business models, amongst which he considers declining growth to be particularly compelling. Writing in a U.S. context, but with arguments generally applicable to mature OECD economies, he argues that the historical growth-driven business model cannot be sustained as economies become less-energy intensive. Data from the US Energy Information Administration shows that annual electricity demand in the United States grew at just 1% over the first decade of this century, compared to 7 to 10% in the 1950s and 60s, and is projected to decline to 0.7% per year. This projection is for business-as-usual conditions, and may already be overly high. With aging population, changing lifestyles (including a possible shrinking of average house sizes), and higher energy efficiency standards for buildings and appliances, growth in electricity demand might be further reduced or eliminated altogether. Adding in policies that promote distributed generation from renewables with net metering schemes that generally undermine the existing business model, Sioshansi concludes it is time to rethink the model.

Boyd (2014) conducts an extensive review of the evolution of public utility companies (PUCs) in the United States, and also argues that there needs to be a revision to the business model in order to develop a low-carbon electricity sector in the USA. He sees value in the initial conception of PUCs, but describes how the business model for PUCs has for various reasons become narrower than its original design. Boyd defines the original, broader, concept of PUCs as follows:

*“… public utility is first and foremost a normative effort directed at ensuring that the governance of essential network industries, such as electric power, proceeds in a manner that protects the public from the abuses of market power by providing stable, reliable, and universal service at just and reasonable rates. Public utility, in this broader sense, is not a thing or type of entity but an understanding - a collective project aimed at harnessing the power of private enterprise and directing it towards pubic ends.”*

Boyd suggests that the regulated investor-owned utilities, which serve 70 percent of the US population, are a narrow version of the PUC, now largely seen as an “obstacle to be overcome” in finding innovative ways to decarbonize. Boyd (2015) does, however, recognize the pluralistic nature of the current electricity market in the United States. Although dominated by large vertically integrated PUCs, there are also rural cooperatives and municipally owned utilities. There are significant differences in how electricity markets are regulated between states, for example with respect to the degree of market competition, the structure of investor owned utilities and the role of independent systems operators. Progress in working towards provision of low carbon electricity differs both between states and between utilities working within the same states. (see for example the performance of different utilities serving Los Angeles (Pincetl and Shumavon, 2015).

The principle reasons that PUCs need reform, according to Boyd, are due the requirements for capital investment and co-ordination. The huge scope of the planning and finance required to modernize the U.S. power grid and build low carbon generation requires a level of certainty that markets alone cannot provide. Moreover, the design and operation of a system that must provide reliable service from highly intermittent renewable generation needs a degree of administration and oversight beyond the capabilities of the current systems operation. There is need for public-private co-operation for policy innovation and commercial-scale demonstration of new technologies, such as storage, smart-grid deployment and integration of electric vehicles.

Boyd warns, however, against approaches that take too much of a revolutionary view to reform of the electricity market. He writes (Boyd, 2014, p.1681):

“*In the specific case of electricity, the rhetoric of disruption ignores the possibility of any sort of positive reform agenda attached to the notion of broader public utility. By emphasizing radical change rather than pragmatic adjustment of existing institutions, it constrains our ability to think about electricity (and energy) as a collective, social enterprise precisely at the time when we are becoming more active participants in that enterprise*.”

**5.0 Possible Future Business Models**

In examining the role of utilities in developing future electric cities we can entertain a range of different possible business models. As discussed above, a variety of market structures – and hence business models – already exist in megacities. Here we make an ambitious attempt to describe three extreme types of broad business models that possibly could emerge in some cities, depending very much upon technological and socio-political developments, as well geographical location. The business models are developed along two axes. The first considers the possibility that technology for micro scale electricity, generation especially from solar photovoltaic continues to develop such that under certain specific conditions, e.g., high solar potential and low spatial intensity of demand, a large proportion of urban electricity is generated in a dispersed fashion within the city. The axis considers the case where electricity generation and storage is predominantly locally dispersed, and the case where electricity is primarily imported from low carbon sources outside of the city. The second axis is concerned with the nature of the ownership of the electric grid within the city (including the possibilities of the there being multiple grids, or no grids). The ends of this axis are cases where grid ownership is either highly centralized (regardless of public or private ownership) or highly dispersed. The three extreme business models (#s II to IV) are shown in Figure 2, along with an existing “Dominant” model (#I) which already currently exists in some megacities.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | **Control of Network** | |
|  |  | Centralized | Dispersed |
| **Power Generation**  **& Storage** | Centralized | 1. Dominant | 1. Competitor |
| Dispersed | 1. Enabler | 1. Technology Provider |

**Figure 2.** Mapping of potential electricity sector business models in terms of network control and ownership of power generation and storage

The “Dominant” business model shown in Figure 2 exists when the city is unable to generate all of the electricity it requires from local sources, and a single company imports low carbon electricity and distributes it on the grid. The company could be either public or private; it could also be vertically integrated and have ownership of renewable electricity generating assets outside of the city; these are just variations on the model. A key characteristic is that the company owns and/or controls the electricity grid, likely subject to regulatory oversight in some cases. Under this business model, it may be possible for a small percentage of electricity to be generated from dispersed sources in the city, and even perhaps some storage – but this generally cuts against the business model. The dominant utility model provides efficiency through economies of scale.

The second business model is also one in which low carbon electricity is primarily generated from sources outside of the city, but is distributed by competing utilities within the city. There are already examples of megacities with multiple distributers providing electrical services within cities (Table 1a), although these might essentially be quasi-monopolists that provide service to different geographically defined areas of a megacity. There might be more competitive versions of the second model, for example, with utilities bidding for time-bound leases to operate and maintain different segments of the grid. A more extreme version of model II, might see the existence of two or more electricity service providers competing in the same geographical location. This would be somewhat similar to the way in which phone and cable companies provide competitive internet services in cities. A possible example might be the co-existence of DC micro-grids and regional AC networks servicing the same area - a replay of the old completion between Thomas Edison and Nikola Tesla.

Model III is a business model that might evolve in future cities where a large proportion of electricity supply is generated locally by photovoltaic (PV) cells, biomass cogeneration or other distributed means within a city. This model might seem technologically infeasible in many of today’s cities, especially those of high population density. With, however, continued decline in the cost of PV cells and electric batteries – and the existence of feed-in-tariffs in many jurisdictions, this model may become viable in some lower density locations. Progression in the development of net zero or near net zero buildings (Athienitis & O'Brien 2015) encouraged by policies in areas such as California and European Union, could result in entire neighbourhoods of new residential buildings and low-rise commercial buildings, for example, contributing electricity to the grid in large quantities during daylight hours. Existing residential and commercial buildings can also contribute substantial quantities of power, while dense city cores, areas of high rise buildings and heavy industrial users will contribute relatively little compared to their demands. Battery storage, whether in stationary form or in the form of electric vehicles is particularly important. Appropriately managed, electrical storage can smooth out problems with the intermittency of distributed generation exchanged with the grid, allowing a high percentage of electric use in cities to come from such local sources.

With such a shift in the dominant sources of power generation for cities, the role of the utility increasingly becomes that of an enabler of exchange with the grid, while continuing a secondary role as an importer of externally generated power, whether generated by the utility or another entity. Under this business model the utility provides service by building, maintaining and operating the city’s electric grid in the most efficient manner.

While progress towards model III has been encouraged by the development of feed-in-tariffs, such tariffs will need to be reformed in order for the business model to be fully realized. Feed-in-tariffs are relatively prevalent in megacities. Out of the 27 megacities, only five did not have feed-in-tariffs at the time of our metabolism survey; these five were: Moscow, Mexico City, Buenos Aires, Tehran, and Dhaka. Feed-in-tariffs, however, have generally been developed so as to encourage investment in small distributed generation while not necessarily recognizing the costs of maintaining the grid. Model III is financially intractable if the majority of power generation is provided by small-scale distributed generators who receive greater financial rewards for their generated power, than their costs in purchasing power. For model III to work, all power generators need to pay a sufficient charge to the utility for maintaining and operating the grid, while still receiving sufficient financial reward for providing power to the grid relative to purchasing power.

Model IV, under which both power generation and grid control are highly distributed seems unlikely at the current time although at least one study shows potential for such a model in the future. In its simplest form this business model is one in which there is no grid. The combination of PV cells and storage batteries does make it technically feasible for large swaths of low density developments in some climates to be independent of the grid, but this is not feasible in dense city neighborhoods. Alternatively there could be a variant of model IV which is based around numerous community-scale micro grids within a city – although economies of scale may tend to work against such organization.

To examine the potential for grid-defection, Khalilpour & Vassallo (2015) assess the optimal size of PV and batter systems under a variety of scenarios applied to case studies in Australia. They conclude that for households to leave the grid requires relatively large PV and battery systems that are far from economically competitive at the current time. Smaller PV-battery systems have better returns on investment, but do not provide sufficient capacity for grid defection. Their overall advice is that it is more economically beneficial for households to stay grid-connected, exploit feed-in-tariffs and size PV-battery systems to minimize electricity purchases.

The economic case for U.S. customers to defect from the grid using PV-battery systems has been examined by Bronski et al. (2014). These authors determined the year in which off-grid systems might be expected to be price competitive with grid prices under various modelling scenarios in five representative regions of the USA. They found that grid deflection is already competitive in Hawaii, and is expected to become so in New York by 2025; California by 2031; and Texas and Kentucky by 2047.

Model IV- with grid defection is potentially of concern to utilities operating under current business models. The challenge for utilities is that if an increasing number of customers leave the grid, the costs of operating and maintaining the system become shared over a smaller number of customers; this leads to a rise in the price of grid electricity, which makes grid-defection more desirable. Such a spiral of falling sales and rising prices would seriously undermine current business models. Some of the technical skills of current utilities might still be employed in a revised model of “technology providers” – helping households to construct and maintain their off-grid systems. Utilities might also use their combination of technical knowledge and financial capabilities to participate in the business of financing off-grid systems. In either case, reformed utilities acting under model IV would be in competition with existing distributed system installers and conventional banks and financial institutions. If they survived, utilities would be unrecognizable from their current form.

While model IV might be seen as liberating for some individual households, whether it would be broadly socially desirable is questionable. In a sense there is already one megacity – Lagos – that operates a carbon-based version of model IV, with a minority of customers receiving grid electricity, while many residents receive power from distributed off-grid diesel generators.

Having outlined some broad possible business models for electric utilities, it should be noted that realization of these models – or variants or hybrids – is far from easy. The experience of business model innovation in the German electricity sector is instructive. There has been substantial growth on electricity generation from renewables in Germany, but with weak participation from utilities (Richter, 2013). A multi-year study by Knab and Rohrbeck (2014) found relatively slow progress in implementation of new business models. Knab and Rohrbeck worked with eight companies from the energy and ICT sectors to identify 21 potential new business models in the German smart energy sector. For a period of over 3 years (Nov. 2010 to Feb. 2014) they tracked the German energy market for development of smart energy business models. While there were many pilot projects often co-funded by government over that period, only five of the business models had been fully implemented; these were: virtual power plants; demand side management; home power solar and storage; smart homes; and smart energy service provision. Moreover, only one of the initiatives had been conducted by an incumbent utility; the rest were by new entrants. The principle reasons identified for the modest progress were: high investment costs for ICT infrastructure; the need to build up new competencies, i.e. skilled staff; and concerns that smart energy business models would undermine traditional revenue streams.

**6.0 Overcoming Technological Challenges in Creating More Resilient Grids**

Beyond issues of business organization, the transition to low carbon electric megacities requires utilities to develop or enhance their technical skills. In particular, competencies in the use of ICT techniques to design more resilient grids is important. The development of electric cities would see an increase in the electricity demand in cities, in place of other energy sources. This might relieve some of the business pressures faced by utilities from stagnant growth in developed countries, but it also places increased responsibility on utilities to achieve higher levels of resilience in the face of climate change and other system shocks.

As a consequence of floods, heat waves and other extreme natural events impacting cities, whether linked to climate change or not, there has become a heightened need to increase the resilience of cities. This is particularly the case for megacities, due to their sheer size and complexity as well as extreme levels of poverty, vulnerability, and social-spatial fragmentation in many cases (WEF 2014; Kraas, 2007). Resilience is understood to be the ability of a system – in our case a city – to rebound following a shock. Assessing or quantifying – and hence improving - the resilience of a city is difficult as it is a complex system. Broad strategies for increasing resilience include general approaches (adding redundancy, diversity, adaptability, enhancing people skills, increasing readiness and making structural changes), as well as specific approaches, which seek to avoid, buffer, strengthen against, or reduce the impacts of particular types of shocks (Uda and Kennedy, 2015). One partial way of quantifying resilience, in the context of urban metabolism, is by the quantity of energy stored in cities. When supply fails, internal buffer capacity becomes vital to meeting demand and hence is an important factor in resilience. Bristow and Kennedy (2013) quantify the number of days supply of transportation fuels, food and biomass for home heating for Toronto as a partial assessment of resilience. The challenge with electric cities is that the diversity of energy sources is reduced – given the dominance of electricity – and this potentially could undermine resilience. So the designers of electric cities need to find clever ways of using smart grids, batteries and other means of energy storage to help keep cities function in the event of disruptions to power supply.

One way in which cities can be made more resilient to electricity supply shocks is through the development of microgrids that can operate in island mode if other parts of the power grid fail (Lopes et al. 2006; Parhizi et al. 2015; Venkatraman & Khaitan, 2015; Kumar & Azad, 2015). A group of interconnected distributed energy resources and electrical loads can be considered a microgrid if it meets three characteristics: i) clearly defined electrical boundaries, when either connected or disconnected from the main grid; ii) existence of a master control system ; iii) sufficient installed capacity to meet peak critical load (Parhizi et al., 2015). Microgrids provide a greater range of benefits beyond straightforward backup generation. The important benefit is the islanding capacity, which through a smart switch at the point of coupling allows disconnection between the microgrid and main grid in the case of a disturbance. Other benefits include higher power quality, reduction in transmission and distribution costs; and potential for distributed generators on the microgrid to sell to the main grid under favourable market conditions (Parhizi et al., 2015). Several studies reviewed by Parhizi et al. (2015) and Wang et al. (2015) have specifically looked a techniques for increasing the resilience using microgrids, while Chandra & Srivastava (2015) have developed measures of the resilience of smart power generation networks.

Energy storage approaches provide a further means of increasing the resilience of cities to power shocks. There are emerging technologies that can be used, beyond conventional fossil fuel stocks for back-up generators. Electric battery storage, whether within electric vehicles or in stationary units is becoming more cost competitive as battery prices declined at about 14% per year from 2007 to 2014. (Nykvist & Nilsson 2015). A long-term vision for deep decarbonisation in the United States also describes energy storage approaches that potentially could be used to increase resilience in cities. The strategy entails generation of hydrogen or synthetic natural gas from excess renewable energy generation, e.g.. at times of high winds (Williams et al. 2014). These fuels are envisioned as being used by industry via conventional combustion, but if planned appropriately the fuel stocks could also provide short term back–up energy storage for electric cities.

Overall the necessity of increasing the resilience of electric cities will require that utilities enhance their already substantial technical and management capabilities. In providing reliable electrical power services to cities, utilities (often working with regional balancing authorities or independent systems operators) already perform a variety of important tasks: scheduling and dispatching power to meet demands, planning and providing adequate reserve generating capacity, and balancing the grid in real time. Conducting these tasks in a system with increased amount of dispersed renewables, with intermittent generation, requires a higher degree of central co-ordination. Summarizing several studies Boyd (2014, p. 1701) describes the technical needs as “more system flexibility, more dispatchable capacity, faster ramping rates, shorter scheduling intervals, increased transmission capacity, and new systems operation capabilities.” The additional responsibility of providing the power to meet the transportation, building and industrial energy needs currently served by fossil fuels, in a world subject to climate change, will mean reaching for even higher standards of reliability and resilience.

**Conclusions**

The electric city, powered by low carbon electricity, is necessary for sustainable development in a carbon constrained world. Progress towards the ideal electric city has been assessed here for the world’s 27 megacities in terms of the percentage of energy provided by electricity and the carbon intensity of that electricity. Differences between the megacities are quite distinctive with Paris, Rio de Janeiro, Sao Paulo and Buenos Aires standing out for low carbon electricity, and Indian cities for high percentage electricity use.

Electric utilities have an important role to play in achieving low carbon electric megacities, but new business models may be required to make this happen in some cities. There is currently wide variation in thestructure of markets for electricity provision in megacities, with a dominant, public utility the most common model. Alternative business models for the power sector have been broadly sketched out here in terms of the predominance of locally dispersed generation and the nature of the ownership of the electric grid within the city. Where power generation and storage are largely centralized, the business model is either one of domination (model I) or competition (model II). Where the solar potential is high enough that a large proportion of electricity can be provided by locally distributed supply within a city, utilities could increasingly play the role of enabler of exchange with the grid (model III). For this model to tractable, however, new pricing structures are necessary, which reward utilities for enabling distributed connections, covering their costs of maintaining and operating the grid. This is perhaps the most desirable model for utilities and society, rather than the fragmented model 4, where there is essentially no longer any grid.

A further challenge for utilities in enabling the electric city is to provide a higher level of resilience to events that disrupt power supply. This might entail developing microgrids with islanded modes, increased prevalence of mobile or stationary electric batteries, or other means of energy storage.

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