Heriot-Watt University

School of Energy, Geoscience, Infrastructure and Society

PhD Thesis

Title:	**Improving the Intersect of the Power Distribution System and the Built Environment in Developing Countries**
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Date:	**May 9, 2019**
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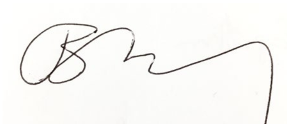

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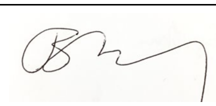
Signature of Candidate*:*		Date:	May 9, 2019

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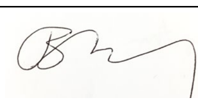
Signature of Individual Submitting:	
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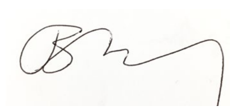
Signature:		Date:	May 9, 2019

Abstract

Power distribution systems, specifically where they intersect with the built environment, are highly underemphasised versus generation in power planning. In a time of technology advances and cost declines in distribution automation and related technologies, this is an area of high potential for improving energy efficiency. This is particularly of impact in developing countries where urbanisation is rapidly increasing. Evidence shows that the same missed opportunities and sub-optimal distribution planning techniques are repeatedly found across multiple geographies. In this research, tools were developed to rank these problems and create solutions. These tools were endorsed by power industry executives from three countries. Following this, the tools were applied in a developing corridor near the Thailand-Cambodia border where power density is increasing, in order to develop power system solutions for live infrastructure projects. The solutions include technologies such as distributed generation, microgrids, digital monitoring systems, CCHP units, and power storage. The solutions from the live example were then honed and endorsed in an interview with Thai power sector experts. The final research and tools developed were confirmed capable of producing actionable solutions for planners across the public and private sectors, who focus on power distribution in urbanising, developing counties.

Keywords

Microgrid, power distribution, power system planning, smart city, urbanisation

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Acronyms and Key Terms

1) **AMI** – advanced metering infrastructure, an integrated system of smart meters, communications, and data management systems that enables two-way data flow between utilities and customers, and a detailed collection of data on consumption.

2) **BSS** – battery storage system. This is used to receive electrical power, convert and store it in various chemical compounds, and convert it back to electrical power when the system demands.

3) **CAIDI** – customer average interruption duration index, a power reliability measure used by power utilities. It provides the average outage duration that a customer could experience.

4) **Capex –** capital expenditure, or the upfront investment required for building a project, facility, or another asset, different from operating expenses, which are the on-going cash costs to operate that asset.

5) **CCHP** – combined cooling, heating, and power. A single unit which is able to generate power, air conditioning, and heat, typically powered by natural gas or refined oil products.

6) **DERs** – distributed energy resources, a variety of electrical generation and/or storage, produced by discreet grid-connected units. These are typically embedded in or nearby a load centre and are typically modular, flexible technologies. Also similar to distributed generation (DG).

7) **DR** – demand response, a program where electricity users decrease their consumption in order to cooperate with the utility on capacity or supply constraints.

8) **DSM** – demand-side management, a program to modify consumer demand for electricity through financial incentives, education and communications, and various other incentives. The goal of DSM is to create a sustained change to energy demand through end-user interaction.

9) **EEC** – Eastern Economic Corridor, an area of Thailand from southeast of Bangkok to coastal regions in-between the Gulf of Thailand and the Cambodia border. The EEC refers to geography, as well as to a $45+ billion investment program in the region designed to boost infrastructure, employment, and quality of life.

10) **ESKOM** – a South African electrical public utility established in 1923. It is a major operator of generation plants, as well as transmission and distribution assets.

11) **FIT** – feed-in tariff, a policy mechanism offering long-term contracts to renewable energy producers, typically targeted towards specific types of renewable energy generation. Two common features include guaranteed grid access with terms on how to connect, and pricing geared towards promoting renewable energy over the long-term.

12) **FLISR** – fault location, isolation, and service restoration.

13) **GDP** – gross domestic product, the monetary value of all goods and services produced in a country's borders within a specific timeframe (typically annually).

14) **GIS** – geographic information system, a system designed to capture, store, analyse, and manage geographical data.

15) **HVAC** – heating, ventilation, and air conditioning, systems in buildings and infrastructure that handle air movement and heating and cooling, which are often major consumers of power.

16) **IED** – intelligent electronic device, sensors, and systems which can facilitate two-way communication between devices and control systems. Often part of SCADA systems (see below).

17) **Load** – an active portion of an electrical circuit, which is consuming power. Also used to indicate power demand.

18) **MAIFI** – momentary average interruption frequency index, reliability indicator defined as the average number of momentary interruptions that a customer would experience during a given period.

19) **Microgrid** – a finite network of electrical supply and demand, which can function independently or in coordination with the broader power grid.

20) **NGO** – non-governmental organisation, usually a non-profit and sometimes international organisation independent of the government (although can be funded by the government), which is active in humanitarian activities, including energy and the environment.

21) **PV** – photovoltaics, the conversion of light into electricity using semiconducting materials, commonly deployed as rooftop or ground-mounted panels.

22) **Rate base** –the value of assets (largely physical, sometimes in the form of services) on which a public utility is permitted to earn a specified rate of return in accordance with the rules set by a regulatory agency.

23) **RE** – renewable energy, the energy produced by renewable forces of nature such as wind, sunlight, waves, tides, and geothermal heat.

24) **SAIDI** – system average interruption duration index, the average outage duration for each customer served, which includes the annual outage time for a location and the total number of customers served.

25) **SAIFI** – system average interruption frequency index, the average outage frequency for each customer served, which includes the annual outage time for a location and the total number of customers served.

26) **SCADA** – supervisory control and data acquisition, a control system architecture that uses computers, networked data communications, and graphical user interfaces for high-level process supervisory management, but uses other peripheral devices such as programmable logic controllers (PLC) and discrete controllers to interface with the process plant or machinery.

27) **SG** – smart grid, an electrical grid which includes a variety of operational and energy measures including smart meters, smart appliances, renewable energy resources, and energy efficient resources, and has abilities to augment supply and demand, predict problems, and heal itself.

28) **SOM** – switching order management, a system which enables power system dispatchers, operators, and managers to request, assign, track, and log switching work orders in various tasks within the network.

29) **T&D** – transmission and distribution, the bulk movement of electrical energy from a generation plant to an electrical substation and from the substation to end users.

30) **TOU** – time of use, or time of use pricing, refers to power pricing systems that have higher or lower power prices at certain times of day, season, year, or another time interval. It is designed to augment demand conditions to accommodate supply conditions.

31) **VAR** – volt-ampere reactive, a unit by which reactive power is expressed in an AC electric power system. Reactive power exists in an AC circuit when the current and voltage are not in phase.

32) **VRE** – volatile renewable energy, renewable energy sources that are volatile in the nature of the output as compared to thermal (coal, gas, nuclear) energy.

33) **VVO** – voltage and VAR optimisation, real-time information and online system modelling providing optimised and coordinated control for unbalanced distribution networks with discrete controls.

Preface

I have spent the last 17 years living and working in developing countries, primarily in Asia, focusing on energy. Development in low-income countries typically features rapid urbanisation rates, which makes cities increasingly large consumers of energy. My interest is in examining how effective power system planning is in developing countries, specifically where the distribution system intersects cities, including infrastructure, urban homes, industry, and the broader built environment. My goals are first to understand the drivers of energy demand in developing countries, then to understand how these drivers are incorporated into power infrastructure, and if possible, to uncover where improvements in planning can be made.

I completed a Master of Science degree in renewable energy engineering from Heriot-Watt University in a part-time program while working in the energy industry full-time. The degree focused on technical aspects of generation and integration of renewable energy, and my dissertation focused on increasing renewable energy integration in China's power sector, which was the focus of my employment over the 12 years I was based in Beijing. Over a 17-year period, I worked in China (12 years), India, Indonesia, Thailand, parts of West Africa, Russia, Saudi Arabia (2 years), and Hong Kong (3 years)

I embarked on PhD studies, and asked the question: Can power sector planning in developing countries be improved? The research followed a discovery and distillation process to answer this and culminated in developing a tool that guides users towards solving significant problems in power sector planning in urbanising, developing countries. This process and the research has created a database of documented problems in distribution planning in developing countries, summarised the causes and effects of these problems, and created a systematic means for structuring these problems into solutions.

The discovery process has led to an electronic package that can be of use in addressing power distribution in urbanising, developing countries. The suite consists of researched and documented commonly found problems, case studies to articulate these 32 problems, and an Excel tool to translate these 32 problems in a local context into tangible power distribution solutions. This suite is aimed to be utilised by aid agencies and power planners in the developing world to improve energy efficiency. It is worth noting that the discovery process and its outcome are articulations of what is underemphasised (distribution planning in developing urban centres), and the Excel tool is a means for developing solutions. The dissertation and its outputs are built on academic research, and were guided into tangible solutions by implementing internationally recognized frameworks, and were verified by expert interviews and testing it on a live case study, and as such can be used in real-world applications.

1. INTRODUCTION

"Rapid urbanization is a global phenomenon. In 2008, for the first time in human history, there were more urban dwellers than rural. Current estimates suggest that by 2030, over 60 per cent of the global population will be living in cities, increasingly concentrated in Africa, Asia and Latin America. This fraction could rise to two thirds by 2050. Comparing the projected rate of growth of urban populations across regions, it is clear that countries in the low-income category will confront far more rapid urban population growth than countries in higher income categories. Recent estimates suggest that the growth of urban areas in the first three decades of the twenty-first century will be greater than the cumulative urban expansion in all of human history."

- United Nations Commission on Science and Technology for Development, 2016. (United Nations Economic and Social Council, p. 2).

A key economic feature of developing countries over the last century, and in particular the last two decades, is urbanisation (Scott and Seth, 2013), which has been inextricably tied to power demand (Sadorsky, 2013). The US Agency for International Development estimates that an additional 1 billion people will be living in urban areas by 2030 (USAID, 2013). The US Department of Energy (US DoE) stated that urbanisation and developing countries are amongst the most important energy challenges we face in the 21st century (Zinaman et al., 2015). Countries that grow from below the lines of poverty to 'developing' status by the United Nations typically see a shift from industrial activity and fixed asset investment representing under 15% of GDP to more than 30% of GDP over a five- to 15-year period (UN DESA, 2013). Populations typically shift from 10–15% dwelling in cities to more than 35–40% dwelling in cities over the same time (IEA, 2011; UN DESA, 2013).

Electrification rates typically increase from 65% to more than 90% during periods of high development (IEA, 2011). However, electrification captures only an individual's access to electricity in their dwelling, not energy intensity of that individual's day-to-day life and economic activities (Diamond, 2012), or real power demand which includes both current consumption and unmet or future potential demand (Naughton, 2018). Real power demand growth in developing countries most closely tracks fixed asset development, commercial and residential real estate development in and around cities, urbanisation rates, and consumer goods consumption rates of urban dwellers. There is a proven, long-term correlation of power demand to the development of cities and consumption of urban dwellers (Muhammad and Lean, 2011; Allouhi et al., 2015). However, the demands for providing utilities and services to an increasing population are limited with finite space and resources. This presents tremendous challenges around urban planning for new cities, and the costs of poor planning are difficult to remedy and have a high impact on the environment.

The current rate of urbanisation in developing countries appears set to increase for decades to come. Given that these demographics are closely linked to energy demand, there is a clear case to examine this area for problems and opportunities. This forms the broad context for the research presented in this thesis. The research started with understanding what drives power demand (load) in developing countries. Five key drivers of load were discovered, the most consistent and long-term of which was urbanisation. Next, the greatest emphasis in power sector planning between generation and distribution – in the public sector, private sector, and the academic community – was searched for, and it was found that generation is clearly emphasised much more than distribution. The subsequent step was to uncover if power planners place sufficient emphasis on urbanisation and distribution networks therein. The answer again was that planning for power distribution in growing urban centres is significantly underemphasised versus large-scale generation capacity planning.

It should be noted that urbanisation in the West in the 1800s and 1900s brought modernity and several benefits to populations that came from rural to urban centres, but it also brought a variety of stresses and problems from poor urban planning. Sanitation, waste management, adequate housing, transportation planning, food provision and networks, and energy and environmental management are a few of the large-scale problems that occurred alongside the benefits of urbanisation. **Figure 6** illustrates some of these issues.

As a background to the research, points are made in the literature review on urbanisation and the nature of cities. It is important to understand electrical load in the context of people in developing countries forming urban centres, employment, GDP, general consumption, and power demand. The movement from rural to urban areas is when people formally make changes to what they consume and produce – how they transport themselves and goods that they use; how they obtain heating, lighting, and cooling; what is the source of their food and its logistics chain; what they produce for a living; and how much time they spend in fixed structures versus outside. The formal move from rural to urban means that people consume more energy and that energy is associated with or delivered through the built environment. All of this has implications for buildings, consumption, production, and associated energy distribution. The research focuses on analysing the energy issues involved in urbanisation, determining if knowledge gaps exist, and exploring what can be learned from both effective and ineffective power distribution planning in urbanising areas.

2. LITERATURE REVIEW, AIMS AND OBJECTIVES

2.1 Urbanisation and Its Impact on the Developing World

2.1.1 What Is a City?

Cities have played a major role in human life driven by agricultural improvements (requiring less labour per output of food), transportation improvements, advances in building, trade, and other issues. There are varying definitions for the term 'city' – some are defined by a boundary set by a government or administrative body, whereas others are defined according to a contiguous area of infrastructure development and population density (Dijkstra and Poleman, 2012; UN DESA, 2016). The variance in definitions is often due to what entity is defining the city, for what purpose, or in what context, for example, economic issues, human population, infrastructure, and human or industrial activity.

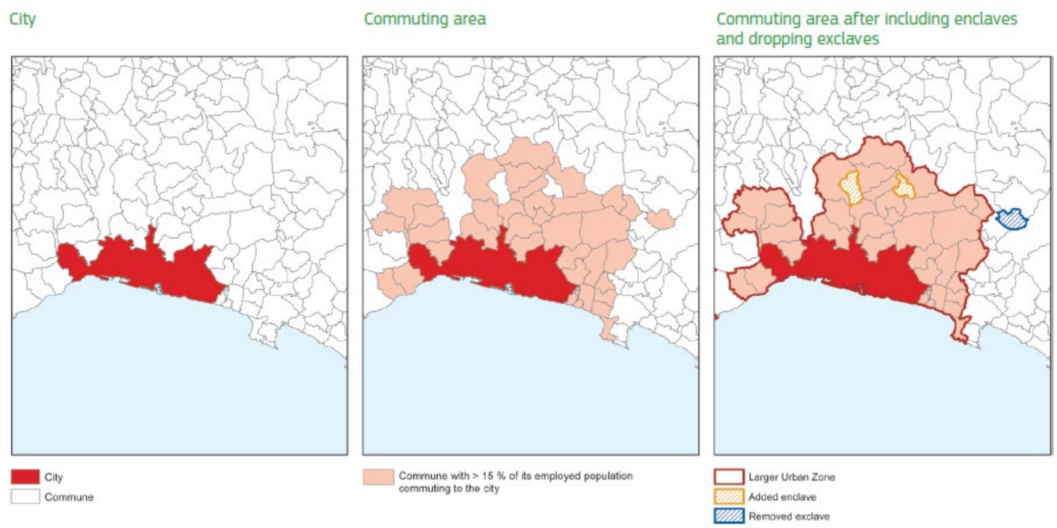


Figure 1. A city and its commuting zone: the case of Genova (source: Dijkstra and Poleman, 2012).

The United Nations leans towards the notion of an 'urban agglomeration' or an area with a certain quantity of social and economic interactions, which can be displayed by commuting, commerce, and other measures (UN DESA, 2016). Cities can be defined as human settlement zones that have systems and infrastructure for housing, utilities, trade, sanitation, land development and use, and transportation (UN DESA, 2016). As seen in **Figure 1**, the European Union and the Organisation for Economic Cooperation and Development (OECD) define a city as 1) having a density of more than 1,500 inhabitants per km^2 and a total contiguous area of the above-stated density totalling 50,000 inhabitants or more; 2) having a commuting zone(s) that shows routes and patterns of transportation for the working population, trade, and consumption; 3) having directly related political bodies which govern and operate that area (Dijkstra and Poleman, 2012). Urbanisation is the process whereby people move their home from nonurban (often agricultural areas) to urban centres (Dijkstra and Poleman, 2012).

2.1.2 Brief History and Current State of Urbanisation

In 1950, 30% of the world's population resided in urban areas; as of 2018, about 55% of the world's population lives in urban areas. This trend towards urbanisation has been steadily increasing since the close of World War II – in 1950, there were 751 million urban dwellers, whereas in 2018 there are 4.2 billion (UN DESA, 2018).

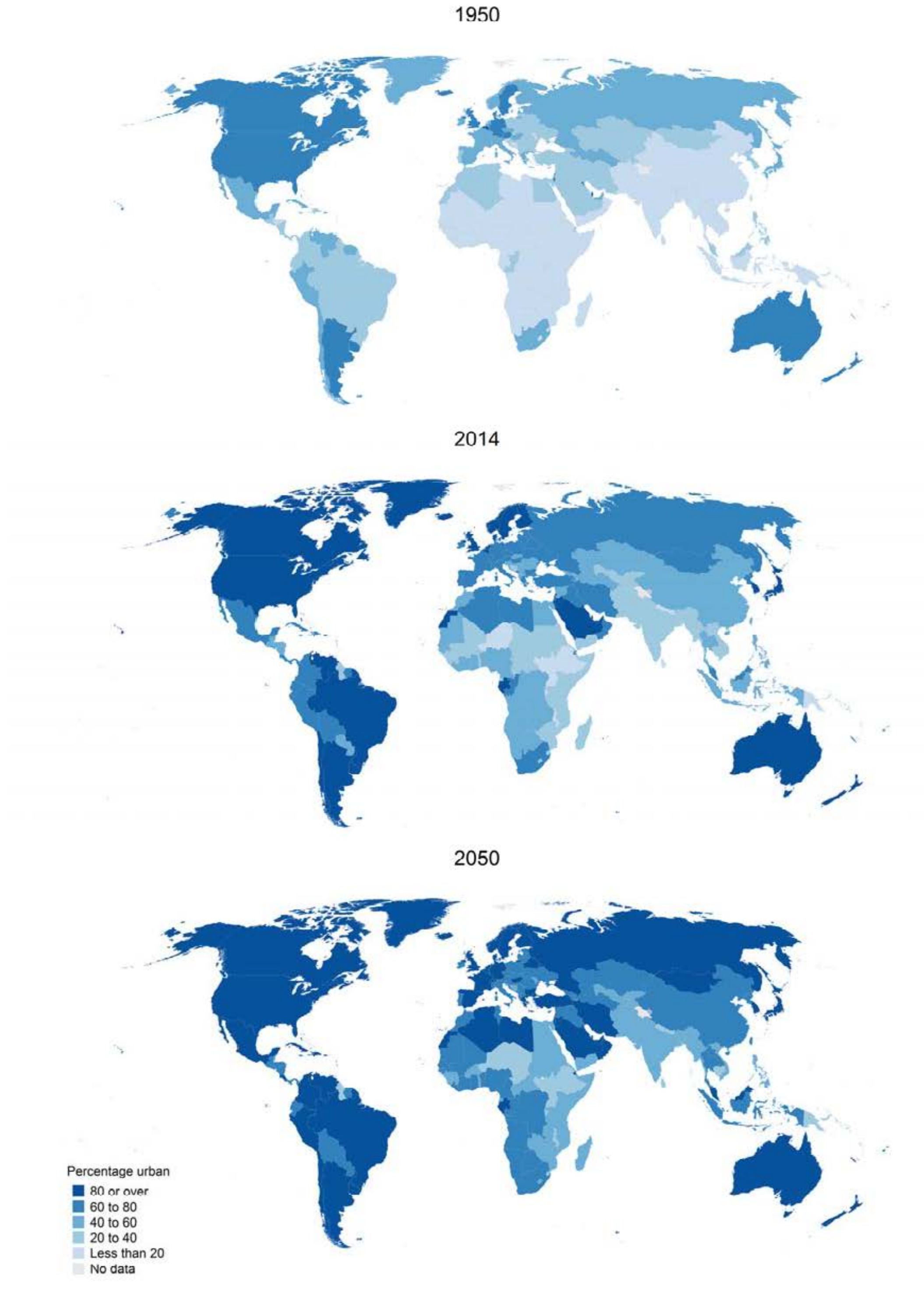


Figure 2. Percentage urban in 233 countries or areas, estimated for 1950 and 2014 and projected to 2050 (source: UN DESA, 2014b).

At a closer look (**Figure 2**), in 1950, 15% of 233 countries had more than 60% of their population living in urban areas. Only 6% of 233 countries had over 80% of their population in urban areas. In 2014, approximately 50% of all countries had more than 60% of their population living in urban areas. Also in 2014, about 25% of countries globally had greater than 80% of their populations living in urban areas. By 2050, nearly 70% of countries are estimated to have over 60% of their population in urban areas, and 38% of countries will have more than 80% of their population in urban areas (UN DESA, 2014b).

In 2018, the most urbanised areas include North America (82% of population living in urban areas), Latin America and the Caribbean (81% of population living in urban areas), Europe (74% of the population living in urban areas), and Oceania (68% living in urban areas). The level of urbanisation in Asia is reaching approximately 50% in 2018. However, there are major differences when viewed country by country. African populations remain largely rural, with 43% of the continent's population living in urban areas (UN DESA, 2018).

Despite having lower urbanisation than other regions, Asia is home to 54% of the world's urban dwellers, followed by Europe and Africa (each with 13% of the world's urban population). Asia is home to some of the world's largest megacities, such as Beijing, Tokyo, Shanghai, Mumbai, Jakarta, Bangkok, and others. Growth in total population and a shift in emphasis from agricultural to industrial and service sectors are key drivers in this trend. These factors are projected to add 2.5 billion to the world's urban population by 2050, with nearly 90% of that increase coming from Asia and Africa. More specifically, three countries – India, China, and Nigeria – together are expected to account for 35% of the growth in the world's urban population from 2018 to 2050. India, China, and Nigeria are expected to add 416 million, 255 million, and 189 million urban dwellers over this time, respectively (UN DESA, 2018).

Figure 4 (UN DESA, 2014b) shows average annual rates (1990–2014) of urban and rural population growth in 201 countries or areas with at least 90,000 inhabitants in 2014. The vertical axis shows per cent growth in urban populations (with positive showing urbanisation, and negative showing people moving to rural areas), while the horizontal axis shows overall population growth (positive meaning a growing population, negative meaning a decrease in population). Many developing countries are clustered around the axes, meaning little or no population growth, and having already urbanised. Many developing countries are higher up the vertical axis, showing urbanising populations.

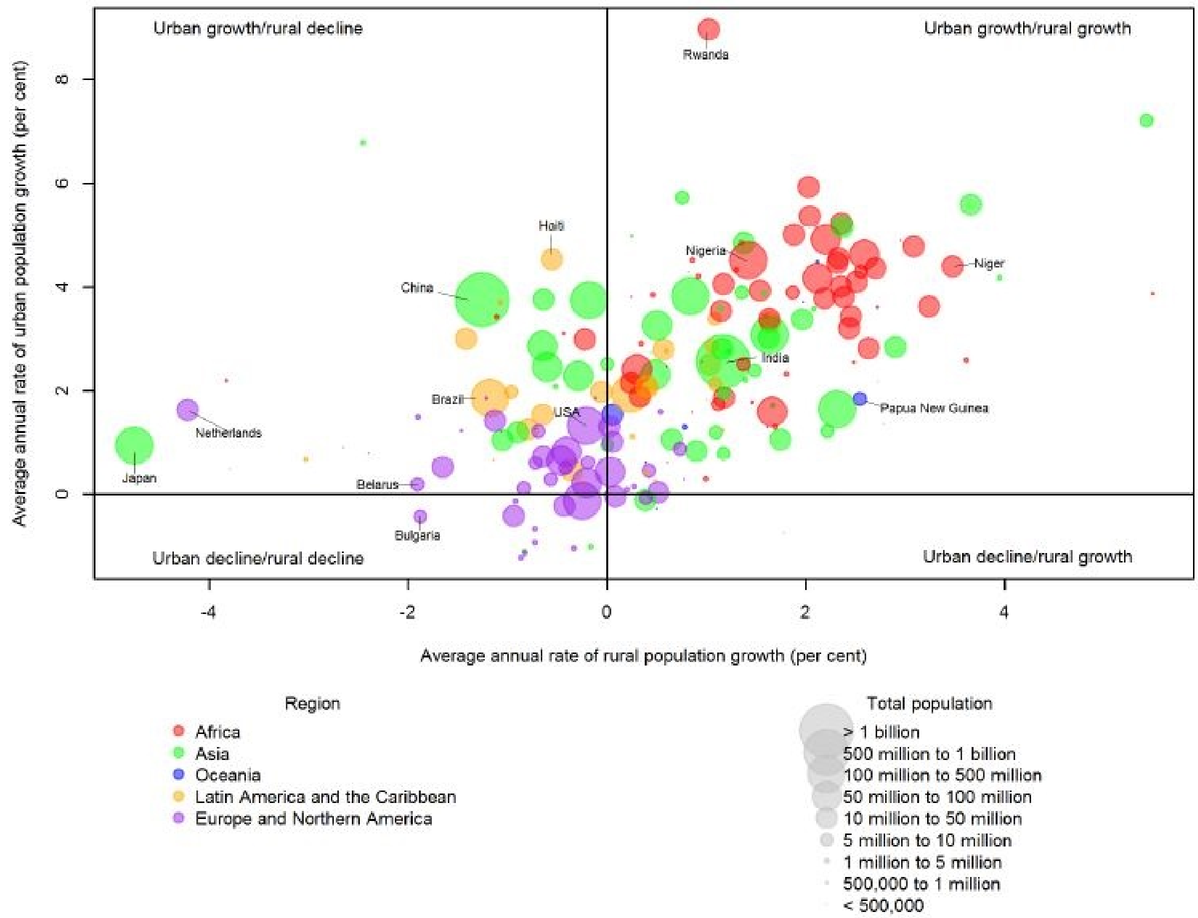


Figure 3. Average annual rates (1990–2014) of urban and rural population growth in 201 countries or areas with at least 90,000 inhabitants in 2014 (source: UN DESA, 2014b).

In 1990, there were ten megacities that featured 10 million or greater in population – these cities together accounted for 153 million people. In 2018, the number of megacities globally has more than doubled. As of 2014, 28 megacities together composed 453 million people, equivalent to about 12% of the world's urban dwellers (**Figure 4**). Of these 28 megacities, 16 are located in Asia, four are in Latin America, three are in Africa, three are in Europe, and two in North America (UN DESA, 2014a).

Greater Shanghai, depending on how this area is accounted for, has the largest population with over 40 million people. Greater Tokyo follows this with 38 million inhabitants, followed by Delhi with 25 million, Mexico City, Mumbai, and São Paulo, each with around 21 million inhabitants. Osaka (Major Metropolitan Area) and Beijing each have about 20 million inhabitants. The New York–Newark area and Greater Cairo follow these with around 18.5 million inhabitants each (UN DESA, 2014a).

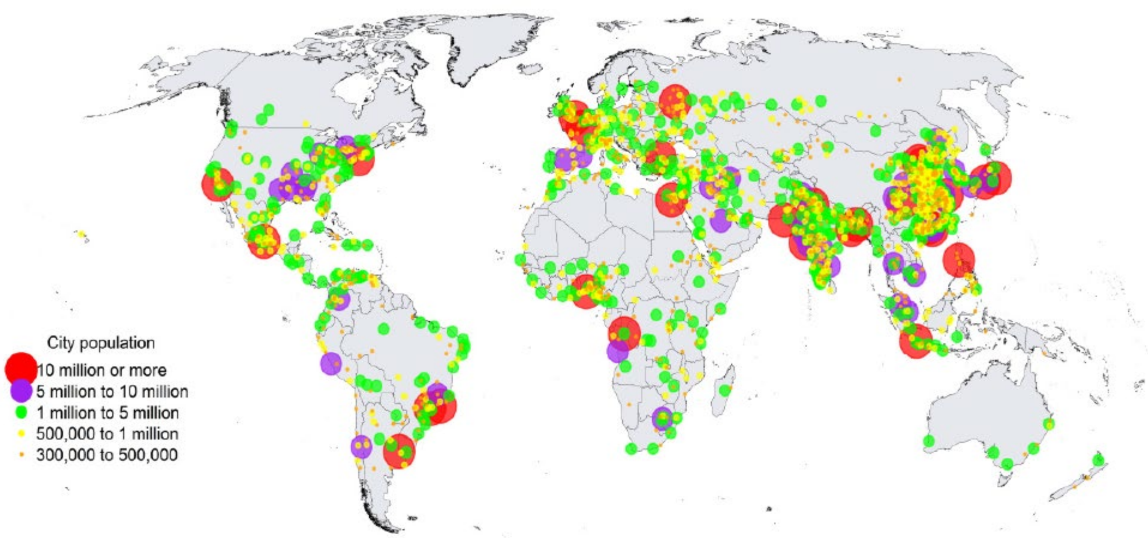


Figure 4. Cities (urban agglomerations of 300,000 inhabitants or more) by size class of urban settlement, 2014 (source: UN DESA, 2014a).

By 2030, we will see the emergence of 13 new megacities, almost exclusively in less developed nations (UN DESA, 2014a). On the other hand, some cities are expected to decline (see **Figure 5**) because of lower fertility rates, for example in Tokyo and Singapore, social conditions decreasing both marriage and procreation rates, and stagnant populations at the country level and migration to areas with greater employment opportunities, for example in Riga and Yerevan (UN DESA, 2016).

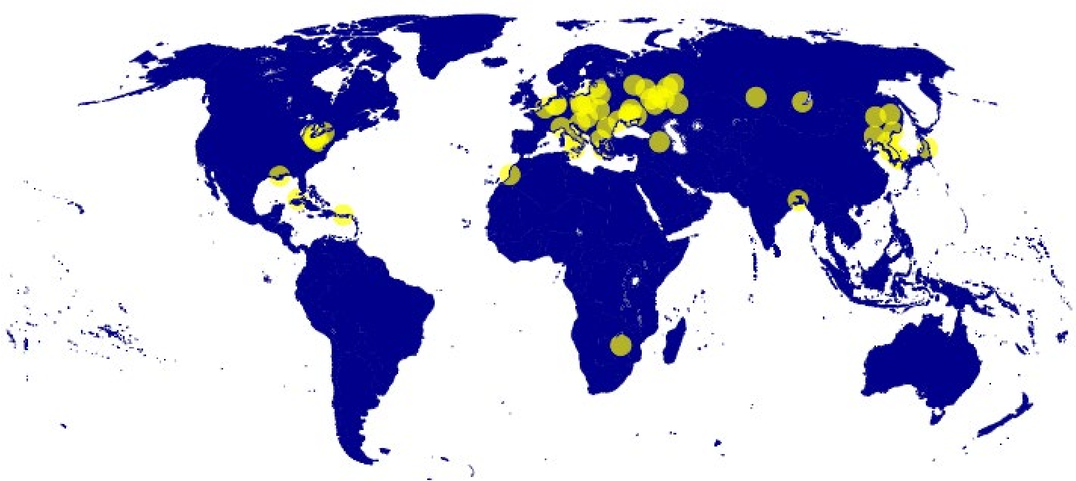


Figure 5. Cities (out of the 1,063 cities with 500,000 inhabitants or more in 2016) where population declined between 2000 and 2016 (source: UN DESA, 2016).

2.1.3 Urbanisation in Developing Countries

Of the world's 31 megacities (those with greater than 10 million inhabitants), 24 are located in less developed countries. China alone is home to six megacities (although this number is increasing), while India has five. The ten cities that are forecasted to become megacities between 2018 and 2030 are all located in developing countries (UN DESA, 2016):

1) Ahmedabad, India;
2) Bangkok, Thailand;
3) Bogotá, Colombia;
4) Chengdu, China,
5) Dar es Salaam, Tanzania;
6) Ho Chi Minh City, Vietnam;
7) Hyderabad, India;
8) Johannesburg, South Africa;
9) Lahore, Pakistan;
10) and Luanda, Angola.

Smaller cities have also increased in population. During the period from 2000 to 2016, the world's cities with 500,000 or more inhabitants grew at an average annual rate of 2.4%; however, 47 of these cities grew at more than double this rate, at over 6% per year. Of these with 6+% growth rates, six are in Africa, 40 are in Asia (20 of which are in China), and only one is in North America. All of the above statistics indicate that urbanisation is very much an issue in developing countries (UN DESA, 2016).

2.1.4 Main Urban Issues that Arise in Developing Countries

The industrial revolution in the UK and US came with significant social, environmental, and health problems new cities formed and as existing cities grew (Williamson, 2002; Kim, 2007). The track record of governments attempting to cope with urbanisation and provide basics such as utilities in a rapidly urbanising environment is poor (Sun et al., 2013). Overall, urbanisation is a difficult issue to manage, and planning has historically been poorly managed by societies and governments (Madlener and Sunak, 2011).

Cities in developing countries have absorbed significant migration from nearby provinces, villages, and in some cases neighbouring countries. Agricultural efficiency is one driver. Urban areas in developing countries are often known for having better utilities, sanitation, education, and other public services than rural areas, which is a motivator for many, especially young families. Another driver is continued high birth rates in rural areas, creating less agricultural-based employment and forcing people to move to cities in search of industrial, service sector, and other employment. The most immediate stresses that can be seen include the supply and demand balances of housing, water, food employment, and energy (Brueckner and Lall, 2015).

A self-perpetuating cycle, stressing energy systems can occur as urbanisation picks up. People rely less on natural resources for housing, cooling, heating, water, and food, and more on utilities and commercial sellers for these necessities. Urbanisation is often associated with increases in per capita income and consumption, which typically means that people purchase more manufactured goods and appliances and consume (directly and indirectly) more energy (Karanfil and Li, 2015). Urbanisation can spur energy consumption, but, without sufficient planning, this can quickly lead to energy poverty or shortages (Singh et al., 2015).

Urbanisation can provide a means for a country to centralise critical services, such as education and healthcare, and provide them more effectively to its masses (Cobbinah et al., 2015a, 2015b). However, negative impacts of urbanisation or very rapid urbanisation, such as food, housing, and energy scarcity, forms an important part of a complex network of threats (**Figure 6**) to the sustainability and stability of developing countries (World Economic Forum, 2018).

Power system evolution in developing countries is typified by high levels of attention and funding being placed on generation. Generation is capital-intensive and is essentially the first major hurdle for a developing country to overcome when electrifying its population. However, this leaves distribution and efficiencies that can be gained in distribution somewhat underemphasised in research and the attention or capital investment plans of companies and governments. Because much of the developing world is, or has, urbanised into megacities, issues around how the power distribution system interacts with people and infrastructure can tremendously impact the system efficiency. While urbanisation and distributing power in megacities in developing countries may be a place of high potential for gaining energy efficiency, there is strong evidence that it is significantly underrepresented in research and system planning. Against this, several new technologies around distribution and end-user interface are now emerging that can potentially create significant carbon savings and efficiency gains.

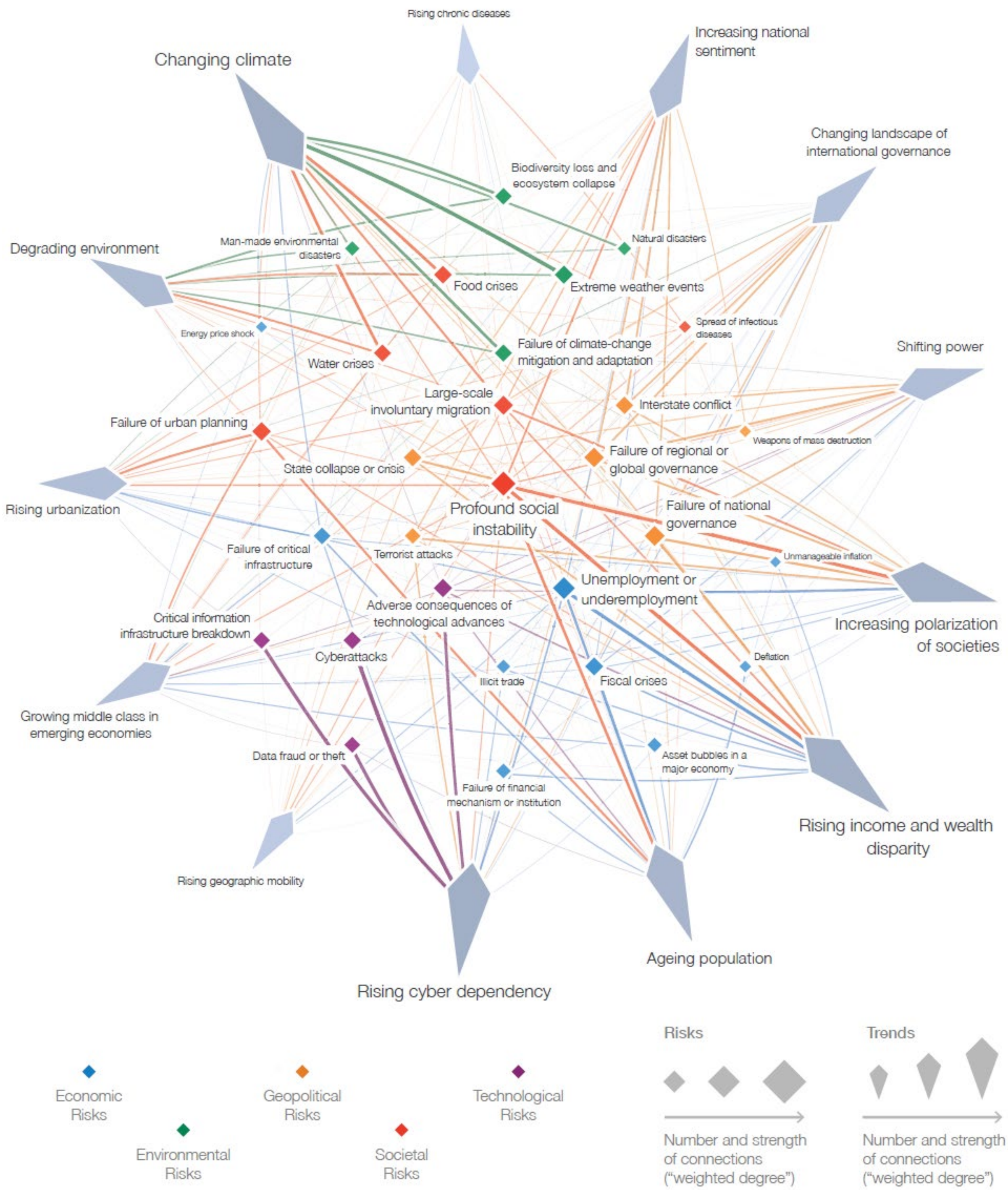


Figure 6. Interconnections among global trends and risks in 2018. The trend of rising urbanisation (middle left) is connected (in order of descending strength) to the risks of failure of urban planning, failure of critical infrastructure, profound social instability, large-scale involuntary migration, food and water crises, energy price shocks, illicit trade, spread of infectious diseases, failure of climate-change mitigation and adaptation, and biodiversity loss and ecosystem collapse (source: World Economic Forum, 2018).

2.2 Power Distribution Planning in Developing Countries

2.2.1 What Drives Power Demand Growth in Developing Countries?

The developing world has high population growth rates, and its energy consumption is increasing rapidly from a low base relative to OECD countries. Cities in developing countries are an epicentre of stresses on energy and the environment. The literature review revealed that developing countries typically see power demand growth from five key drivers. Four of the five were found to be short-term or non-recurring drivers, well-covered by existing research. The fifth driver, urbanisation and infrastructure development, was shown to be systemically recurring and long-term in nature. The drivers are as follows:

1) Acceleration or rapid growth of a particular industry, such as textiles production and export, or mineral extraction.
2) Alleviation of system constraints – this refers to meeting previously unmet demand by building infrastructure (e.g., building a power station in an area which had a power shortage).
3) Political or economic reform – this typically involves removing dysfunctional political or economic structures that have limited economic activity and energy consumption.
4) Subsidies for the economy and/or power sector, encouraging an increase in consumption.
5) Urbanising populations and the corresponding development of cities and infrastructure.

2.2.1.1 Acceleration of a Particular Industry

A common occurrence in developing counties is an investment in a particular industry that drives power demand. Textile production and export in Bangladesh and oil production and export in Nigeria are examples of this. Heavy industry in China after the Cultural Revolution drove more than 60% of the demand growth for power in the early 1970s (Lin and Li, 2014). Historically, these changes produce short-term, often one- to five-year increases in power demand, followed by a flattening of demand (Ruhl et al., 2012). In Pakistan and other developing countries, this driver produced sudden increases in demand, which are often short-lived and commonly cause breakdowns in the power system due to their rapid, one-off nature (Yasmin and Qamar, 2013). These drivers of power growth tend to be centred around the industry driving it (e.g., mineral extraction or textiles) and its immediate value chain, rather than around the broader economy or country. As noted by the World Bank (Kojima et al., 2010; Bacon and Kojima, 2011), these are non-sustained and localised drivers of power demand that reduce or flatten power demand after a short-term surge.

An example of this can be found in Zhao et al. (2010), who analysed the energy demand in China from 1998 to 2006 and displayed a strong correlation between industry acceleration and energy demand. While China did go through great efforts to achieve lower energy consumption per unit of GDP, the overall trend displays a rural-to-urban shift and a permanent upward shift in energy demand (Liao et al., 2007). The main contributors to this trend are energy-intensive industries, such as metal and chemicals processing (namely steel), which saw rapid growth rates in investment in the early part of this period. China became one of the largest steel producers and was engaging in heavy trade in steel and finished products, such as auto parts. Energy demand closely followed the observed pattern of industrial capacity utilisation in these sectors – plummeting in 1997 during the Asian financial crisis and sharply increasing 2003–2006 as Chinese metal and steel demand rose rapidly (Liao et al., 2007). While this driver has links to issues such as labour cost differentials and globalisation, it is essentially rooted in the acceleration of one or a few energy-intensive industries that can be a significant driver of energy demand. This driver is well-covered by academic and non-governmental organisation (NGO) publications and is outside of the focus of this research.

2.2.1.2 Alleviation of System Constraints

This is categorised as a driver of demand, but in reality it occurs when a supply constraint is lifted. Examples include islanded areas of Indonesia or remote villages in India with no local power generation being connected to a nearby grid or having their own dedicated power generation built. This was noted as a key issue in India, where interoperability between local villages and nearby grids as well as overall system constraints, when addressed, produced increases in power demand (Jairaj et al., 2016). Typical constraints involve funding for generation, transmission, and distribution lines, and geographic constraints to building power infrastructure in a particular area. Kumari and Sharma (2016) demonstrated a strong correlation between simply investing in rural distribution systems and nation-wide power demand in India and other developing countries. The typical power demand profile from this driver is a one-off surge as constraints are lifted, followed by a more normalised growth or no growth as pre-existing demands are met.

An example of this can be found in Kanagawa and Nakata (2008). This study focused on India, which has traditionally had poor electrification rates and poverty. In 2004, the Indian government started a nationwide policy aimed to electrify all households by 2012. This kind of top-down intervention was deemed necessary as the country's electrification spread to rural areas with the increase in GDP, yet the economic growth was largely limited to urban areas. The program has made significant progress but did not succeed in full electrification by 2012 and is still underway. Electrifying villages led to demand from simple issues such as replacing kerosene in cooking and lighting, electrifying some basic labour-oriented and mechanical processes, and powering basic appliances such as televisions and fans. This study displays the second key driver of load – when system constraints are lifted in developing countries, power demand shows an increase, followed by growth at a normalised or even flat rate. These underserved or islanded demand areas are well-covered by academic publications and entities like the World Bank (Bacon et al., 2010) and are thus not the focus of this research.

2.2.1.3 Political and/or Economic Reform

A driver of power demand in developing countries can be reform to the political or economic system. The opening of an economy to trade, currency policy, government reform, and other similar issues can create an acceleration in power demand. China is an example where economic reform in the early 2000s resulted in policies that favoured certain industries and foreign direct investment, which directly drove power demand (Song et al., 2017). Reforming political systems, such as communism in China and the former Soviet Union (USSR), directly produced one-off increases in power demand. Energy demand in the USSR fell as the broader market economy and steel market collapsed (Schipper and Martinot, 1993), while China's government-engineered economy and development of megacities has created sustained demand for energy (Liao et al., 2007; Zhao et al., 2010). It has been noted in both developing and developed countries that policies which favour or discourage industries based on their energy intensity can directly, and in a period of one to three years, impact power consumption (Forbes, 2017).

An example of this can be found in Narayan and Smyth (2009). This study used multivariate framework analysis to show how different economic factors in China influenced energy demand and energy consumption in this country. The main finding of their study is that there is a bidirectional relationship between economic development (reform of monetary and fiscal policy, banking sector, and lending) and energy demand – increased economic reform leads to increased power demand and vice versa. The authors note that growth in energy demand typically follows broader political economic and political reforms. Data available on this from countries such as China and India typically feature sociological, economic, and political reforms that took place in one period. One can say that government policies to open a previously restricted economy or monetary system typically results in activities that create energy demand. The study of Narayan and Smyth (2009) supports the notion that economic, fiscal, and political policies influence energy demand. Political and economic reforms and their impacts on power demand are well-covered in academic and NGO publications and are not the focus of this research.

2.2.1.4 Subsidies for the Power Sector and/or Broader Economy

Subsidies to parts of the economy and/or the power sector (typically by reduced power prices) can drive power demand in developing countries. Research showed that in a sample of 12 developing African countries over a 30-year period, power price holds the largest correlation to power consumption, greater than that of GDP growth and other economic indicators (Keho, 2016). Power itself can be subsidised where the government simply encourages consumption by not charging end consumers for fuel, power generation, or use of the system. Subsidies or price controls in basic resources can encourage greater consumption and trade, processing, and transport, and hence energy demand. Subsidies can take the form of lowering lending rates and increasing the money supply, which was a key part of the economic growth seen in parts of Latin America in the 1990s, and in China in the early 2000s (Resnier et al., 2007). Subsidies often produce unsustainable, non-recurring power demand as this runs a deficit in some portion of the broader country or power sector budget (Dilip and Tatsutani, 2009). Also, this is a politico-economic matter and is not the focus of this research. The World Bank (Bacon et al., 2010; Bacon and Kojima, 2011), Asian Development Bank (2015) and others have extensively covered this area in their publications.

An example of this can be found in Ahmad et al. (2011). The authors assessed energy in Malaysia, which is heavily subsidised, with annual subsidies of more than $200 million. The authors noted that subsidies encourage road transport and industry that would not normally be economically viable in Malaysia (such as electronics, photovoltaics, and automotive), and excessive household consumption. The subsidies are creating unsustainable demand and market distortions, which, the authors argue, are preventing more sustainable energy production. This study shows the strong relationship between subsidising energy and unsustainable demand. Further, Lin and Jiang (2011) show similar issues in China. The authors noted that energy subsidies were repeatedly used as a means to stimulate industrial activities and employment. However, energy subsidies had only short-term results, as the removal of subsidies directly contributed to a decline in energy demand. Acharya and Sadath (2017) demonstrate these issues in India. The authors noted a direct correlation between energy subsidies and energy demand in India over several years from 2000 onward. The authors also noted that a negative impact of energy subsidies was not just unsustainable demand, but also inefficient power distribution, unnecessary consumption, and increased obstacles for introducing renewable energy sources. Subsidies are often utilised as a rapid means to appease masses by reducing the costs of transportation, fuel for farming equipment (farmers are typically low-income earners), and electricity for home use. The subsidy is shifted either to a state-run company (such as a refinery, power plant, or distribution company) or the federal budget. This is a short-term easing of economic pressure on the poor but does not address broader structural issues in sustainable energy.

2.2.1.5 Urbanisation and Infrastructure Development

Urbanisation typically results in the majority of people's day to day lives taking place in buildings, or the built environment, adding significant energy consumption through heating, air conditioning and ventilation (HVAC) systems, imported food, and the use of water utilities (Lilley, 2009). The construction of commercial and residential real estate, utility systems, HVAC systems, transport systems, and other elements of urban life have their own energy consumption in terms of construction; however, more importantly, these additions to the built environment have an ongoing, recurring energy demand in their day to day operation (Berardi, 2017). Research not only supports the importance of urbanisation in energy consumption but also states that this is an area that planners should be looking for efficiency gains from scale and concentration of load (Topcu and Girgin, 2016).

An example of this can be found in Sadorsky (2013). The authors conducted a study on 76 developing countries using heterogeneous panel regression techniques (i.e., regression models where the coefficients in the model differ for each cross-section in the panel dataset) for assessing the effects of urbanisation on energy demand. The authors identified different ways in which urbanisation has a long-term impact on energy demand. They noted a shift from low energy intensity, agriculture-oriented employment to more energetically intensive, manufacturing-oriented employment with labourers dwelling in cities and communities around industrial facilities. Another driver was noted in the areas of heating and other utilities (e.g., water), which became larger and centralised as people in the countries studied consumed utilities from centrally provided facilities. Other changes and impacts to energy were noted in transportation, development of the informal economy, food production, and food transportation systems. One of the largest impacts to energy demand noted in the study was from infrastructure, as it continuously influences energy demand both during the development phase of infrastructure and afterwards, when the infrastructure is utilised (often for economic activities which involve energy). The authors noted that urbanisation also impacts patterns of private energy consumption. The study noted that urbanisation leads to more efficient energy consumption as heating and cooking fuels are handled by larger centralised facilities (rather than burning fuels in one's home), but that overall, urbanisation and infrastructure development are inextricably linked to long-term energy demand.

2.2.2 How Well Are Urbanisation and The Built Environment as a Driver of Power Demand Understood and Leveraged?

Sections 2.1.4 (page 19) and **2.2.1** (page 22), have illustrated how urbanisation and infrastructure development are key drivers of sustained power demand in developing countries. The next steps in the research were to understand if there is a research or knowledge gap in these critical areas and what can be done to address any gap. This was revealed by reviewing research from the academic community, the public sector, and the private sector. The determination of whether or not a research gap exists is detailed in the three subsections below, which are also noted in the logic map in **Appendix A**:

1) How well understood is this driver of power demand in academic and other research?
2) Do policymakers understand and incorporate this driver of power demand into planning?

3) Do energy companies understand and incorporate this driver of power demand into planning?

2.2.2.1 How Well Is This Driver of Load Understood in Academic and Other Research?

This is a crucial point – is this well understood, or can further research in this area develop learning that can benefit energy systems and the environment? The International Energy Agency (IEA) is one of many bodies which point out that power system planning and the research behind it are excessively focused on power generation, even though the planning process is influenced by a multitude of factors (IEA, 2017). The World Energy Council (2014) has stated that generating affordable power is the greatest challenge and the single largest focus of their current research on power planning in developing countries. The World Economic Forum's key research – *The WEF Future of Electricity* (Bosco et al., 2016) – on power in developing countries emphasises affordable and clean generation, yet has no sections dedicated to distribution systems in urban centres. Several studies on the energy challenges in Africa make no mention of distribution at all – only capital expenditure and fuels for generation (Brew-Hammond, 2010). This is understandable, as developing nations by definition face financing constraints, and generation is the starting point of the electrical value chain. However, it is important to understand whether this heavy focus on generation has created a gap in available information on the importance of distribution and distribution in urban areas.

In an attempt to determine whether or not a gap in this area exists, and an overemphasis on generation planning, a simple statistical analysis was conducted. One hundred and three articles were gathered using Google, Google Scholar, and Kobson search engines. All of the articles were related to power systems in developing countries. A content analysis was applied to determine whether these articles focus on power distribution or power generation. Three measurements were taken into account: 1) the total number of words in a particular article (not including references), 2) the total number of words dedicated to or related to power distribution, 3) the total number of words dedicated to or related to power generation. *t*-tests were conducted to determine whether there is a statistically significant difference between the total number of words and the number of words dedicated to each of the topics. The following results were obtained (**Table 1**):

Table 1. Statistical analysis of the content in 103 articles related to power distribution or power generation in developing countries.

	t-statistic	*p*-value
The total number of words and the total number of words with 'power distribution'.	2.01	0.005
The total number of words and the total number of words with 'power generation'.	1.67	0.05

In both cases, it was established that there was a statistically significant difference, but a greater discrepancy was in the case of power distribution. A simple inspection of the raw data showed that 26 articles focusing on power in developing countries did not mention power distribution at all, while all of the sample articles did feature information on power generation at least to some extent.

This was further explored by researching and counting the emphasis on power distribution versus power generation in 'cornerstone documents'. These are strategic policy documents by major research entities, aid agencies, and NGOs, often several hundred pages in length, which attempt to address energy holistically. The word count and topic emphasis in such cornerstone documents were as follows (**Table 2**):

Table 2. The emphasis on power distribution versus power generation in cornerstone documents.

Document	**Dominant words (number of appearances)**	**Total word count**	**Total number of words referring to "power distribution"**	**Total number of words referring to "power generation"**
Energy for a Sustainable Future (UN Secretary-General's Advisory Group on Energy and Climate Change (AGECC), 2010)	consumption (19) emission(s) (23) distribution (5) generation (11)	12,590	0	2
Energy Efficiency: Market Report 2016 (IEA, 2016)	consumption (214) emission(s) (69) distribution (7) generation (44)	56,522	0	10
The Future of Electricity in Fast-Growing Economies (Bosco et al., 2016)	consumption (3) emission(s) (8) distribution (27) generation (59)	11,299	0	15
World Energy Resources 2016 (World Energy Council, 2016)	consumption (374) emission(s) (443) distribution (81) generation (887)	289,475	0	181
Integrating Strategic Environmental Assessment into Power Planning (Asian Development Bank, 2015)	consumption (0) emission(s) (12) distribution (1) generation (16)	14,309	0	9
Status of power system transformation (IEA, 2017)	consumption (53) emission(s) (21) distribution (104) generation (348)	70,069	1	20
The future electricity grid: Key questions and	consumption (12) emission(s) (0)	25,294	0	11

considerations for developing countries (Jairaj et al., 2016)	distribution (39) generation (204)			
Power Systems of the Future: A 21st Century Power Partnership Thought Leadership Report (Zinaman et al., 2015)	consumption (5) emission(s) (7) distribution (37) generation (49)	18,230	0	1

In addition to what appears to be a lack of available research on power distribution in developing countries, when the research is done, it is often simply from the view of distribution cost (Winkler et al., 2012) rather than how it can be utilised to create system efficiency. Research often refers to distribution in developing countries and urban planning therein as only applying to physical accessibility and cost recovery (Hartvigsson et al., 2015).

Understandably, in developing countries where finances can be challenging, generation, which is highly capital-intensive and involves both an initial expenditure for machinery and often for on-going fuel costs, is the emphasis of most research. Also, installing solar panels in an area can easily be translated into positive public relations and provides one simple area for masses to focus on. Improving distribution efficiency in crowded urban centres may have the same impact in terms of carbon reduction, but provides a more complicated focus area and relief method for a problem. It is understandable why many policymakers choose to focus on single, large, 'green' generation targets rather than on complex solutions for distribution efficiency, and why the latter is underemphasised in existing research. This comparative lack of research emphasis may also indicate that system efficiency gains could be found in this area through further investigation.

2.2.2.2 Do Policymakers Incorporate This Driver of Load In System Planning and Why?

Policy documents directly state that the greatest driver in policy and planning in the world's largest power markets – China, India, Russia, UK and the USA – is affordable generation (Asif and Muneer, 2007; Severance, 2011; Milligan et al., 2015). Research from the Association of Southeast Asian Nations (Thavasi and Ramakrishna, 2009) clearly states that policy on power must emphasise sustainable generation and meet the needs of growing populations and industrial sectors. Distribution and urbanisation are not at all mentioned in these planning documents. Countries such as Pakistan have mentioned urbanisation as an important factor in policy documents, but have not promulgated specific policies or directives on how to incorporate urbanisation and its intersect with the distribution system in power planning (Mirjat et al., 2017). The United States Agency for International Development (2013) has published statistics about urbanisation in developing countries and encourages policymakers to take this into account in power planning, but does not offer specific guidance on distribution of power into growing urban areas. The United Nations Human Settlements Programme (2016) similarly emphasises the need for efficiency in the built environment in cities but does not offer specific paths for this. Lin et al. (2017) have shown that while China is encouraging urbanisation in its economic growth policies, it is not reflecting this in its power planning policies. The African Development Bank Group (2013) states this as the single largest problem and area of policy focus. The Organisation for Economic Co-operation and Development and the IEA (2010) encourage policymakers in developing countries to manage the gradual reduction of subsidies and an increase in effective cost pass-through mechanisms into tariffs.

Some authors attribute the lack of distribution planning and urbanisation in power systems to the notion that there is no 'best practice' or model on how to do this (Moghadam et al., 2017). Many smart cities and other more data- and consumer-goods-oriented models are suitable for wealthy nations but do not help in planning for urbanisation in the developing world (Schwartz, 2010; Schwartz and Sheaff er, 2011). Much of the policy planning methodologies for urban power distribution systems are focused on the developed world (Nahman and Perić, 2017). Both the United Nations (Compton, 2011) and the World Bank (2013) have noted the deficit of information on effective planning for distribution systems in developing countries and the major impact of this on energy systems and the environment.

Academic research, non-academic research, and policy all point to a deficit of knowledge in how to effectively plan at the intersect of power distribution systems with urbanisation in developing countries.

2.2.2.3 Do Power Companies Incorporate Urbanisation in System Planning?

Developing countries typically focus on spurring demand through economic growth, and encouraging power companies to produce power with specifications around quantity, safety, reliability, and environmental impacts. Incentives and profit drivers for power companies are typically around meeting these generation requirements (Lin and Li, 2014). Developing counties have made progress in encouraging and developing renewable energy generation (Farell and Remes, 2009). However, incentives should be more geared towards system efficiency (Kessides, 2012; KPMG International, 2015), rather than just towards clean generation. In Brazil and other developing countries, investment patterns closely follow what the private sector is financially incentivised to do from policymakers, which does not involve distribution or urban planning (Costa et al., 2017) but rather generation capacity and, second to this, transmission capacity.

In the developed world, the private energy sector has already started exploiting big data (Kolokotsa, 2016), and its utilisation to profit from energy consumption and consumer behaviours (Zhou and Yang, 2016). Data on temperature, weather, utilisation of critical loads such as hospitals, and other activities driving energy demand are being used for forecasting, system balancing, demand response, and other activities which make the power system more efficient. These come in the form of smart city applications and often impact the distribution system in urban centres by augmenting the demand and, in many cases, the supply of power. Key requirements of these systems, however, are robust telecom and data connectivity (Sodenkamp et al., 2015), and key profit drivers of these are often oriented around data sales and consumer spending (Koutitas and Demestichas, 2010). These issues do not make such smart city platforms profitable or appropriate for developing countries (Bekker et al., 2008; Kolloch and Dellermann, 2017).

The power sector largely profits from generation and availability. Globally, the vast majority of power systems provides revenue for power generation, power distribution, the ability to generate power as needed (stand-by services, black start capabilities), and power regulation (voltage control and frequency regulation); very few provide revenue for efficiency or reduction of load. This impacts planning and the operating model of the value chain. The key models for other areas of profits outside of this that would fall into the distribution system or would impact urbanisation are not appropriate for developing countries due to lower GDP per capita and potential for services related to data, telecom, or consumer spending.

There are attempts to make models for how power companies can be incentivised and can profit from creating system efficiency in the distribution level in developing countries, but these are in nascent phases (Kumar et al., 2016). For example, Hong Kong offers demand-response revenues to its two utilities (China Light & Power, Hong Kong Electric) on seven days per year when the ambient temperatures reach a peak and air conditioning load is typically at its highest. While executing a successful demand-response program requires significant coordination across the network operations and in customer outreach, these rewards are only granted on seven hottest days per year rather than regularly, which would allow the operator to shape demand and incorporate VRE. Moreover, lack of data, lack of incentives, lack of research, and lack of pre-existing models or best practices are hindrances to making power distribution in developing countries an attractive area to invest in (Poggi et al., 2017).

2.2.2.4 What Are the Implications of This?

It has been shown in **Sections 2.1.4** (page 19) and **2.2.1** (page 22) that urbanisation and infrastructure development are key drivers of power demand in developing countries. The literature review in **Sections 2.2.2.1** (page 27), **2.2.2.2** (page 29), and **2.2.2.3** (page 30) identified a clear gap in research and knowledge on the role of urbanisation and the built environment as a driver of power demand in developing countries. This aspect of energy system development is generally not addressed in research papers, policy documents, or power sector investment. It has also been shown that there is a lack of models and best practices (Muringathuparambil et al., 2017) and that this is a hindrance to obtaining (ex-generation) power system efficiency in developing countries (Osorio and Sauma, 2015). Distribution systems hold major potential for creating power system efficiency (US DoE, 2015) and developing countries are major drivers of energy demand growth.

The focus of subsequent research was on quantifying and qualifying solutions for developing countries to plan an efficient intersect of the built environment and power distribution. Ultimately the tools developed would be tested on a real-world example – an area with increasing urbanisation and load density (**Section 2.3**, page 33). This was done in order to obtain feedback on the effectiveness of the research and tools and determine whether they are applicable to real-world situations.

2.3 Overview of the Selected Geography Used in the Case Study

In the second part of this research, we performed a case study on an area that contains the components of the research gap identified in **Sections 2.2.2.1** (page 27), **2.2.2.2** (page 29), and **2.2.2.3** (page 30). This tests the application of the research outputs in an area where the research gap has been identified, and, in the process, supports the utility and functionality of the research and solution methodology. A web search was done in order to identify a case study location meeting the following criteria:

1) Is in a developing country;
2) Is currently undergoing urbanisation (not planned, but currently occurring);
3) Is seeing an increase in the built environment;
4) Has the information on the area and its development publicly available and in the English language;
5) Practicable (i.e., close to the researcher's base and accessible for site visits).

The search revealed one area fitting these criteria; was Thailand's Easter Economic Corridor (EEC), a development alongside the Cambodia border, which is described below.

2.3.1 The Eastern Economic Corridor of Thailand

Thailand's EEC project is a $45 billion investment in infrastructure, connectivity, employment generation, and poverty alleviation in Thailand's eastern coastal provinces Chonburi, Rayong, and Chachoengsao, spanning over 13,000 km^2. It is targeted to be completed by 2021 (Royal Thai Embassy, 2015). This area spans the Thailand–Cambodia border and is currently a series of small- and medium-sized towns with significant trade and immigration across the border (**Figure 7**). The EEC project is designed to develop and support infrastructure and employment in this area.

The government of Thailand has promulgated various measures, including the EEC Bill, to support the economic growth in the EEC, including bolstering utilities, transportation systems, logistics, training, and human resource needs. The stated mission of the EEC is to support the modernisation and development of Thailand, specifically within three states bordering the Gulf of Thailand and Cambodia, focusing on key physical and social infrastructure. The government has also launched a campaign aimed to simplify and facilitate private sector investment (Royal Thai Embassy, 2015).

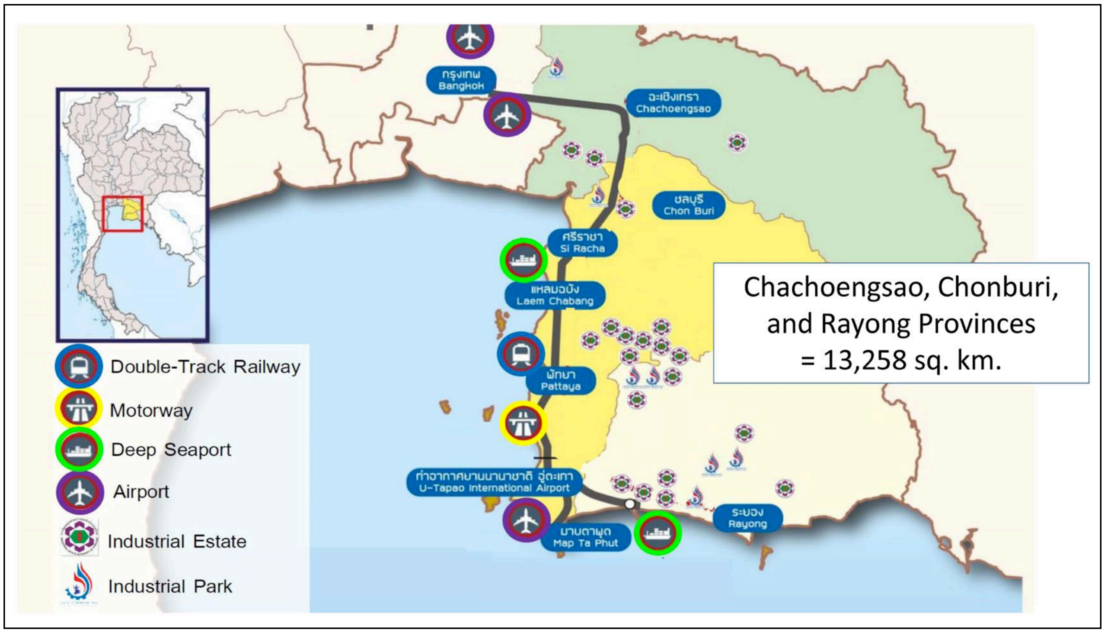


Figure 7. Existing infrastructure in the EEC area (Royal Thai Embassy, Washington D.C., 2015).

The EEC Bill provides tax incentives and multiple fiscal measures for entities to invest in EEC projects. Land leases of 99 years and tax reductions are examples of ways by which the government is an enticing investment in the region. The government has also allowed for relaxed visa procedures for foreign professionals of several qualifications and also utilised executive powers to help speed investment approval (Baker McKenzie, 2018; Reuters, 2018).

<u>There are ten focus industries for the EEC</u> (PUGNATORIUS Ltd., 2018):

1) Next-generation automotive,
2) Intelligent electronics,
3) High-income tourism and medical tourism,
4) Biotechnology and advanced agriculture,
5) Food processing,
6) Advanced robotics,
7) Logistics and aviation,
8) Biofuels and biochemical,
9) Digital,
10) Holistic medicine and health services.

Of the total quantity of EEC infrastructure investment (**Figure 8**), Thailand government spending will account for approximately 30%, with public-private partnerships composing approximately 59%, state-owned entities composing approximately 10%, and the Royal Thai Army with approximately 1% (Theparat, 2018).

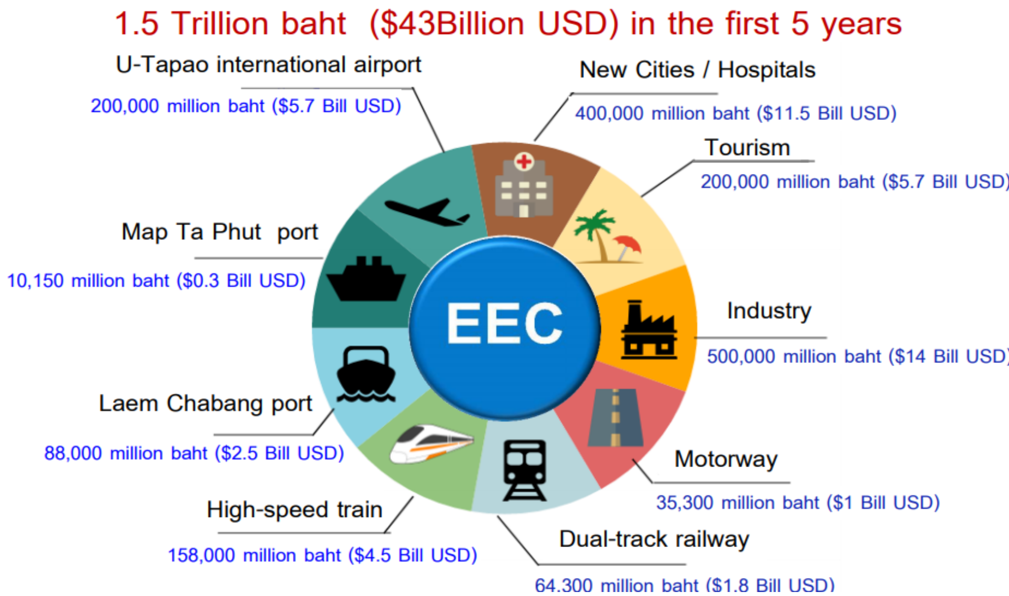


Figure 8. Combined public and private investments in the EEC (Eastern Economic Corridor Office, 2017).

This will have large-scale implications for power demand and related infrastructure. The Thai government and a state-owned power entity are focusing on addressing this in two ways. The first is by energy diversification, encouraging a high quantity of renewables and 'new energy' projects into the existing conventional system in the area. The second is to mandate and encourage a focus on demand-side management and energy efficiency (Harakunarak, 2017).

Thailand's Power Development Plan (PDP2015) provides detail on a long-term investment plan for the power sector and significant projects like the EEC. According to PDP2015, security of energy supply will come from several sources, including reducing natural gas dependency, increasing the share of clean coal in power generation, importing power from neighbouring countries (predominantly Laos with large hydropower reserves, **Figure 9**), and developing both large-scale and distributed renewable energy (Harakunarak, 2017).

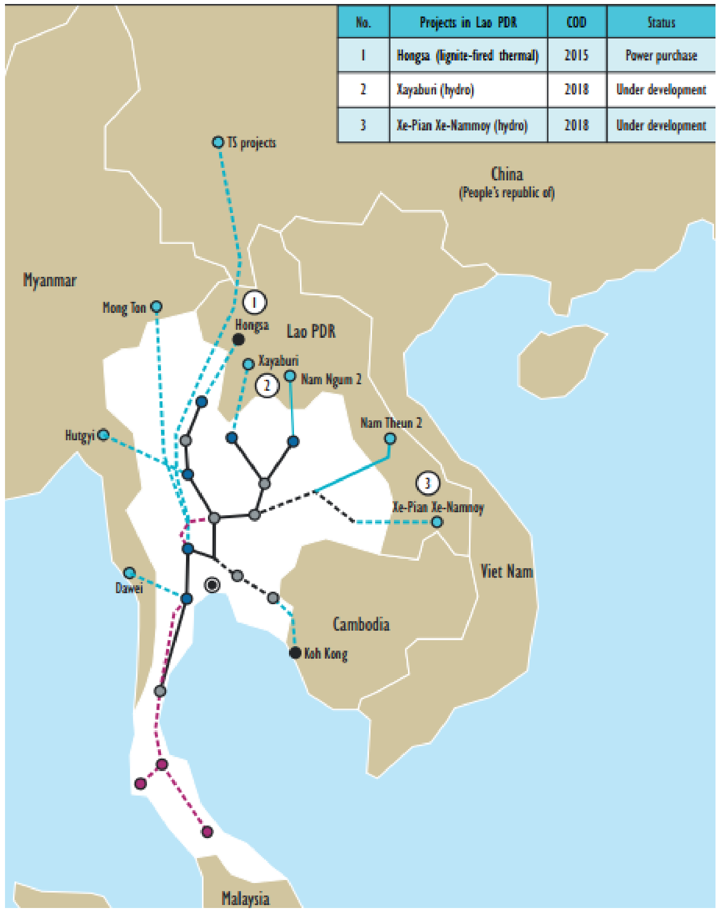


Figure 9. Map of the transmission system of Thailand. The solid line means existing; the dashed line means planned or under construction. Source: EGAT (2016), '*Grid governance and management*', presentation to IEA Review Team.

The current decision-making process for EEC infrastructure has a simple structure. The EEC commission directs the Electricity Generating-Authority of Thailand (EGAT), the Ministry of Transport (MOT), and other departments and ministries to develop key infrastructure in areas within the EEC region. Those entities then issue non-binding requests for proposal (RFP) to the public on their websites. This allows various contractors and service providers to issue statements of their qualifications and how they would perform the tasks detailed in the RFP. The government entities review these non-binding proposals, hone their RFP and requirements, and re-issue a new RFP, which is binding. Companies can then respond to the binding RFP with a commercial (costs of the project) and technical (how they will execute) bid. The government bureau is first obliged to review technical proposals, reject those that are unfit, and then review the commercial proposal among those that are fit, and select the lowest-cost provider. While there are some minimal technical and experience requirements, the proposals are scored on a project-by-project basis, and the criteria and system for this are not publicly available. As such, there is a system in place, but the means for scoring proposals is not transparent. The EEC commission could utilise this research and tool to objectively screen projects and make the solution selection process transparent. It could also use the tool to advise

EGAT on what areas it should emphasise in infrastructure projects and corresponding RFPs, and why.

2.3.2 Planned Infrastructure

The EEC acronym pertains to both the physical land area, as well as to the governmental organisation that focuses on the implementation of development projects. The EEC organisation will place significant emphasis on leveraging new infrastructure, transportation, and logistics systems (**Figure 10**) to bolster employment and poverty alleviation along the Thailand–Cambodia border (Eastern Economic Corridor Office, 2017).

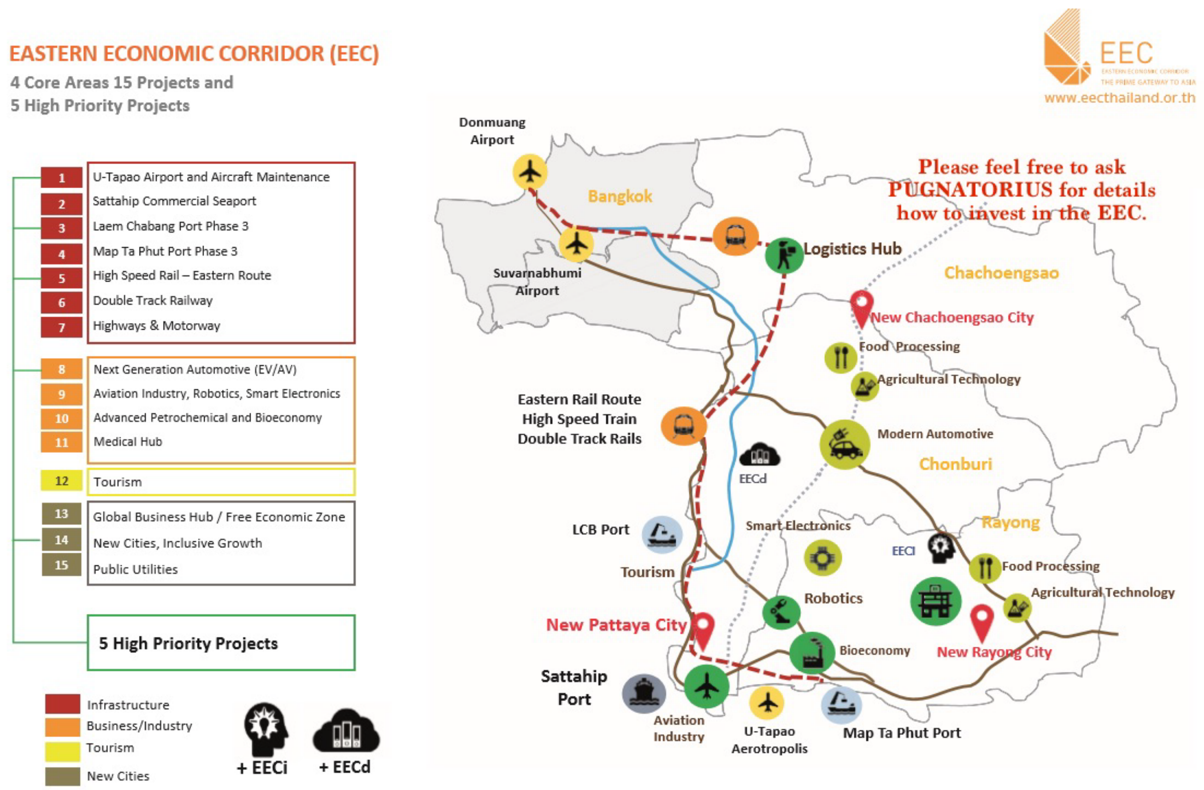


Figure 10. Three phases of infrastructure development in the EEC (Eastern Economic Corridor Office, 2017).

The EEC organisation will attempt this through two focuses:

1) Connecting the EEC area to regional airways through the development of 1) the 'Eastern Aviation Specialised Zone' and 2) the Eastern Airport City. The latter will attempt to raise the prominence of the region as an aviation and logistics hub. This will be supported by goods and passenger connections to major airports (Don Muang of Bangkok, Suvarnabhumi International of Bangkok, and U-Tapao Airport of Rayong Province). These locations will be connected by high-speed trains allowing for reduced travel times between the EEC and Bangkok of less than 1 hour (Rastogi, 2018).

2) Connecting the transportation of Thai goods with other countries through the development of dual-track railways between Laos, China, other areas of Thailand, and Cambodia. This will be supported by automated transport and operation systems new distribution centre in Chachoengsao. This will be a fully digitised control centre for passenger and freight movement, and managing seaports and airports.

2.3.3 Notable new energy developments in the EEC Area

1) Thailand's Smart Park at Map Ta Phut, Rayong

- The Smart Park is planned to include 100 MW of distributed (small- and medium-scale) solar photovoltaic generation and 30–40 MWh of battery storage. It is expected to be completed by 2020 and will play a significant role in renewable energy integration, power trading, and system stability (Power Ledger, 2018).
- Using energy-trading platforms in the Smart Park, building managers will be able to trade stored energy and variable renewable energy with pre-planned financial incentives for assisting in system balancing (Power Ledger, 2018).

2) Digital Park Thailand

- This Digital Park is planned to be Thailand's ultra-high broadband area in Chonburi province and the first major foray into this level of data management. It is designed to attract investment from high-tech and data management companies globally.

2.3.4 New Energy Planning

Due to economic growth, Thailand has seen a steady rise in power consumption across all sectors in the last 16 years (**Figure 11**). The compound annual growth rate in power consumption, 3.5%, closely mirrors the 3.2% economic growth over the same period. Over the next five years, electricity demand is expected to increase further at a compound annual growth rate of 3.3% (DBS Vickers Securities, 2017). The EGAT has announced intentions to launch smart city and electric vehicle initiatives for the EEC area, but details for implementation are still under review.

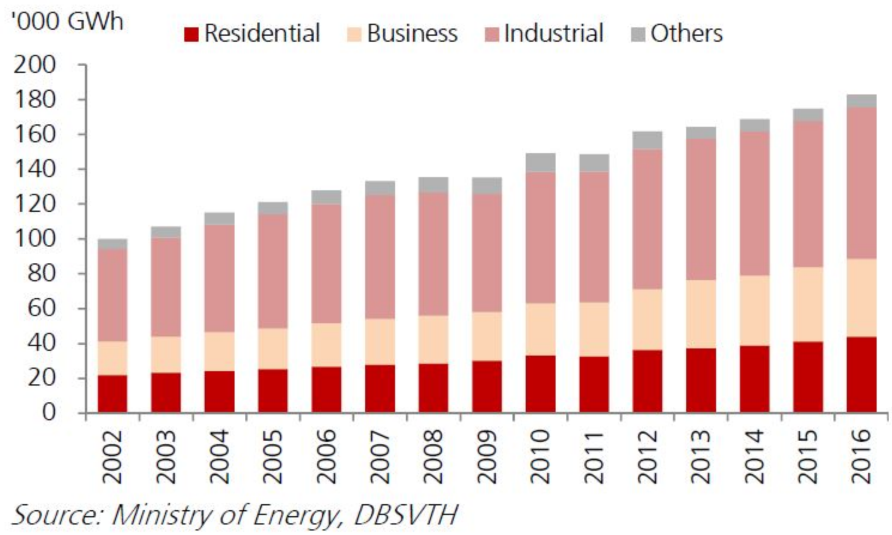


Figure 11. Power consumption by sector (source: DBS Vickers Securities, 2017).

In Thailand, the period of peak power demand occurs from March to June when citizens counteract the summer heat with air conditioning. Since 2012, the peak summer power demand has steadily risen, reflecting the increased purchasing power of the Thai people (**Figure 12**). The Thai government has already appealed the public to minimise the electricity consumption from April to May because of the transition to more expensive imported liquefied natural gas during the approaching maintenance shutdown of piped natural gas from Myanmar (DBS Vickers Securities, 2017).

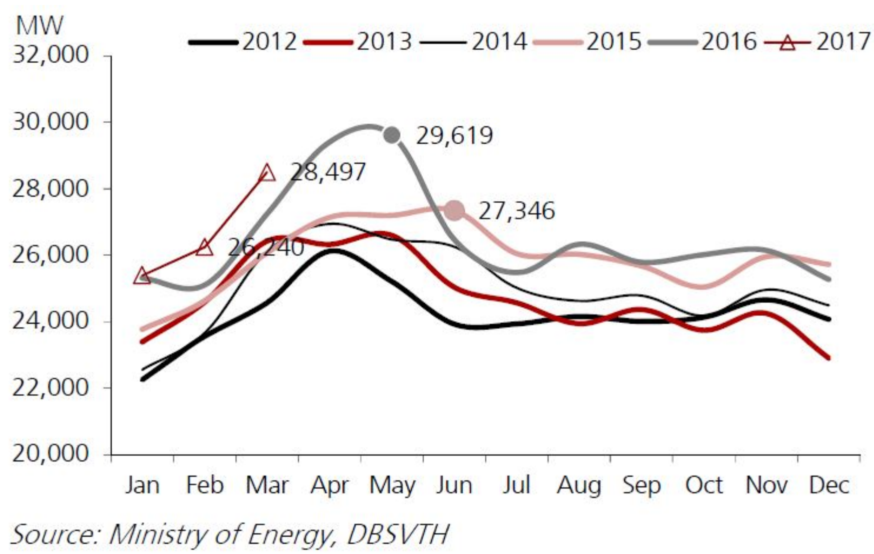


Figure 12. Thailand's peak demand for electricity – notice the continual increase in the slope of the load curve over time (source: DBS Vickers Securities, 2017).

To manage the anticipated rapid increase in urbanisation and related issues along this corridor and large land area, Thailand has introduced new measures to streamline and fast-track power production for very small power producers (VSPP, <10 MW per location) and small power producers (SPP, <30 MW per location) (Eastern Economic Corridor Office, 2017). A variety of biomass and waste-to-energy projects have been proposed since this was promulgated (**Figure 13**, **Figure 14**).

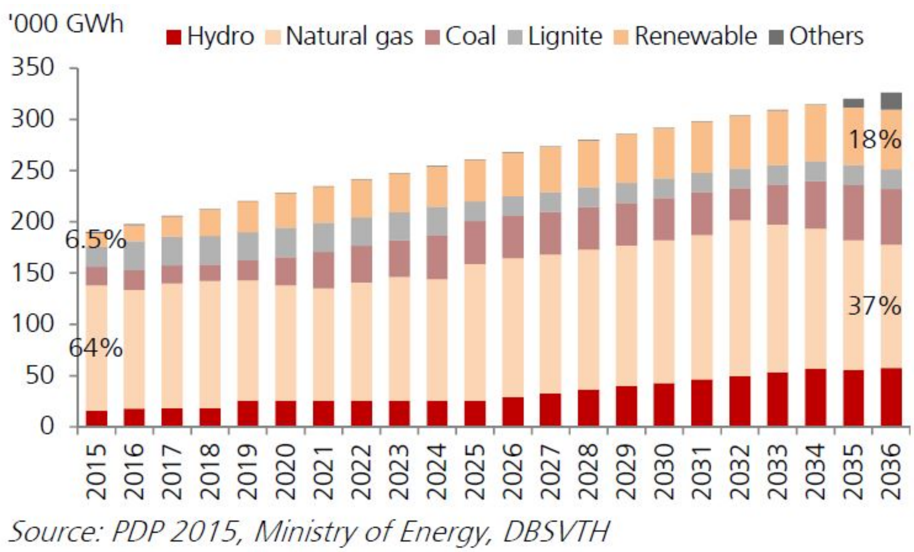


Figure 13. Thailand's electricity generation by fuel type (source: DBS Vickers Securities, 2017).

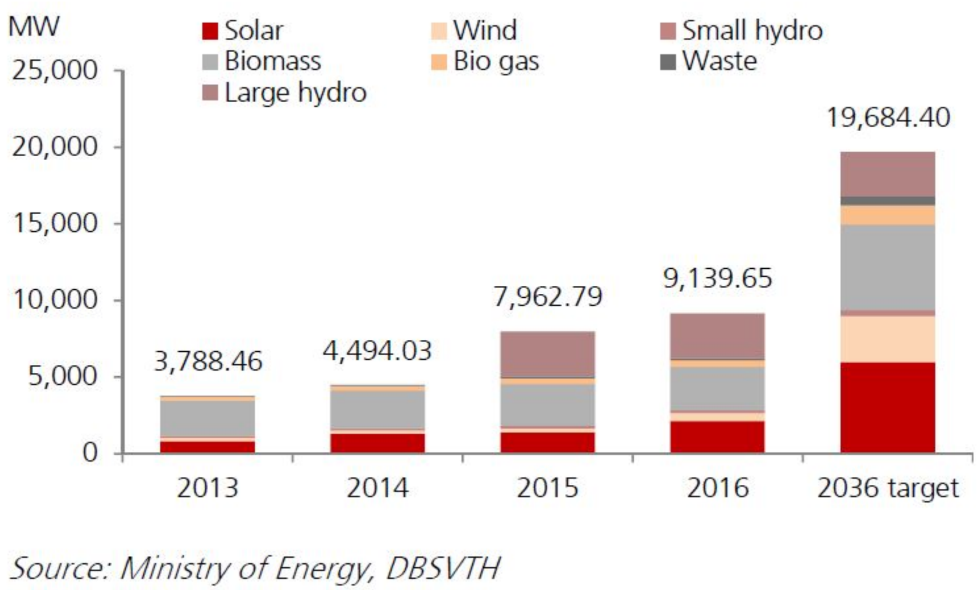


Figure 14. Electricity capacity by renewable power (source: DBS Vickers Securities, 2017).

2.3.5 The current state of the EEC region and Implications of the EEC Program

Included here is a map showing gross domestic product (GDP) per capita of the EEC area (**Figure 15**). This, however, can be deceiving. The EEC area features major import and export facilities where raw materials and finished goods come in and out of the country. It is a major area for importing gas, processing it into plastic products, and manufacturing items such as auto parts. It is also a hub for distributing these parts to landlocked Laos and Yunnan (Southern Central China), and infrastructure-poor Cambodia and Myanmar. So the GDP that takes place here is driven by industrial activity, but the quality of life and wages for many of the inhabitants of the area are not high. While these wages are not attractive to many, they are better in many cases than what people can obtain in Cambodia, which borders the EEC area. Consequently, the EEC area has a large amount of migrant labour. Building infrastructure and developing a more diverse base of employment is a major driver behind the EEC program.

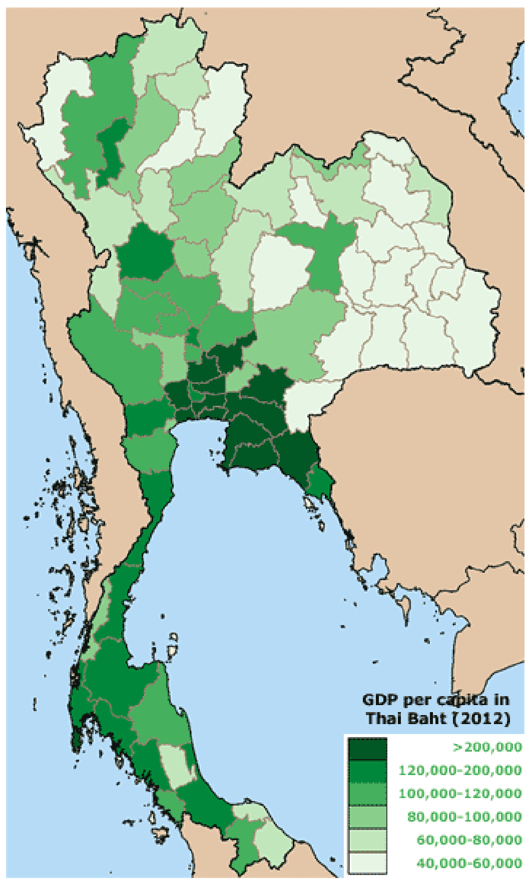


Figure 15. Thailand's gross domestic product per capita by province in Thai baht in 2012 (map by Guido Vanhaleweyk based on the data from Thailand's Office of the National Economic and Social Development Board).

Another driver is to divert urban pressures from Bangkok. Metropolitan Bangkok is large, traffic and transportation are very challenging, and accommodating a steady flow of migrants from the countryside is challenging for the city. Developing a satellite city connected to Bangkok is a way of easing some of these urbanisation pressures (**Figure 16**). A similar approach is being adopted in the Philippines – to divert urbanisation pressures, Clarke New City is being developed and connected to Manila by a bullet train.

In sum, the Thai government views the EEC as critical to creating more and new types of employment in a poor region and in easing urbanisation pressures on the capital.

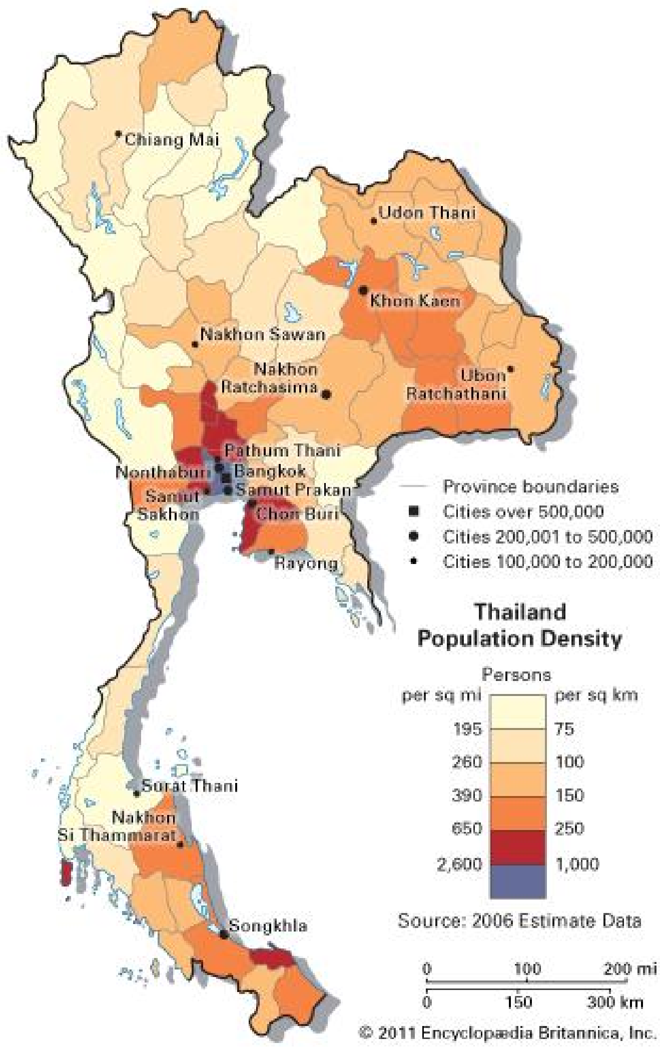


Figure 16. Population density in Thailand in 2011 (source: Encyclopaedia Britannica Online).

2.4 Aims and Objectives of the Research

The aim of the research was to first look at developing countries and then understand if and where improvements can be made in their energy systems, and where additions to research and knowledge can be made. The desired end outcome was thus to equip academics, engineers, policymakers, and planners working in developing countries with a methodology to create and rank energy efficiency solutions. Given the importance of urbanisation in driving the long-term load, and the forecasts for urbanisation in developing countries to grow at rapid rates through the 21st century, developing and understanding of these issues is critical to energy systems and the environment. In order to understand these critical areas and contribute to academic knowledge, the following research objectives were set:

1) Understand the long-term drivers of load in developing countries. Understand not what drives singular or short-term increases in energy demand, but long-term, recurring energy demand.

2) Determine if there is a research and knowledge gap in these areas. Review what is currently available in the literature, and determine if knowledge gaps exist and if knowledge of this area can be enhanced.

3) Based on academic, public, and private sector documents, conduct further research on the identified research gap, document, summarise, and analyse the research gap.

4) From researching the gap, understand systemic sources of problems and missed opportunities. Separate anecdotal and location-specific issues from systemic, recurring issues.

5) Group these systemic problems and create a database that displays them. In doing so, produce a repository of information to analyse.

6) Develop a framework for translating the problems and missed opportunities into planning tools and solutions. Once the systemic issues have been determined and qualified, develop a solution framework to address power-planning issues.

7) Conduct interviews to obtain feedback on the methodology and solution framework. It is important to complement research with industry expert views so that a holistic understanding of the research focus areas can be achieved.

8) Apply the solution framework to a live case study to test its suitability. This is a critical step to test the viability and applicability of the solution framework.

9) Summarise conclusions for the benefit of the academic community and interested parties.

3. METHODOLOGY

3.1 Research Process

The research started simply by asking 'What drives power demand growth in developing countries?' The research essentially took the form of a process of discovery, starting with fundamental-level problems and with each phase of discovery guiding the next steps. **Appendix A** shows a logic map made at the start of the research, which demonstrates the initial path of distilling the research roadmap. This was derived from the initial literature review and designed to identify any significant gaps in the academic literature and policy environments. The gap identified (planning distribution systems in rapidly urbanising countries) became the focus of the research. The logic map starts by identifying what drives long-term power demand in developing countries, and how well these drivers are understood and incorporated into action by policymakers, industry, and the academic community. This was an initial framework derived from the early portions of the literature review. The research then sought to identify areas where there were problems and to create a framework for solutions. As such, it dealt with significant areas where critical problems, their roots, interconnections, and a systematic means for improving them needed to be discovered, rather than located in existing documents. A rapidly evolving energy sector means that published literature can quickly be out of date. As a consequence, it was important to seek external verification of any results. Consequently, both identified gaps and possible improvements were endorsed by expert interviewees, scorecards were created to rank them. Ultimately, a framework was established to translate them into solutions. These solutions were tested on a live example and again endorsed by expert interviewees.

The sequence of the discovery process and the methodology used can be summarised as follows:

1) **Understand what is of greatest emphasis in academic research, and public and private sector activities in power sectors in developing countries.** It was critical to first start with understanding what drives power demand in developing countries and to identify what creates singular short-term power demand versus what creates a long-term or permanent increase to power demand. Research showed that generation is emphasised significantly more than power distribution (**Section 2.2.2**, page 26).

2) **Define what drives consistent, long-term power demand in developing countries.** The importance of this step is to ensure that the research does not focus on short-term problems but rather on those with a long-term impact to the environment, and on the fundamentals of power demand rather than problems with a short-lived impact. Research and case studies revealed five core drivers of power demand throughout developing countries (**Section 2.2.1**, page 22). Those that were one-off or created short-term impacts on power demand were deemed out of scope.

3) **Understand if urbanisation and its impacts are being sufficiently incorporated in academic research, and in public and private sector activities in power sectors in developing countries.** Through research, it was discovered that this area is underemphasised versus generation capacity, subsidies, and financing structures for generation. From here, urbanisation as the driver of long-term, sustainable power demand was further analysed for its root causes, problems it creates in power planning, and opportunities that can be seized for improvement (**Section 2.2.2**, page 26).

4) **Understand the impacts of the lack of emphasis on distribution in developing countries.** Through global research, a list of 32 commonly found distribution issues were discovered in under-emphasising power distribution in developing countries (**Section 4.1**, page 67).

5) **Rank problems arising from the lack of emphasis on power distribution.** Scorecards were developed to rank and score the list of 32 distribution problems and their impact (**Section 4.2**, page 92). The scorecard was then further developed by leveraging the IEA framework to guide the user toward developing solutions (**Section 5.3**, page 147).

6) **Discuss the suitability of scorecards with expert interviewees.** Three industry executives from three countries were interviewed on the exhaustiveness and accuracy of the 32 distribution problems. The experts were then asked to rank them in the scorecards (**Section 5.1**, page 113).

7) **Apply the solution framework to a live example of infrastructure and power development in a developing country**. The scorecards and the solution development methodology were applied to an area of Thailand along the Cambodia border where power density and power demand are increasing due to urbanisation and infrastructure development (**Section 5.3**, page 147).

8) **Discuss the solutions developed for the area along the Thai-Cambodia border with expert interviewees.** The solutions specific to this developing area were presented to a major Thai power company. Executives were interviewed on the effectiveness of the solutions and broader methodology (**Section 5.2**, page 115).

3.1.1 Ethics

The expert interviews followed the Research Ethical Guidelines from the School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University. I consulted my Heriot-Watt mentor to review the ethics policies and filed the related documents necessary for Heriot-Watt's ethics procedures (**Appendix B**). I then contacted the three interviewees (**Section 3.4**, page 52) by email, with the ethics policy attached, and asked their willingness to participate. When they responded positively, I emailed them a summary of the 32 problems (**Section 4.1**, page 67) and the Excel scorecard. Following this, I drafted a list of questions for the interview

(**Section 3.4.1**, page 54), and reviewed this with my Heriot-Watt mentor. The interview transcriptions can be found in **Appendices C–E**.

3.1.2 Positionality and Reflexivity

There is an obvious presence of reflexivity in the interview questions. This problem is potentially compounded by the researcher's personal work experience in the energy sector in Southeast Asia. This was partially addressed by ensuring that the questionnaire and its structure were supported by evidence from the literature. Furthermore, the interviewees, once finished with answering the interview questions, were allowed to guide the discussion as they saw fit. Nevertheless, the interviewees were impacted by my introduction of the topic, and therefore positionality and reflexivity are inevitably of some impact. All of the interviewees politely indicated that they could participate in the research but asked to not create an audio recording and not publish the names of their employers. While this is a drawback, it is nevertheless somewhat balanced and explained by their sharing details of having worked closely with governments and major stakeholders in large energy projects. Ideally, more interviews would have been conducted; however, accessing professionals with experience in the focus areas – distribution planning in developing countries – was not easy. Also, asking seasoned executives to take the time to speak on the phone with someone they do not know directly was difficult (personal networks were used to access these individuals; however, they are not direct friends or colleagues of the researcher). It would have been preferable to have conducted more interviewees. However, it is positive to note that, while contacted and interviewed separately, the participants shared common views on many critical areas.

3.2 Identifying the Problems Impacting the Intersect of Power Distribution and the Built Environment: Literature Review

The focus of the literature review was on systematic problems in power distribution planning, structural problems in designated planning bodies, planning methodology issues, sector reform issues, general practices of power sector planners, and missed opportunities that are becoming more attractive with emerging distribution technologies as well as cost declines in these technologies. The literature review was conducted using Google, Google Scholar, and Kobson search engines. Searches were conducted using the phrases 'power distribution', 'urbanisation', 'developing countries', and 'power system modernisation'. Over 600 documents focusing on these areas were researched, including academic papers (original research papers, reviews, and case studies) and policy documents from various sources such as government bodies, non-profit organisations, and consultancy firms. Following this initial sift, the case studies containing a clear root and impact related to the focus areas were saved in a repository.

Despite a large number of documents examined, it must be noted that this literature review had challenges and limitations. Google and Google Scholar are currently the most powerful and comprehensive search engines for both academic and non-academic documents (Gusenbauer, 2019). However, some key information sources, such as institutional repositories, are not necessarily accessible to search engines (Arlitsch and O'Brien, 2012), and the documents they contain thus cannot be found using exclusively internet. Also, the documents gathered were limited to those returned by the search engines for the queries used. Different search queries may have yielded different results.

The research resulted in a list of 32 identified problems accompanied by case studies that articulate the problems. The list was compiled by frequency of appearance in academic papers, policy documents and case studies (rather than problems only seen in one place or one particular circumstance), by having a root in the system planning process (or lack thereof), and by being noted by the author or issuing body as consequential to the system and to the environment. These problems were only amalgamated if both their roots and their outputs or impacts matched; if not, they were left as separate items. It was required that 5 or more case studies needed to be found which articulate the problem in order for it to be amalgamated into the list of 32 problems. A list of the key case studies is located under each of the problems in **Section 4.1** (page 67). All documents that satisfied the research conditions and were selected from the initial 600+ search results are listed in **Table 3**.

The research does not consider the following three items, which are deemed out of scope. This is because they represent non-systematic issues, issues well covered by existing research, and issues of human behaviour, respectively.

1) Point problems (storage is needed in X location) with point solutions (put a battery in X location);
2) Markets, tariffs, and deregulation, as this is well-covered by existing research;
3) Corruption and human behaviour aspects.

3.3 Development of the Analysis Tool

3.3.1 Understanding and Ranking Problems

The first portion of the research involved displaying a gap in academic, industry focus, and government attention in the three focus areas (distribution planning in developing, urbanising countries), followed by detailing the most significant problems in the focus areas. After this, a ranking and prioritising exercise was developed and executed. This was necessitated by the fact that not all solutions can manage all of the problems at once, and, in practical application, there will be capital and operating rationing of system plans. The ranking and scoring help to prioritise problems and create guidance for formulating solutions.

This was facilitated by three activities:

1) The creation of scorecards to rank and characterise the problems and missed opportunities in the focus areas. One overall system scorecard, and four impact- and result-oriented scorecards specific to the focus areas were built from engineering texts for analysing and planning power systems.
2) Interviews with three industry specialists were conducted. These involved three power industry engineers and policy specialists with over three decades of experience. Their feedback on the focus areas, planning and distribution problems, and their ranking was recorded and is detailed below.
3) From here, the scorecards and their outputs from interviews were then analysed to start the process of developing solutions to improve energy efficiency in the focus areas.

The process of problem characterisation, their ranking and scoring, and finally deriving a solution is commonly known in business and policymaking as "multi-criteria analysis," which is explained below.

3.3.1.1 Multi-Criteria Analysis

Multi-criteria analysis (MCA) is a methodology for producing a logical conclusion from multiple data points, which in one single analytical action may not be feasible, but a sequential or systematic analysis can produce a clear outcome of these multiple data points. Simpler sets or smaller quantities of data can be analysed through simple tools such as a table. The purpose of a multi-criteria analysis is to gather multiple points or sets of data that cannot be managed with single (or simple) tools and to utilise a sequence to produce a logical conclusion or determination. Its outcome is a hierarchy of preferences between options that have been judged against an explicit set of objectives (The Government of the United Kingdom, 2009).

Traditional decision-supporting tools, such as cost-benefit analysis (CBA) or cost-effectiveness analysis (CEA), are inextricably connected to valuing the outputs in money terms, which is neither always applicable nor always desired (The Government of the United Kingdom, 2009). Although its underlying methodology is different from that of CBA and CEA, MCA also provides an entire decision-making framework − from defining the problem and weighing of decision alternatives to the ranking of solutions. The multi-criteria analysis employs both qualitative and quantitative evaluation tools and is thus applicable to multidisciplinary problems. Although CBA is more widely known and more often legally prescribed, MCA is a notable alternative for public decision making. Namely, MCA can support a complex decision process, for example in environmental or sustainability policies, and handle qualitative or ambiguous criteria with unpredictable outcomes (Gamper and Turcanu, 2007).

Furthermore, MCA also presents many advantages over unsupported informal judgement, such as (The Government of the United Kingdom, 2009):

1) Openness and explicitness;
2) When necessary, the choice of objectives and criteria is open to analysis and change;
3) Scores and weights are developed according to established techniques, and their relative values can be supported by literature and amended if necessary;
4) Experts can be called upon for performance measurements;
5) It provides common ground for communication between different stakeholders;
6) It provides an audit trail.

One limitation of MCA is that it cannot show that a positive contribution of a certain factor outweighs its negative contribution. Unlike in CBA, there is no explicit rationale or necessity for a Pareto Improvement rule that benefits should exceed costs. Thus in MCA (as well as in CEA), the most favourable option may not be consistent with the overall improvement, so no action could in principle be preferable (The Government of the United Kingdom, 2009).

Multi-criteria analysis has been increasingly recommended for use by public authorities and similar entities in decision-making processes (Gamper and Turcanu, 2007; The Government of the United Kingdom, 2009). For example, MCA has long been a popular tool for environmental impact assessment in the Netherlands, where it is used by environmental consultants (Janssen, 2001). Blechinger and Shah (2011) used MCA for academic purposes to evaluate policy instruments for climate change mitigation in the power generation sector of Trinidad and Tobago. As a special case of MCA, the scorecard approach has been used, for example, by Pelegrini et al. (2009) to qualitatively and quantitatively evaluate the electricity distribution system in Brazil; by Jürgensen et al. (2015) to track reliability performance of distribution system operators in Sweden; and by du Toit (2009) to improve sustainability of transportation planning in Cape Town.

3.3.1.2 Performance Matrix

A standard feature of MCA is a performance matrix, or a consequence table, which is a collection of criteria which together form a matrix or attribute series showing the aggregate status or full description of the topic of focus. The rows of a performance matrix describe options (ramifications) of a topic, and columns describe the performance of the options against each identified criterion. The purpose of a decision matrix is to incorporate multiple criteria to describe and rank a single or single finite set of topics. It also can allow the creator and user of the matrix to incorporate weights or ranges of scores, rather than simple binary or yes/no ranks. These can be high, medium, low, or colours that indicate a certain level of the attribute being scored (The Government of the United Kingdom, 2009). For greater clarity, the performance matrices developed in this work were termed as "scorecards."

3.3.1.3 Constructing a Performance Matrix (Scorecard)

To construct a performance matrix (scorecard), we need to start with a few basic questions (The Government of the United Kingdom, 2009):

1) Who are using these scorecards? In the case of this research, it is power system planners from aid agencies focusing on developing countries. Know the focus and background of the intended end user.
2) What elements are we judging? Develop the full list of items being ranked, judged, and described by the performance matrix. In the case of the research, it is the area being reviewed for power projects in the overall system scorecard, and the planning and distribution problems in the four subsequent scorecards.
3) Decide what types of outcomes, or types of decisions, we want the user to be able to make. What should the end users be able to do or decide as a result of utilising the scorecard? In the case of the research, they can prioritise what elements should be included in power planning decisions and solution creation.
4) What attributes of these elements do we want to rank? Develop the full list of attributes based on reputable, peer-reviewed sources of the major topics. In the case of the research, these focused on how severe is the problem, what efficiencies are lost, and how new energy technologies may be limited by these problems.
    a) Decide any sub-attributes that should be ranked.
    b) Decide if the attributes have any groups or subgroups by their characteristics.
    c) Decide what levels (e.g., high, medium, low) need to be applied to the attributes being ranked.
5) Check the scorecard's suitability with industry practitioners. In the case of the research, this was done by interviews with the selected industry professionals.
6) Examine the results. Clearly demark where the scorecard shows definitive, consistent rankings. In the case of the research, this was the severity of some of the planning and distribution problems.

3.3.1.4 Constructing Solutions from the Performance Matrix (Scorecard)

The topics being reviewed in **Section 4.1** (page 67) were objectively scored with the use of the following performance matrices (scorecards). Taking these results and creating solutions from the performance matrices requires the use of industry-accepted structure or framework (The Government of the United Kingdom, 2009). In this research, the IEA's annual white paper on modernising energy systems was utilised (IEA, 2017). The document is produced by the System Integration of Renewables unit of the IEA in conjunction with the USA's National Renewable Energy Laboratory. The document's focus and the definition of power system transformation is '*the processes that facilitate and manage requisite changes in the power sector, is an active process of creating policy, market and regulatory environments, as well as establishing operational and planning practices, that accelerate investment, innovation and the use of smart, efficient, resilient and environmentally sound technology options.*' This is a comprehensive document by a world-recognised body in energy systems.

In the white paper, the IEA lists four categories for solutions to modernising energy systems (see **Section 3.6.1**, page 59, for the descriptions). The results of the performance matrix are then grouped into the IEA's framework, depending on the source or impact of the item. The IEA framework provides a bridge to the static outcomes of the performance matrix, where past problems have been scored, with forward-looking creative solutions. As such, the sequence from MCA to a performance matrix, and from a performance matrix to the IEA framework (or another industry-accepted body) enables one to go from objective data scoring to a logical means of developing solutions to problems (The Government of the United Kingdom, 2009).

The scorecard from the research has two key components:

1) The outputs of the four scorecards.
2) The IEA framework for prioritising and grouping the outputs of the four scorecards into solutions for specific areas. The prioritisation system encourages the users to solve problems that were deemed high in impact by the five scorecards. It also provides a simple multiplier for those solutions that can resolve problems in more than one category of the IEA framework.

3.3.2 Development of Scorecards

In order to measure and rank the impacts and importance of the distribution problems, four scorecards were developed from standard textbooks that outline the analysis and formulation of distribution networks and how to modernise them. These include:

1) *'Understanding Electric Power Systems: An Overview of Technology, the Marketplace, and Government Regulation'* (Casazza and Delea, 2010),
2) *'Energy Systems and Sustainability: Power for a Sustainable Future*' (Everett et al., 2011),

3) ‘*Smart Grid: Fundamentals of Design and Analysis’* (Momoh, 2012),

4) ‘*Practical Guidance for Designing a Smart Grid Modernisation Strategy: The Case of Distribution’* (Madrigal and Uluski, 2015), and

5) ‘*Renewable Energy: Power for a Sustainable Future*’ (Peake, 2017).

Standard metrics and power value chain components from these texts were inserted in columns of the scorecards, with the planning and distribution problems in rows. The standard metrics and power value chain components were grouped into four scorecards by their impact on various areas of the built environment and their management:

1) What portion of the power system is impacted;

2) What part of the city or urbanisation planning process is impacted;

3) The magnitude of corrective measure to these problems;

4) How these problems impact new energy products and services, or emerging technologies that are now creating power system efficiencies.

3.3.3 Scoring

To score the magnitude of the 32 problems, a unipolar, 6-point scale ranging from 0 to 5 was implemented based on the recommendation from Krosnick and Fabrigar (1997). A unipolar scale represents a gradient of the same construct with no conceptual midpoint; it usually begins with a zero. In unipolar scales, the information gathered with too few scale points is too crude, whereas too many scale points obscure the meaning of the results. The optimal length of a unipolar scale thus ranges between 4 and 7 points (Krosnick and Fabrigar, 1997). The scale is ordinal and should be scored with integers. The ordinal scale allows the calculation of median values in scorecards 1–4 (**Tables 3–6**). Note that zero is the lowest score, which also included in the calculation of the medians of the four scorecards. For the overall system scorecard, 0 denotes ‘not applicable’ (NA).

The scorecards help the user to understand the 32 distribution problems in the context of power system planning and urbanisation. They also provide a framework for developing solutions through comparing problems documented in case studies, with critical components of distribution systems from modern engineering texts, complemented by expert interviews.

3.4 Expert Interviews

Interviews were utilised to obtain feedback on the research, methodology, and outputs. The goal of the research was not to obtain a large sample size and distribute a questionnaire, but instead to have detailed discussions with senior professionals who have direct experience in the focus areas of the research. Personal networks from the researcher's work experience were utilised to locate three people, each with over two decades of direct experience in working on energy projects in developing countries, and specifically those who have an understanding of generation versus distribution. While these individuals were accessed through personal networks, it should be stressed that they were neither personal friends nor work colleagues of the researcher. In addition, it was important to find interviewees who were technologically agnostic – meaning not someone who sold specific brands (e.g. General Electric or Siemens technologies) for years. Professionals were identified that produce designs (with no ties to hardware or software production) or who planned and operated power systems (a power company) and had worked with multiple technologies and vendors. Career and work experience not heavily invested in one vendor, or one technology, was a critical feature of selecting the interviewees.

The chosen interviewees were as follows:

1) **Interviewee 1:** Managing Director of power delivery for a US engineering firm. He is an Indian national now based in the US, with much of his work focused on sub-Saharan Africa and developing Asia.
2) **Interviewee 2:** Director of power systems for a global-scale energy company. He is a US national based in Saudi Arabia, with a background in Middle East power projects.
3) **Interviewee 3:** Director, an electrical engineer in a major generation and distribution company in Asia. He has worked on distributing power in the Philippines and Southeast Asia.

Before the interviews, the interviewees were sent a Word document detailing the 32 commonly found distribution problems (**Section 4.1**, page 67). They were also sent an Excel spreadsheet with four-dimensional scoring systems to rank the problems (see **Section 4.2**, page 92). Interviewees were asked to fill in what scores they felt were most appropriate given their experience. The interviews were then conducted over the phone, and the responses were typed out during the conversation. The interviewees were first asked standard questions and then openly asked to share their views on system planning from their experience. The goal of the questions was to balance asking the interviewees about the documented areas while allowing them to guide the discussion to areas that they felt were important given their experience. Following this, they were asked to rank the problems in the Excel spreadsheet. They were also invited to share their views on the scorecards and the interview questions. The interviews were roughly 90 minutes each. **Section 5.1** (page 113) summarises the salient points of the interviews, and the transcripts can be found in **Appendices C–E**. The ethics guidelines that were followed when conducting interviews are provided in **Appendix B**.

In interviewing seasoned professionals, their time was difficult to obtain. They returned the scorecards to me largely finished, and we completed the remaining scores via phone during the interview. This was due to a combination of busy schedules and wanting to discuss the scorecards as they filled them in. The prepared questions were used to initiate the discussion; however, being highly experienced and having seen many successful and unsuccessful projects throughout their careers, the interviewees tended to guide the discussion to what they thought was most important.

3.4.1 Questionnaire Design

The questionnaire design followed the recommendations by Brown (2009) and Krosnick and Presser (2018). As the goal of the questionnaire was not to extract quantitative data from the interviewees' responses but rather assess already created quantitative assessment tools (**Section 4.2**, page 92), all questions were broad and open-ended. The question list was initially a longer set and later narrowed to a smaller set of areas focusing on the research gaps. The interviewees were encouraged to express their full opinions and perspectives on the topic, and the length of their responses was not limited. Further, the following best practices of open-ended question design were implemented:

1) The questions were kept at a length of fewer than 30 words;
2) The syntax was kept simple, and concrete, non-ambiguous language was used;
3) No negation was used;
4) The questions were not loaded, leading, biased, or irrelevant;
5) The questions were asked in a logical order, with the first question opening the survey topic;
6) Two questions grouped distribution system enablers by a common denominator (data acquisition vs. data utilisation) to drive the point across more clearly;
7) All interviewees were experts on the topic, so none of the questions was out of their areas of competence.

The questions, which were derived from the list of researched distribution planning problems, were as follows:

1) Do you believe that the attached word document adequately covers key problems in the focus areas? If not, what problems were missed?
2) Which of the problems strikes you as of highest impact, or of greatest need to address?
3) What problems or opportunities do you see in advanced metering, advanced distribution and network planning, IT systems, and in SCADA and similar systems?

4) What problems or opportunities do you see in microgrids, power storage, and demand-side management (DSM)?

5) What recommendations do you have for improving distribution planning in the three focus areas?

3.5 Case Study: Thailand Eastern Economic Corridor (EEC) Development

The next step was to apply the tools and framework to a live example of where power demand and power density is increasing in a developing country with increasing urbanisation. This provided a testing ground for this methodology and the tools that have been developed. The selected area for the case study had to meet the following criteria:

1) In a developing country,

2) In an area where urbanisation is increasing,

3) In an area where power demand and load density are increasing,

4) Currently under live development,

5) Have available information to access and utilise in the tools that have been developed,

6) In a country where one can access experts for interviews to review and critique the proposed solutions in order to test the tools and their outputs.

Thailand's EEC, an area along the Thailand–Cambodia border where significant development and urbanisation is taking place (see **Section 2.3**, page 33), presented a regional opportunity for this; however, it was critical how to conduct this research and find a local counterpart with whom to test the research results. The case study application was thus reviewed by power industry experts who work in the geographic area of the case study's focus.

3.5.1 Research Counterpart: A Thai Power Company

For applying the research and tools to the EEC, four basic screens were applied for an appropriate local partner:

1) Non-state owned and having as much independence from government and political problems as possible,

2) Exclusion from engineering, procurement, and construction (EPC) and other non-power generation and distribution businesses,

3) Scale and regional presence – publicly listed and present in one country beyond Thailand due to the project taking place alongside the Cambodia border,

4) Having a dedicated renewable energy clean technology, or a similar sub-entity, and not simply focusing on thermal or conventional energy.

The power sector in Thailand is largely state-owned or state-controlled throughout the value chain from generation to transmission and distribution. The Electric Generation Authority of Thailand, a government-controlled power entity, is the largest state-owned entity in the power industry, followed by the Metropolitan Energy Authority (MEA, or state-owned distribution entity for Bangkok), and then the Provincial Energy Authority (PEA, or state-owned distribution entity for areas outside of Bangkok). While EGAT is the single largest power generator and the sole operator of the national transmission network, MEA and PEA are responsible for the distribution and retail. To meet growing demand, Thailand adopted what it calls an 'Enhanced Single Buyer (ESB) Structure' (**Figure 17**), where EGAT purchases power from independent power producers (IPPs) and then distributes their power. Purchases from IPPs are under long-term contracts called power-purchase agreements (PPAs), which guarantee a minimum annual purchase of power over a fixed amount of time.

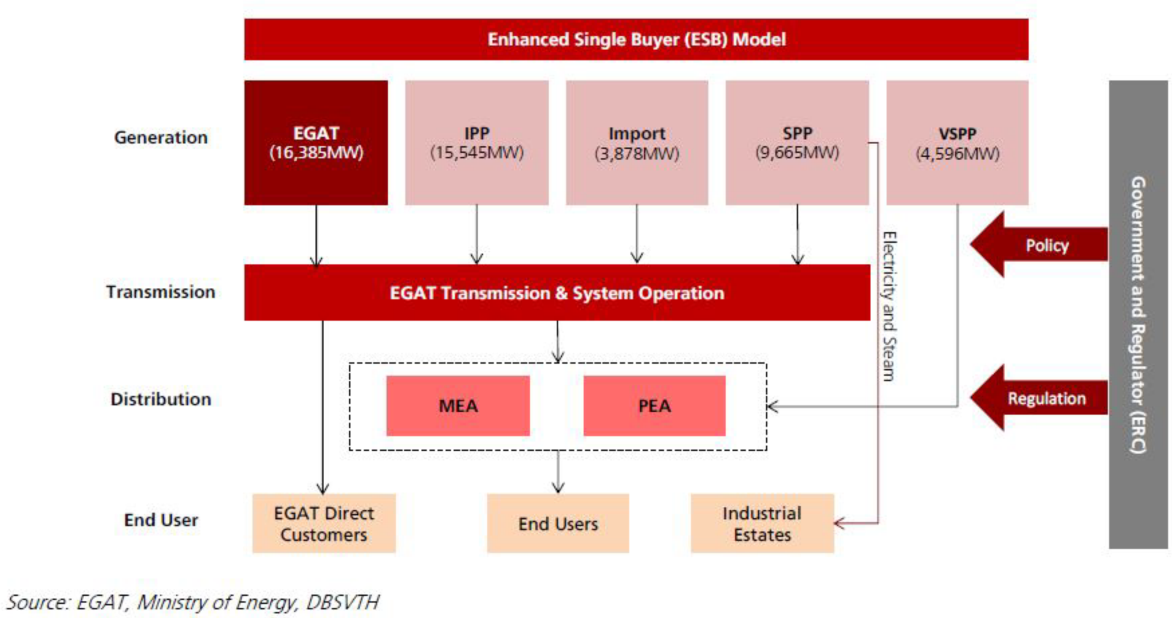
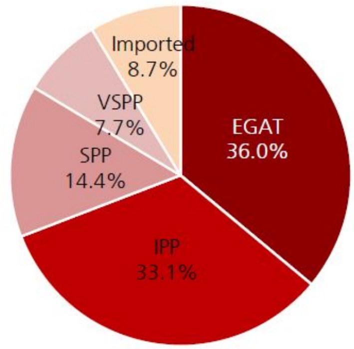


Figure 17. The structure of Thailand's electricity industry (source: DBS Vickers Securities, 2017).

Participation from the private sector has been allowed since the early 1990s, when the government privatised the generation business and reduced EGAT's investment burden (and control) by promulgating open bidding for power projects in 1994 under the IPP scheme. However, EGAT still maintains significant control over the sector through its majority-owned generation (**Figure 18**), minority stakes in generators, and influence over engineering, procurement and construction (EPC) entities (DBS Vickers Securities, 2018). Because EGAT is the system operator, orchestrator, and ruling body, it is critical to power in Thailand, and its actions are also heavily intertwined with politics.



Source: Ministry of Energy, DBSVTH
Note: c.92% on EGAT system

Figure 18. Thailand's installed capacity breakdown (source: DBS Vickers Securities, 2017).

Due to EGAT's heavy presence in the Thai power sector, only one company fits these criteria. It is Thailand's largest non-state owned power company and the most active Thai power company in the EEC region. The company is Bangkok-based, active throughout the region, and has developed thermal and renewable energy, microgrids, smart cities, and other conventional and 'new' energy projects. It has the scale and a long history of operations, yet has no ties to the government. It is one of the largest companies on the Thai Stock Exchange and is a member of the Dow Jones Sustainability Index. The company was founded in 1983 and is a leader in operations, research and development of a variety of energy technologies. The company operates in ten countries: Thailand, Laos, Vietnam, Indonesia, Singapore, China, Mongolia, Japan, Australia, and the United States of America.

The company has a subsidiary dedicated to low-carbon energy and new energy solutions such as smart cities, electric vehicles, power storage, and microgrids. The subsidiary has a small team dedicated to focusing on the EEC. It was approached by e-mail (from its website) for cooperation on this research, and kindly agreed to work together. The company agreed to provide a regular forum to communicate and display progress on the research, as well as an interview with a senior executive manager to endorse the results.

3.5.2 Methodology for Cooperation with the Thai Power Company

Methodology for working with the Thai power company was as follows:

1) The company was kind enough to elect one manager for serving as a communication counterpart ('Counterpart'). The company's EEC team and my Counterpart were introduced to the broader methodology of the research during a two-hour presentation.
2) The Counterpart and EEC team were sent the overall system scorecard and asked to score the broader EEC area. Their scores are displayed below in **Table 8.**

3) Then the 32 distribution problems were presented, and the case studies displaying the 32 problems were sent to the Counterpart and the EEC team.
   a) The EEC team was asked to score the four sub-scorecards, which rank the 32 problems (System Impacts, Other Industries Impacted, Corrective Measure Costs, Impacts to New Energy). Their scores are displayed below in **Tables 9–12**. This was intentionally conducted before any discussions of possible solutions.
4) The Counterpart arranged a site visit to the EEC focus area in June 2018. The Counterpart, other company's colleagues, and I did a driving tour of the area. This was a high-level introduction of the condition of housing, roads, existing infrastructure, existing critical loads such as hospitals, sites for planned major infrastructure projects, other utilities, and power distribution infrastructure. The Counterpart and I reviewed public data (summarised in **Section 2.3**, *Overview of The Sampled Geography Used in the Case Study*, page 33) on planned EEC projects.
   a) A simple Excel listing major types of infrastructure projects to be built in the EEC area, load characteristics of these infrastructure projects, opportunities, and challenges from these loads was produced with the Counterpart. This is displayed below in **Table 13**.
5) The scorecards, data on planned infrastructure projects, and the IEA framework were combined to develop solutions for guidance on the planning of the EEC area.
   a) One large-scale solution was developed per IEA category.
   b) Solutions were honed using the scorecards to achieve the maximum possible total score.
6) The research, methodology, and solutions were presented to a senior vice-president of the company over a three-hour presentation.
   a) Feedback was provided by the senior vice-president. The transcript of this is included below in **Appendix F**.
   b) Based on feedback, solutions were honed and finalised. These are included below in **Table 14** and **Appendix F**.

3.5.3 Scorecard Inputs from the Thai Power Company

As a starting point, the Thai power company was first asked to utilise the overall system scorecard and score the conditions of the local EEC area. This helped to set a base the attributes of the local energy system. They were provided with a Word document including the 32 distribution problems and asked to review them. Following this, they were asked to score the four scorecards detailing their views on the severity and impact of the 32 problems. I then worked with the company to map basic energy characteristics of the major infrastructure the EEC planning intends to put in place. Following this, they ascribed which of the 32 problems apply to which of the IEA categories, and the output was utilised to create solutions specific to the EEC area. The solutions were presented to their senior manager handling the EEC area, and she was interviewed on the fit and adequacy of the system to create solutions, and on the solutions themselves.

3.6 Leveraging the Research Framework

The goal of the final research step was to equip an analyst or engineer working on power solutions in developing countries with a systematic means to identify problems and develop solutions that improve energy efficiency and improve environmental impacts of rapid load increases. As part of the case study, the following was utilised to develop solutions for the EEC:

1) A review of the 32 distribution problems with the Thai power company,
2) A review of the three interviews with industry executives on the 32 problems,
3) The company's inputs on the overall system scorecard, and four impact specific scorecards
4) A multi-day site visit with the company to the EEC area,
5) A review of major announced infrastructure projects (highlighted in **Section 2.3.2**, page 37),
6) Creating with the Thai Power company a basic description of the characteristics, opportunities and challenges of these EEC projects (**Table 14**),
7) Reviewing with the company the IEA categories and their focuses,
8) The company's inputs on which IEA categories the 32 problems fall into (populating **Table 15**),
9) Utilising the overall scorecard to optimise the solution.

A **core solution** for each IEA category was developed through steps 1–9 above. In particular, knowledge from steps 1–3 was applied to local problems in steps 4–6, to the IEA category definition in step 7, and, finally, to the scorecards in steps 8–9. This process distilled the core functionality of the solution for the IEA category.

Solution optimisation was achieved by iterating steps 8–9. This consisted of using all of the research and framework, and local problems, within the framework of the scorecards to determine how to optimise the core solution best and achieve the highest possible score.

3.6.1 Grouping power system distribution problems

After scoring the overall power system (see **Sections 3.3.1**, page 47, on MCA and **3.3.3**, page 52, on scoring), we utilise a framework to cluster the 32 distribution problems into groups. The IEA and OECD (IEA, 2017) provide a framework in its '*Status of Power System*

Transformation 2017, System Integration and Local Grids' for assessing a power system in a developing country. The document is a comprehensive assessment of power systems in developing countries, including detailed case studies. The document focuses on the modernisation of power systems and suggests categorising initiatives into four macro groupings. The IEA provides a description and relevance of the four categories as follows:

1) **Markets and operations:** 'The structure of electricity markets and how they are operated, both at the wholesale and retail levels, is a key driver of power system transformation. Emerging market frameworks and improved system operations can help cost-effectively manage electricity delivery infrastructure with greater shares of VRE resources; changes to retail rate structures and regulatory paradigms can help to activate and engage demand-side resources to contribute to the system. The structure of electricity markets and how they are operated, both at the wholesale and retail levels, is a key driver of power system transformation. Emerging market frameworks and improved system operations can help cost-effectively manage electricity delivery infrastructure with greater shares of VRE (volatile renewable energy) resources; changes to retail rate structures and regulatory paradigms can help to activate and engage demand-side resources to contribute to the system.'

2) **Planning and infrastructure: '**Power system planning determines the future architecture of the power generation, transmission and distribution systems. Emerging, integrated approaches to power system planning and grid expansion can facilitate an efficient transformation of the power system, while maintaining affordability and reliability; it can also prepare electricity grids for the effective integration of greater technological innovation.'

3) **Uptake of innovative technology:** 'An array of emerging innovative technologies, including smart technologies, flexible resources, and system-friendly VRE, can enable a more flexible, reliable and affordable power system.'

4) **Efficiency and sector coupling:** 'Greater energy efficiency in the power sector can help reduce costs both at the system and customer level. Electrification across the transport, and heating and cooling sectors, in combination with the broader trend of cross-sector integration of the demand-side into electricity markets, can compound the benefits of clean energy deployment and hasten the transition to a low-carbon power system.'

This provides an excellent holistic framework for planning, which covers what market and operational problems need to be introduced, what key planning and infrastructure (both hardware and software) need to be in place to enable efficient systems, what technologies can function to make all components of these systems interoperable and turn volatility into smooth operations, and how we can couple various sectors and their loads into energy efficiency. These are four critical pillars described by the IEA, which provide part of the framework for transcribing problems into solutions.

To move in a logical sequence to forming solutions, we now combine three frameworks:

1) The researched list of 32 distribution problems,
2) Expert interviews and the four scorecards from these interviews showing impacts and magnitude of the 32 distribution problems,
3) The IEA's four critical aspects of power system transformation.

These three frameworks joined constitute a starting point for solutions. The 32 distribution problems are grouped by the scorecard user into the IEA categories (**Figure 19**) depending on what their cause is or where they occur operationally. Each category (i.e., each row) is populated with the subset of the 32 problems that are most relevant to that IEA category, and some problems may fall into more than one IEA focus area. Below is an illustration of this, taken from interviews with the Thai power company (**Section 5.2.1**, page 115) where the methodology was tested on a live example, which is detailed in **Section 2.3** (page 33). In this example, the Thai power company interviewed assigned scores indicating that Markets and Operations is a relevant category for the following problems (see **Table 15**):

- 4 – *Absence of proper accounting and auditing, and lack of distribution-level metering*,
- 6 – *Poor billing practices leading to lack of re-investment in critical parts of the distribution network*,
- 7 – *Lack of investment in and attention to load flow studies at distribution and retail levels*,
- 8 – *One-off rather than iterative customer and load mapping in urbanising areas*,
- 9 – *Insufficient management of theft and disconnection*,
- 10 – *SCADA systems at the distribution level are typically underinvested, which leads to insufficient data for generating reports on system performance and problems*,
- 11 – *Insufficient interaction with stakeholders and customers on energy efficiency, pricing signals, and from this, an inability to shape demand*,
- 12 – *Cross-subsidising within the power sector resulting in parts of the industry being left underfunded or insolvent*,
- 16 – *Poor system balancing due to lack of network area coordination*,
- 17 – *Bidirectional flow of power and data in the distribution system needs to be planned for*,
- 18 – *Clear and effective policies need to be enacted to produce, consume, store, delay or augment power at the distribution level*,

- 19 – *Coordinating with other utilities needs to occur, as this can unlock significant synergies and savings*,
- 20 – *Power sector planners should guide property developers on where urban centres should expand to, rather than attempt to follow and catch-up in network building*,
- 23 – *Distribution planners need to work closely with infrastructure developers (e.g., ports, rail stations), and with property developers who will have large loads in their network (e.g., campuses, industrials, hotels, schools) to create energy efficiency, and DSM/DR capabilities in load centres*,
- and 26 – *As the network is expanding, planners must continually identify medium and large demand response (DR) targets*.

Enter Issues 1 to 32 in Blue Cells

Step 1: Use IEA Framework for Grouping Problems and Opportunities

Aspect	**Description and Relevance**	**List of Problems Distributed Here: Cluster list of 32 problems into these 4 groups by IEA framework**														
1. Markets and Operations	The structure of electricity markets and how they are operated, both at the wholesale and retail levels, is a key driver of power system transformation. Emerging market frameworks and improved system operations can help cost-effectively manage electricity delivery infrastructure with greater shares of VRE resources; changes to retail rate structures and regulatory paradigms can help to activate and engage demand-side resources to contribute to the system.															
2. Planning and Infrastructure	Power system planning determines the future architecture of the power generation, transmission, and distribution systems. Emerging, integrated approaches to power system planning and grid expansion can facilitate an efficient transformation of the power system, while maintaining affordability and reliability; they can also prepare electricity grids for the effective integration of greater technological innovation.															
3. Uptake of Innovative Technology	An array of emerging innovative technologies, including smart technologies, flexible resources, and system-friendly VRE, can enable a more flexible, reliable, and affordable power system.															
4. Efficiency and Sector Coupling	Greater energy efficiency in the power sector can help reduce costs both at the system and customer level. Electrification across the transport, and heating and cooling sectors, in combination with the broader trend of cross-sectoral integration of the demand side into electricity markets, can compound the benefits of clean energy deployment and hasten the transition to a low-carbon power system.															

Figure 19. Applying the IEA Framework to clustering the 32 distribution problems in developing countries.

From here, the subset of the 32 problems belonging to each IEA category is distributed in a corresponding ranking box (**Figure 20**); for example, the upper left box displays the problems categorised as Markets and Operations, namely 4, 6, 7, 8, 9, 10, 11, 12, 16, 17, 18, 19, 20, 23, and 26 (see above). Each box consists of four quadrants that correspond to each of the four scorecards (**Tables 2–5**).

The subset of the 32 problems is then ranked in magnitude according to the scoring that the selected problems received in each of the four scorecards (**Tables 2–5**). They are placed in the cells in the ranking matrices (shown in **Figure 9**), starting with the highest-ranking problem in the cell closest to the centre and then within increasing distance from the centre according to their rank. The highest scoring problems from the four scorecards are highlighted in dark green, the second-highest in medium green, the second-lowest in light green, and the lowest in white. The green areas are focus points for building solutions – where, according to the IEA and expert interviews, we should start to build solutions.

When solutions are developed, they are scored by their total impact according to the expert interviews and the four scorecards. If a solution addresses problems in more than one IEA category, then it receives a multiplier of 1.25 to highlight its functionality. This multiplier is simply derived by there being four categories, so each additional category included in the solution receives an uplift of 0.25 (1/4), which awards cross-functional solutions but does not skew the mathematics of the scoring system. As solutions are developed, they are displayed and scored in the table below (**Figure 21**).

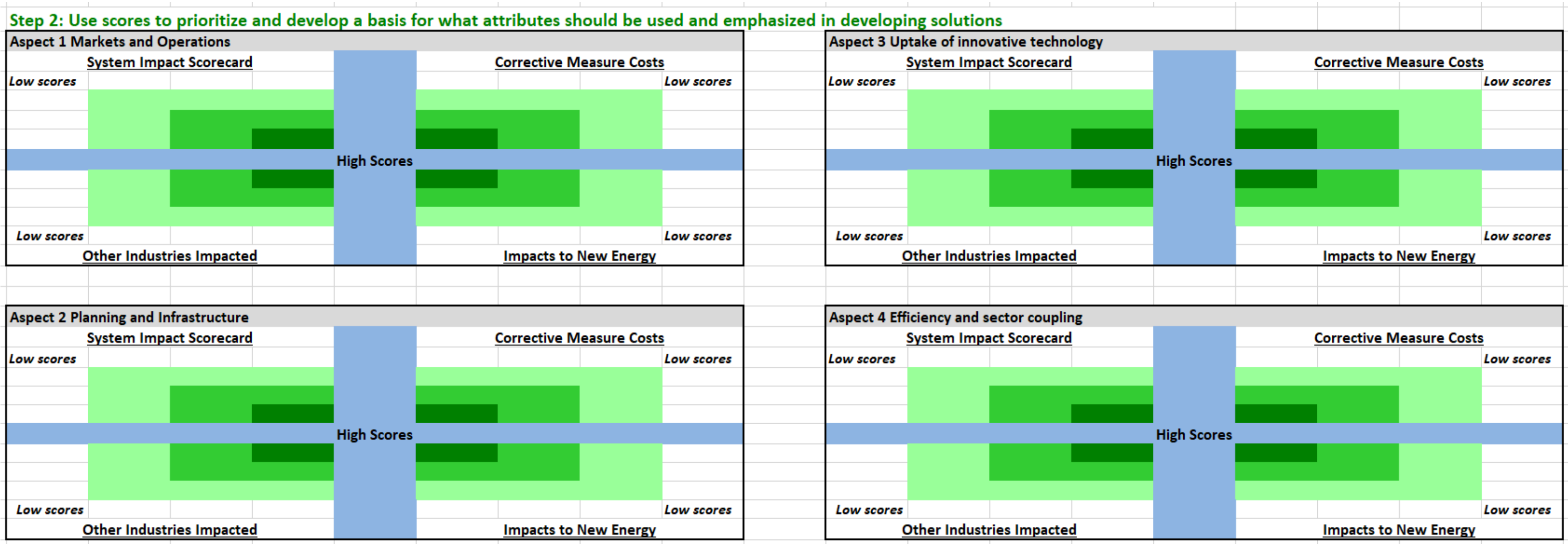


Figure 20. A snapshot of the IEA categories applied to each scorecard. Each of the above four boxes represents an IEA aspect from Figure 1. Within this are the four scorecards (Tables 2–5). The user of this tool scores the 32 distribution problems in the four scorecards and then assigns them to IEA categories depending on their root or place in the value chain. They are automatically then grouped into the green (high-score) or surrounding white (low-score) areas. This green area then becomes a starting point for solution development.

Step 3: Create solutions in blue cells below, tally scores of solutions

Step 4: Select issues that each solution addresses

Results

Aspect	Solution Description			Total	Multiplier	Total Score	Solution Score	Rank
1		1. Markets and Operations		-	1	0	0	1
		2. Planning and Infrastructure		-	1.25	0		
		3. Uptake of Innovative Technology		-	1.25	0		
		4. Efficiency and Sector Coupling		-	1.25	0		

Aspect	Solution Description			Total	Multiplier	Total Score	Solution Score	Rank
2		1. Markets and Operations		-	1.25	0	0	1
		2. Planning and Infrastructure		-	1	0		
		3. Uptake of Innovative Technology		-	1.25	0		
		4. Efficiency and Sector Coupling		-	1.25	0		

Aspect	Solution Description			Total	Multiplier	Total Score	Solution Score	Rank
3		1. Markets and Operations		-	1.25	0	0	1
		2. Planning and Infrastructure		-	1.25	0		
		3. Uptake of Innovative Technology		-	1	0		
		4. Efficiency and Sector Coupling		-	1.25	0		

Aspect	Solution Description			Total	Multiplier	Total Score	Solution Score	Rank
4		1. Markets and Operations		-	1.25	0	0	1
		2. Planning and Infrastructure		-	1.25	0		
		3. Uptake of Innovative Technology		-	1.25	0		
		4. Efficiency and Sector Coupling		-	1	0		

Figure 21. A snapshot of the table for displaying and scoring the solutions to power distribution problems.

4. RESULTS, Part 1: Problems Impacting the Intersect of Power Distribution and the Built Environment and Their Assessment

The results from this research showed that there is a significant gap in understanding and planning for the intersect of the power distribution system and the built environment in urbanising, developing countries, and that additional research and solutions to this area can positively impact the energy industry and humankind. There is an obvious lack of emphasis on distribution planning versus generation planning, which is particularly problematic in developing countries undergoing urbanisation. The research then identified 32 distribution problems that regularly occur due to this. These were discovered through case studies and verified by expert interviews. Ranking tools were developed from standard engineering texts to understand the magnitude of these problems during the expert interviews. Finally, the 32 problems and scorecards have been assembled into an Excel-based tool to link problems into solution development.

4.1 The '32 Problems' Identified in the Literature

The review of research and case studies has revealed 32 repeatedly found problems seen in power distribution planning in urbanising developing countries. This is presented below in **Table 3** and elaborated on in a list of problems, missed opportunities, or areas that could be further emphasised in power distribution planning in urbanising developing countries. Initially, a longer set of problems was discovered, which was later amalgamated and narrowed by the following criteria:

1) Evidence that the problem was not anecdotal or unique to a particular situation but rather systematic.
2) Having a clear cause or root in power system planning, and a clear impact or effect on the functionality of the power system.
3) Occurring in multiple geographies.
4) The nature of the problem having attributes of planning, rather than lacking a particular asset (e.g. needing a transformer in location X to alleviate problem Y).

The list was amalgamated to 32 based on these criteria, and to harmonise the terminology, these identified shortcomings will be hereafter referred to as 'the 32 distribution problems.'

Table 3. An account of studied literature and case studies demonstrating the 32 power distribution planning problem seen in urbanising developing countries.

Power distribution planning problem seen in urbanising developing countries	Studies describing this problem	Case studies on this problem
1) Over-reliance on simple radial distribution.	Jha et al. (2002) Shukla et al. (2010) Saboori et al. (2015)	Barker and de Mello (2000) Jha et al. (2002) Chiradeja (2005) Wu et al. (2010)

		Pagani and Aiello (2011)
2) Insufficient focus and investment on voltage regulation	Jha et al. (2002) Passey et al. (2011) Openshaw (2017)	Jha et al. (2002) Borges and Falcão (2006) Eminoglu and Hocaoglu (2007) Passey et al. (2011) Chen et al. (2012)
3) Lack of development of a medium-voltage distribution network	Parshall et al. (2009) Ziari (2011)	Parshall et al. (2009) van Ruijven et al. (2012) Sanoh et al. (2012) Ziari et al. (2012) Ziari et al. (2013)
4) Absence of proper accounting and auditing and lack of distribution-level metering	Pau et al. (2018) Raposo et al. (2017)	Sinha et al. (2011) Nejad et al. (2013) Pau et al. (2018) Ponce-Jara et al. (2017) Raposo et al. (2017)
5) Lack of planning for reactive power at load points	Jha et al. (2002) Passey et al. (2011) ShiHong et al. (2012)	Jha et al. (2002) Khiat et al. (2003) Chettih et al. (2008) Marcolini et al. (2010) Khiat et al. (2012)
6) Poor billing practices leading to lack of re-investment in critical parts of the distribution network	Weston (2001) Schwartz and Sheaffer (2011) Mulky (2013)	Dasuki et al. (2012) Mwaura (2012) Mazibuko (2013) Han and Xiao (2014) Telles Esteves et al. (2016)
7) Lack of investment in and attention to load flow studies at distribution and retail levels	Weston (2001) Schwartz (2010) Schwartz and Sheaffer (2011) Pérez-Arriaga (2013)	Chen et al. (2002) Pantoš and Gubina (2004) Geidl and Andersson (2007) Pollitt (2008) Pérez-Arriaga (2013)
8) One-off rather than iterative customer and load mapping in urbanising areas	Schwartz (2010) Schwartz and Sheaffer (2011) Lenz (2015)	Szabó et al. (2011) Mentis et al. (2015) Mentis et al. (2016) Bertheau (2017) Mentis et al. (2017)
9) Insufficient management of theft and disconnection	Depuru et al. (2011) Redaelli (2014)	Depuru et al. (2011) Winther (2012) Jamil (2013) Jiang et al. (2014) Jiménez et al. (2014)
10) SCADA systems at the distribution level are typically underinvested, which leads to insufficient data for generating reports on system performance and problems	Parshall et al. (2009) Schwartz (2010) Electrical Technology (2015)	Davidson et al. (2000) Parshall et al. (2009) Jiménez-Estévez et al. (2014) Karunakaran (2014) Dhend and Chile (2015)
11) Insufficient interaction with stakeholders and customers on energy efficiency, pricing	Barnes et al. (1997) Weston (2001) Torpey (2011)	Barnes et al. (1997) Ul Hassan et al. (2015) Ellabban and Abu-Rub (2016)

signals, and from this, an inability to shape demand	Di Maddaloni et al. (2017) Lundmark (2017) Li (2018)	Di Maddaloni et al. (2017) Li (2018)
12) Cross-subsidising within the power sector resulting in parts of the industry being left underfunded or insolvent	Barnes et al. (1997) Yamada et al. (2011) Van Dievel et al. (2014) He et al. (2018)	Barnes et al. (1997) Yamada et al. (2011) Lin and Jiang (2011) Fattouh and El-Katiri (2013) He et al. (2018)
13) Knowledge transfer from installation company to the operating company and overall workforce inadequacy	Siemens (2014b) Collier (2015) US DoE (2017)	Giroud (2000) Duanmu and Fai (2007) Hansen et al. (2009) Alkhatatneh (2011) Jasimuddin et al. (2015)
14) Insufficient renewable energy resource assessment	Schwartz (2010) Thirumurthy (2015)	Mondal and Denich (2010) Deichmann et al. (2011) Asrari et al. (2012) Farooq and Kumar (2013) Gyamfi et al. (2015)
15) Generation, transmission and distribution planning need to be integrated	Weston (2001) Schwartz (2010) Schwartz and Sheaffer (2011) Singh et al. (2015) IEA (2017)	D'Sa (2005) Hu et al. (2010) Amirnekooei et al. (2012) Zheng et al. (2014) Alasseri et al. (2017)
16) Poor system balancing due to lack of network area coordination	IEA (2017) Gerard et al. (2018)	Dondi et al. (2002) Richardot et al. (2006) Castanheira et al. (2015) Muttalib et al. (2016) Gerard et al. (2018)
17) Bidirectional flow of power and data in the distribution system needs to be planned for	Pass et al. (2018)	Mashhour et al. (2009) Razmara et al. (2015) Razmara et al. (2017) Mumtaz and Bayram (2017) Jiang et al. (2018)
18) Clear and effective policies need to be enacted to produce, consume, store, delay, or augment power at the distribution level	Crabtree et al. (2011) US DoE (2017) Gissey et al. (2018)	Gomes and Saraiva (2009) Samimi and Kazemi (2016) Samimi and Nikzad (2017) Samimi et al. (2017) Shigenobu et al. (2018)
19) Coordinating with other utilities needs to occur, as this can unlock significant synergies and savings	Tice et al. (2012) Martinez-Cesena et al. (2015)	Fraquelli et al. (2004) Martinez-Cesena et al. (2015) Selvarajoo et al. (2018) Steiner et al. (2018) Vakilifard et al. (2018)
20) Power sector planners should guide property developers on where urban centres should expand to, rather than attempt to follow and catch-up in network building	Parshall et al. (2008) The Government of Ireland (2009) Colom (2011) Yazdanie et al. (2017) Chan et al. (2018)	Parshall et al. (2008) Mentis et al. (2015) Trotter et al. (2017) Yazdanie et al. (2017) Chan et al. (2018)

21) Power sector reform and liberalisation should occur at an equal pace from generation through transmission, distribution, and retail	Manibog et al. (2003) Joskow (2008) Loksha (2015) IFC (2018)	Nepal and Jamasb (2015) Zhou and Yang (2015) Eshun and Amoako-Tuffour (2016) Alpizar-Castro and Rodríguez-Monroy (2016) Qazi (2017)
22) Asset management at the distribution level is underinvested and needs to be emphasised	Schwartz (2010) Schwartz and Sheaffer (2011) Yarka (2012)	Schwartz (2010) Schwartz and Sheaffer (2011) Yarka (2012) Jiang et al. (2017) Jamasb et al. (2018)
23) Distribution planners need to work closely with infrastructure developers (e.g., ports, rail stations), and with property developers who will have large loads in their network (e.g., campuses, industrials, hotels, schools) to create energy efficiency, and DSM/DR capabilities in load centres	Volk (2013) Eller (2018)	Bai and Qian (2010) Kemausuor et al. (2014) Trebilcock and Rosenstock (2015) Mentis et al. (2016) Rafique and Rehman (2017)
24) Effectively managing rapid urbanisation and preventing cluttered and hazardous network planning	Reiche et al. (2000) UN DESA (2008) Keivani (2010) Palit and Chaurey (2011) Mandelli et al. (2016) Shahraki (2017) Yazdanie et al. (2017)	Keivani (2010) Palit and Chaurey (2011) Mandelli et al. (2016) Shahraki (2017) Yazdanie et al. (2017)
25) Microgrids are underutilised as a tool in network planning in urbanising, developing countries	Torpey (2011) Siemens (2014a) Pschetz et al. (2018)	Torpey (2011) Gaona et al. (2015) Zhu et al. (2015) Murenzi and Ustun (2015) López-González et al. (2017)
26) As the network is expanding, planners must continually identify medium and large demand response (DR) targets	Weston (2001) Schwartz (2010) Schwartz and Sheaffer (2011) The National Association of Clean Air Agencies (2015)	Weston (2001) Wang et al. (2010) Choi and Thomas (2012) Aghaei and Alizadeh (2013) Monyei and Adewumi (2018)
27) Lack of target setting and on-going improvement standards in network operation needs to be addressed	Legros et al. (2009) Leal and Azevedo (2016)	Teera-Achariyakul et al. (2010) Ballanca and Garside (2013) Ahlborg and Hanmar (2014) Leal and Azevedo (2016) Bisaga et al. (2019)
28) Lack of streamlining and matching network design standards with the demand to develop efficient distribution systems in a timely fashion	Smith (1995) Barnes et al. (1997) Barnes (2011) Herran and Nakata (2012) Kolokotsa (2016) Mandelli et al. (2016)	Barnes et al. (1997) Barnes (2011) Herran and Nakata (2012) Kolokotsa (2016) Mandelli et al. (2016)

29) Non-standardisation of both home and industrial electrical equipment and resistance to internationally agreed standards	Kershaw (2007) IEA (2017) Ibanescu et al. (2018) Ikhlayel (2018)	Kershaw (2007) Ibanescu et al. (2018) Ikhlayel (2018) Simiari et al. (2018) Jayaraman et al. (2019)
30) Planners do not sufficiently include resiliency and secure infrastructure in grid planning	Collier (2015) Gholami et al. (2016) Panteli et al. (2016) Liu et al. (2017) US DoE (2017) US DoE (2018)	Gholami et al. (2016) Panteli et al. (2016) Liu et al. (2017) Venizelos et al. (2017) Wang et al. (2017)
31) In order to stay competitive, distribution utilities must transform themselves into more digital enterprises	Barnes et al. (1997) Schwartz (2010) Schwartz and Sheaffer (2011) Taipale and Fellini (2012) Yasmin and Qamar (2013) Fadaeenejad et al. (2014) Collier (2015) Scott (2015) UNCTAD (2016) Weichhart et al. (2016) US DoE (2017) Jamasb et al. (2018) Kauer et al. (2018)	Barnes et al. (1997) Fadaeenejad et al. (2014) Rashid and Rehmani (2016) Weichhart et al. (2016) Jamasb et al. (2018)
32) Problems with governance and management	Keivani (2010) Schwartz (2010) Schwartz and Sheaffer (2011) Ponce-Jara et al. (2017)	Keivani (2010) Bifulco et al. (2016) Hajduk (2016) Meijer and Bolívar (2016) Ponce-Jara et al. (2017)

Specifically, the problems identified are as follows:

1) **Over-reliance on simple radial distribution**. Radial networks can be sufficient for suburban areas, but when population increases in an area over time, radial networks are too simple for managing urbanisation and rapid load growth. Often one high-voltage line feeds large quantities of end users, which means maintenance is difficult and unexpected system problems impact larger numbers of end users than a broader network distribution system. Planners need to shift from radial to network-based planning when urbanisation increases, rather than attempt to add redundancy to a congested and overly simplified radial system after load growth has exceeded its capacity. Jha et al. (2002) describe how many urbanising parts of India, for example, Bihar, Uttar Pradesh, and Maharashtra, have been electrified radially with the network capacity up to 132 kV. If a fault occurs at any part of the radial network, the supply to entire areas may be disrupted. Also, simple system maintenance that requires a network shut-down, such as re-conducting of the lines or replacing rusted poles, affect the power supply to the remaining feeding areas. There are various approaches on how to overcome radial network disadvantages in the future planning of radial distribution

systems. For example, Shukla et al. (2010) developed a genetic algorithm for determining an optimal sizing of distributed generation to minimise system losses and increase network reliability, and Saboori et al. (2015) developed a method for planning radial electrical distribution systems by implementing energy storage facilities of appropriate size at appropriate locations. Such approaches can help minimise stability issues and facilitate managing events.

This problem is corroborated by the following studies:

- Barker and de Mello (2000) on correct integration of distributed generation into existing radial networks;
- Jha et al. (2002) on the shortcomings of radial distribution networks in the urbanising areas of India;
- Chiradeja (2005) demonstrating a line loss reduction after the introduction of distributed generation in a simple network of a radial distribution feeder with concentrated load and distributed generator;
- Wu et al. (2010) on the reconfiguration of a radial distribution system with distributed generators using an Ant Colony Algorithm.
- Pagani and Aiello (2011) on a topological investigation of medium- and low-voltage grids with the aim of decentralization.

2) **Insufficient focus and investment in voltage regulation.** As load grows with urbanisation, insufficient focus on voltage regulation creates volatility in voltage and power quality problems that impact end users. Power distribution and retail in developing countries are often seen simply as power delivery rather than management of voltage and power quality, which causes underinvestment in voltage regulation and creates system problems. In developing countries, transmission, distribution and retail are not always clearly delineated. For simplicity, we refer to distribution as carrying power from the end of a high voltage transmission system to a low voltage system that matches end-user loads, where it is then referred to as retail power. From here, it is delivered to the end user, metered, and invoiced. Jha et al. (2002), Passey et al. (2011), and Openshaw (2017) all discuss the importance of voltage regulation and how this is often under-represented in system planning. Openshaw (2017) also discusses how insufficient focus on voltage regulation impacts the full power system, including expanding generation and transmission networks. This becomes a larger problem as cities grow and loads become more complex, with different reactive power, voltage, and power quality profiles.

   This problem is corroborated by the following studies:

   - Jha et al. (2002) on impermissible voltage fluctuations due to the unplanned and haphazard development of the distribution network in India;

- Borges and Falcão (2006) on optimal allocation and sizing of distributed generation to minimise electrical network losses and achieve stable voltage profile;
- Eminoglu and Hocaoglu (2007) on a voltage stability index for radial distribution networks, tested at different loading conditions for different load models and different substation voltage levels;
- Passey et al. (2011) reviewing the impacts of grid-connected distributed generation and how to address them;
- Chen et al. (2012) on the impacts of different penetration levels of distributed generation on voltage profiles in low-voltage secondary distribution networks.

3) **Lack of development of a medium-voltage distribution network.** Distribution in developing countries typically consists of a long mesh of low-voltage distribution lines, often with insufficient transformer capacity. This results in voltage problems, technical losses, and loss of reliability. Planners need to develop both medium- and low-voltage networks as urbanisation and load increase, as this is critical in reducing technical losses as cities grow and geographically expand. This also supports the integration of distributed energy resources, storage, and demand-side management. Ziari (2011) displays in detail how developing a medium-voltage network plays a critical role in planning and efficiency of capital equipment, such as transformers and capacitors. Parshall et al. (2009) provide details on how effective planning of a medium-voltage network could create efficiency and savings in Kenya. According to their model, over 30% of households could be connected for significantly less than the current cost per connection through infilling of an adequate pre-existing medium-voltage network. In urban areas and denser rural regions, connection costs would be lower than in more remote areas, but an extension of the national grid would still outweigh off-grid solutions.

   This problem is corroborated by the following studies:
   - Parshall et al. (2009) on infilling of an adequate pre-existing medium-voltage network to achieve greater efficiency and savings in rural parts of Kenya;
   - van Ruijven et al. (2012) modelling rural electrification in line with future trends and the associated investment needs under various electrification scenarios;
   - Sanoh et al. (2012) on local and national electricity distribution planning in Senegal utilizing medium-voltage networks;
   - Ziari et al. (2012) on planning integrated distribution systems to improve reliability under load growth, including distribution lines and high-voltage/medium-voltage (HV/MV) transformers;
   - Ziari et al. (2013) on the implementation of distribution network reinforcement, including load growth, voltage profile, distribution line loss, and reliability.

4) **Absence of proper accounting and auditing and lack of distribution-level metering.** This leaves technical and commercial losses undefined, poorly understood, and improperly addressed. Metering is critical in identifying problems, details, and patterns of load growth and system constraints, but is often underinvested in due to budgetary constraints. Pau et al. (2018) and Raposo et al. (2017) detail the importance of metering, how critical this is to achieve a modern grid, and how many options now exist for digital and cloud-based systems, which are more effective and affordable than traditional systems. Raposo et al. (2017) also propose an algorithm for increasing the accuracy of the state estimation by allocating meters in distribution networks, and Pau et al. (2018) propose a cloud-based metering architecture that allows communication between smart meters and the distribution network, helps automate the distribution system, and enables scalability, interoperability and flexibility.

   This problem is corroborated by the following studies:
   - Sinha et al. (2011) on the smart grid initiative for power distribution utility in India;
   - Nejad et al. (2013) on the application of smart power grid in developing countries;
   - Pau et al. (2018) on a cloud-based smart metering infrastructure for distribution grid services and automation;
   - Ponce-Jara et al. (2017) on the current state of smart gridding in developed and developing countries;
   - Raposo et al. (2017) on an optimal meter placement algorithm for state estimation in power distribution networks.

5) **Lack of planning for reactive power at load points.** The view in developing countries that distribution and retail are simply for power delivery means that changes in load and corresponding reactive power needs are often poorly addressed. This often features a lack of investment in capacitors throughout the system – at load points, substations, and other distribution infrastructure, and leads to power quality problems, technical losses, and voltage regulation problems. This becomes especially critical as cities form, as commercial and residential real estate grow, and as large infrastructure and overall fixed asset investment grow. Jha et al. (2002) describe how rising industrial and agricultural pumping loads in India increased the reactive power needs, but those were inadequately compensated, which caused poor voltage conditions and power losses. Passey et al. (2011) and ShiHong et al. (2012) review various planning solutions for this problem, such as inverters operating in voltage-regulating mode, static VAR compensators, or STATCOMS.

   This problem is corroborated by the following studies:
   - Jha et al. (2002) on inadequate compensation of reactive power needs from the rising power loads in India;

- Khiat et al. (2003) on reactive power optimisation and voltage control in Western Algeria;
- Chettih et al. (2008) on var/voltage control by particle swarm optimisation method in Western Algeria;
- Marcolini et al. (2010) on preventive voltage control actions to securely face load evolution in power systems;
- Khiat et al. (2012) on a hybrid methodology for optimal var dispatch in the Western Algerian power system.

6) **Poor billing practices leading to lack of re-investment in critical parts of the distribution network.** Billing collects not only capital costs but also information on what areas of the system are being used. When billing practices are insufficient, the recycling of money back into the system in the form of finance for maintenance, upgrades, or equipment replacement often does not occur or does not occur where needed (Weston, 2001; Schwartz and Sheaffer, 2011). Mulky (2013) details how this problem has hindered the growth of both distribution and retail systems and has led to poor capital allocation in the Indian power system. As cities expand, poor billing practices and their impacts on capital recovery and redeployment become a serious issue over the medium- and long-term.

   This problem is corroborated by the following studies:
   - Dasuki et al. (2012) on the impact of investments in the information and communications technology on the Nigerian pre-paid electricity billing system;
   - Mwaura (2012) on the reduction of non-technical energy losses by adopting electricity prepayment billing system in Uganda and Rwanda;
   - Mazibuko (2013) on the impact of municipal billing system on revenue collection in selected South African cities;
   - Han and Xiao (2014) on a practical scheme to detect non-technical loss fraud in the smart grid;
   - Telles Esteves et al. (2016) on the experiences with electricity prepayment billing system in Brazil.

7) **Lack of investment in and attention to load flow studies at distribution and retail levels**. Investments in the analysis of total load, system stresses, and other issues are often ignored in developing countries, which impacts system planning and reliability (Weston, 2001; Schwartz, 2010; Schwartz and Sheaffer, 2011). Pérez-Arriaga (2013) details how load flow studies are critical to the development of power systems and, when not done thoroughly and iteratively, can lead to significant system constraints. Load flow studies need to be executed iteratively at the distribution level as urbanisation occurs to understand and properly manage changes in load attributes and identify system bottlenecks and efficiency opportunities.

This problem is corroborated by the following studies:

- Chen et al. (2002) on setting nodal prices by breaking them down into a variety of parts corresponding to the factors such as generations, transmission congestion, voltage limitations and other constraints or elements;
- Pantoš and Gubina (2004) on ex-ante transmission-service pricing via power-flow tracing;
- Geidl and Andersson (2007) on optimising coupled power flows of different energy infrastructures such as electricity, gas, and district heating systems;
- Pollitt (2008) on the electricity reform in Argentina, which included network restructuring;
- Pérez-Arriaga (2013) on the importance of load flow studies for the development of power systems and mitigation of system constraints;

8) **One-off rather than iterative customer and load mapping in urbanising areas.** Particularly in urbanising, developing countries, mapping customers and load needs to be an iterative process. Handling this as a one-off exercise will lead to inefficient distribution systems (Schwartz, 2010; Schwartz and Sheaffer, 2011). Lenz (2015) discusses low-cost methods for load mapping and how critical this is to the formation of cities and large clusters of load. This includes software where users provide inputs on population, weather, fixed asset development, economic activity, and other factors, and receive outputs that map scenarios of load over different timeframes. Customer load needs to be mapped iteratively in order to understand how the city, its inhabitants, and their energy uses are changing, and how this impacts system planning and build-out.

   This problem is corroborated by the following studies:

   - Szabó et al. (2011) on mapping electrification costs of distributed solar and diesel generation versus grid extension in rural Africa;
   - Mentis et al. (2015) on GIS-based approach for electrification planning in Nigeria;
   - Mentis et al. (2016) on the benefits of geospatial planning of energy access in Ethiopia;
   - Bertheau (2017) on visualising national electrification scenarios for sub-Saharan African countries;
   - Mentis et al. (2017) on the application of an open source, spatial electrification tool in sub-Saharan Africa.

9) **Insufficient management of theft and disconnection**. This has historically cost power companies in developing countries large quantities of capital and serves as an unintended subsidy to populations who need to get accustomed to the cost of energy. Governments can offer subsidies to poor populations, but it is argued that this should not be in the form of allowing power theft to occur and allowing issues to prevail that

impact the solvency of the distribution and retail entities. Redaelli (2014) describes the great operational and economic challenges created by theft and lack of fair and effective disconnection practices, and how critical this is to power systems globally, and especially in developing countries. In South Africa, this has led to power theft becoming a source of de-facto subsidies, where the government reimburses ESKOM (the local utility) for power theft. This leads to poor populations expecting a continued subsidy in the form of free power, not understanding their role in energy consumption, and has led to financial difficulties for ESKOM (Depuru et al., 2011).

This problem is corroborated by the following studies:

- Depuru et al. (2011) on a smart-meter-based approach to controlling electricity theft and theft prevention;
- Winther (2012) on the socio-technical and relational context of electricity theft in Zanzibar, Tanzania, and the Sunderban Islands (India);
- Jamil (2013) on the impact of electricity theft on electricity shortfalls in Pakistani post-2006 electricity crisis;
- Jiang et al. (2014) on energy-theft detection issues for advanced metering infrastructure in a smart grid;
- Jiménez et al. (2014) on electricity losses in transmission and distribution systems in Latin America and the Caribbean.

10) **SCADA systems at the distribution level are typically underinvested, which leads to insufficient data for generating reports on system performance and problems.** SCADA is standard in generation systems, but in developing countries, this is underinvested at the distribution level. Generating reports on system performance, modelling, and forecasting the system is not automated or easy to manage without effective SCADA systems at the distribution level (Schwartz, 2010). Parshall et al. (2009) discuss how this has impacted Kenya's developing power sector, and Electrical Technology (2015) details the criticality of this at load points. SCADA is critical to understanding performance in critical equipment, nodes, and the broader system.

This problem is corroborated by the following studies:

- Davidson et al. (2000) on power system control automation in Nigeria;
- Parshall et al. (2009) on SCADA implementation in national electricity planning in Kenya;
- Jiménez-Estévez et al. (2014) on community engagement in the implementation of SCADA on isolated microgrids in developing countries (the so-called "social SCADA");
- Karunakaran (2014) on the optimisation of the electric power grid by implementing SCADA in the state of Sarawak, Malaysia;

- Dhend and Chile (2015) on an innovative scheme for smart grid distribution SCADA system in small distribution networks.

11) **Insufficient interaction with stakeholders and customers on energy efficiency, pricing signals, and from this, an inability to shape demand**. It is important for energy companies and governments to interact with communities and key stakeholders on energy, pricing, and consumption issues in order to shape demand and save energy. This is often ignored in developing countries. Weston (2001) and Torpey (2011) describe the importance of this in developing smart cities and efficient load centres. Barnes et al. (1997) and Lundmark (2017) describe the importance of working with communities and stakeholders to incentivise customers, encourage participation in energy, and drive the system efficiency. Li (2018) notes that China is encouraging its power system to increasingly rely on local private firms and individuals to participate in DSM projects and energy efficiency. Di Maddaloni et al. (2017) show a direct relationship between the effectiveness of energy efficiency projects and community involvement.

    This problem is corroborated by the following studies:

    - Barnes et al. (1997) on the importance of working with rural communities to improve the energy system efficiency in developing countries;
    - Ul Hassan et al. (2015) on customer engagement plans for peak load reduction in residential smart grids;
    - Ellabban and Abu-Rub (2016) on customers' acceptance and engagement in smart grids;
    - Di Maddaloni et al. (2017) on the influence of local community stakeholders in energy efficiency projects;
    - Li (2018) on the role of local private participation in China’s transition to domestically developed renewable energy technologies;

12) **Cross-subsidising within the power sector resulting in parts of the industry being left underfunded or insolvent.** A common occurrence in developing countries is that distribution and retail costs are not sufficiently recovered in billing, whereas large capital generation and transmission projects are. In addition to economic and operational pressure at the distribution and retail levels as cities grow, long-term capital reinvestment does not occur in the right places due to this imbalance of recovery of funds through billing. Yamada et al. (2011) detail how this has occurred in Southeast Asia and sub-Saharan Africa and can lead to significant system constraints. Barnes et al. (1997) and van Dievel et al. (2014) highlight how cross-subsidies inhibit demand-side management and participation in energy efficiency projects. He et al. (2018) describe how China recognises that this is a major issue and is now attempting to address it by re-organising tariffs and billing throughout the power sector.

This problem is corroborated by the following studies:

- Barnes (2011) on the impacts of cross-subsidies within rural electrification in developing countries;
- Yamada et al. (2011) on cross-subsidising causing significant system constraints in Southeast Asia and sub-Saharan Africa;
- Lin and Jiang (2011) on the impact of energy subsidy reform in China;
- Fattouh and El-Katiri (2013) on energy subsidies in the Middle East and North Africa;
- He et al. (2018) on the optimisation of Chinese power grid investment based on transmission and distribution tariff policy.

13) **Knowledge transfer from installation company to operating company and overall workforce inadequacy.** In many developing countries, knowledge transfer from an installation company to an operating company often does not take place or does not take place properly. Companies (often foreign) that manage the installation of distribution infrastructure are for a variety of reasons not retained to transfer knowledge to local people who operate the system. This and other problems leave the power system with an insufficient workforce. Siemens (2014b) describes the importance of training and effective handover after large capital projects. Collier (2015) and the US DoE (2017) describe the shortage of adequately trained staff to deal with changes to power systems, which is especially acute in developing countries.

    This problem is corroborated by the following studies:

    - Giroud (2000) on the Japanese transnational corporations' knowledge transfer to the electrical and electronics sector in Malaysia;
    - Duanmu and Fai (2007) on vertical knowledge transfer from inward-invested multinational enterprises to indigenous Chinese suppliers in the electrical and electronics industry;
    - Hansen et al. (2009) on the multinational corporation strategies and linkage effects in developing countries;
    - Alkhatatneh (2011) on technology transfer from foreign firms to local suppliers through backward linkages in Jordan;
    - Jasimuddin et al. (2015) on knowledge recipients, acquisition mechanisms, and knowledge transfer at Japanese subsidiaries in China.

14) **Insufficient renewable energy resource assessment** creates common problems around untapped generation potential. This also impacts distribution planning as small-scale and distributed renewable energy can become a component of an urban or semi-urban power grid, which then impacts the distribution system (Schwartz, 2010). Openly available data on renewable energy resource assessment is important in planning distribution networks. States and generation authorities need to sponsor open

access to renewable energy resource data. Thirumurthy (2015) describes how accurate, openly available data on renewable energy is critical not only to generation but also at the distribution level, both in India and globally.

This problem is corroborated by the following studies:

- Mondal and Denich (2010) on the assessment of renewable energy resources potential for electricity generation in Bangladesh;
- Deichmann et al. (2011) on the economics of renewable energy expansion in rural Sub-Saharan Africa;
- Asrari et al. (2012) on economic evaluation of hybrid renewable energy systems for rural electrification in Iran;
- Farooq and Kumar (2013) on the assessment of renewable energy potential for electricity generation in Pakistan;
- Gyamfi et al. (2015) on the potential of renewable energy to improve electricity supply security in Ghana.

15) **Generation, transmission, and distribution planning need to be integrated.** These often occur separately and without synchronisation. This is becoming especially critical as intermittent renewable energy increases in power systems, as storage becomes more affordable, and as DSM/DR technologies become more affordable and easier to propagate. Over the long-term, this lack of integrated planning can be a significant problem in non-liberalised power systems, where market forces do not guide capital investment and cost recovery. Weston (2001), Schwartz (2010), Schwartz and Sheaffer (2011), and Singh et al. (2015) detail the critical nature of this and how not doing this in a coordinated fashion can significantly impact demand-side management and energy efficiency programs. The IEA (2017) notes that this is critical to the successful rollout of electric vehicle fleets, power storage, building energy management, and other low-carbon technologies.

This problem is corroborated by the following studies:

- D'Sa (2005) on integrated resource planning and power sector reform in developing countries;
- Hu et al. (2010) on integrated resource strategic planning in the Chinese power sector;
- Amirnekooei et al. (2012) on integrated resource planning in Iran, with a focus on the development of reference energy system, forecast, and long-term energy-environment plan;
- Zheng et al. (2014) on integrated resource strategic planning with interconnected smart grids for the integration of renewable energy and implementation of demand-side management in China

- Alasseri et al. (2017) on implementation strategies for demand-side management in Kuwait through incentive-based demand response programs.

16) **Poor system balancing due to lack of network area coordination**. Network planning and interconnection for balancing between geographic areas can remove significant technical losses. Often this does not occur in developing countries due to budget constraints and lack of an effective, overarching power authority. This leaves an untapped ability to balance through area coordination and inefficiency in the overall power system. The IEA (2017) discusses this, and Gerard et al. (2018) further elaborate on balancing efficiencies that can be gained from the cooperation between TSO and DNO and between grids.

    This problem is corroborated by the following studies:
    - Dondi et al. (2002) on network integration for distributed power generation;
    - Richardot et al. (2006) on coordinated voltage control in distribution networks using distributed generation;
    - Castanheira et al. (2015) on coordinating transmission and distribution planning and operations to maximise power system efficiency;
    - Muttalib et al. (2016) on developing and enhancing business processes to enable higher levels of TSO-DSO interaction;
    - Gerard et al. (2018) on coordination between transmission and distribution system operators in the electricity sector.

17) **Bidirectional flow of power and data in the distribution system needs to be planned for.** Equipment for this is becoming more affordable and interoperable and should be accounted for in network planning and large HVAC installations. Vehicle-to-grid power exchanges, storage in the form of hot water or ice, and smart devices that can shift the energy use of a machine in response to the condition of the grid are all becoming more widely available regarding hardware and software for these systems, and lower in cost. Moreover, retrofitting can be considerably costlier than a greenfield installation. This can significantly increase the efficiency of the distribution network. Pass et al. (2018) go into detail on efficiencies that can be gained from bidirectional power movement, especially in systems involving HVAC loads and other utilities such as water provision. This is especially relevant to areas like sub-Saharan Africa and Southeast Asia, which are urbanising and seeing steeper load curves driven by air conditioning.

    This problem is corroborated by the following studies:
    - Mashhour et al. (2009) on optimal sizing and siting of distributed generation in a radial distribution network to account for unidirectional and bidirectional power flow;

- Razmara et al. (2015) on optimal bidirectional operation of smart-building-to-grid systems;
- Razmara et al. (2017) on building-to-grid predictive power flow control for demand response and demand flexibility programs;
- Mumtaz and Bayram (2017) on planning, operation, and protection of microgrids that include bidirectional power flow;
- Jiang et al. (2018) on the flexible operation of active distribution network using integrated smart buildings with heating, ventilation and air-conditioning systems.

18) **Clear and effective policies need to be enacted to produce, consume, store, delay, or augment power at the distribution level**. Planners need two-way interaction with the distribution and retail systems to enable shaping load in real time and dynamically balance the system. The US DoE and American Physical Society (Crabtree et al., 2011) note the importance of distribution-level storage and augmenting supply and demand at the distribution and retail levels in smart cities and energy efficiency projects. The US DoE (2017) details this further, discussing the need for storage systems embedded in dense, urban load centres. Gissey et al. (2018) note that storage options are hindered by regulatory issues and market incentives and that this is a key constraint to energy efficiency in dense urban centres.

    This problem is corroborated by the following studies:

    - Gomes and Saraiva (2009) on a market-based active/reactive dispatch including transformer taps and reactor and capacitor banks using simulated annealing;
    - Samimi and Kazemi (2016) on coordinated volt/var control in distribution systems with distributed generations based on joint active and reactive powers dispatch;
    - Samimi and Nikzad (2017) on complete active-reactive power resource scheduling of smart distribution system with high penetration of distributed energy resources;
    - Samimi et al. (2017) on a scenario-based stochastic framework for coupled active and reactive power market in smart distribution systems with demand response programs;
    - Shigenobu et al. (2018) on optimal operation method for distribution systems considering distributed generators imparted with reactive power incentive.

19) **Coordinating with other utilities needs to occur, as this can unlock significant synergies and savings.** Gas, water, transport, waste disposal, and other utilities can share information on their assets, inputs and outputs, and customer base, in order to maximise their operations collectively. This can also improve the planning of capital deployment and infrastructure investments in construction in public or highly used areas, tunnelling, metering and billing systems, and coordinating or augmenting load. The US Environmental Protection Agency notes the efficiencies that can be gained

from cooperating with water utilities (Tice et al., 2012). Water utilities are an example of large-scale loads where parts of their operations are not time critical, as it can utilise storage tanks to shift the timing of operations. Water utilities can work with the power utility to shift demand, coordinate its operations with the status of the grid, and utilise any space on major sites to generate and store power. Coordination of loads, shared infrastructure, and other issues are critical to urban centres as water, gas, power, and other utilities all increase with urbanisation. Martinez-Cesena et al. (2015) used Senegal as an example to display how data sharing between the power and telecom industry can help power planners forecast where urbanisation will occur, and how to manage corresponding utility issues.

This problem is corroborated by the following studies:

- Fraquelli et al. (2004) on scope and scale economies in combined gas, water and electricity utilities;
- Martinez-Cesena et al. (2015) on using mobile phone data for electricity infrastructure planning in Senegal;
- Selvarajoo et al. (2018) on urban electric load forecasting with mobile phone location data;
- Steiner et al. (2018) on sustainability assessment of urban water infrastructure systems with special focus on the urban water-energy nexus;
- Vakilifard et al. (2018) on the role of water-energy nexus in optimising water supply systems.

20) **Power sector planners should guide property developers on where urban centres should expand to, rather than attempt to follow and catch-up in network building**. Network planners need access and entitlement to work with the real estate sector and corresponding government departments to guide urbanisation as much as possible. Guatemala is a rare example of a developing country where the power sector encouraged the property sector to expand cities into areas that were more convenient for them to connect, lowering costs and supporting higher electrification rates (Colom, 2011). Parshall et al. (2008) discuss a similar planning scheme in Kenya. The Government of Ireland (2009) notes that the top barriers to green building planning were government-related, human-related, knowledge- and information-related, market-related, and cost- and risk-related. Chan et al. (2018) discuss how real estate does and could, to a greater extent, play a critical role in Ghana’s power sector. Yazdanie et al. (2017) emphasise the importance of synchronising urban and land planning with power sector planning.

This problem is corroborated by the following studies:

- Parshall et al. (2009) on national electricity planning in Kenya, where pre-existing grid coverage was low;

- Mentis et al. (2015) on the GIS-based approach for electrification planning in Nigeria;
- Trotter et al. (2017) on electricity planning and implementation in sub-Saharan Africa;
- Yazdanie et al. (2017) on the importance of synchronising urban and land planning with power sector planning;
- Chan et al. (2018) on the role of real estate in Ghana's power sector.

21) **Power sector reform and liberalisation should occur at an equal pace from generation through transmission, distribution, and retail**. Liberalisation (pricing, market competition, participation, policy) of generation and transmission first and distribution and retail later leads to distribution companies in many developing countries nearly going bankrupt and later being unable to pay generators, leaving the full power system in disarray. This is shown in detail in Manibog et al. (2003), Joskow (2008), Loksha (2015), and IFC (2018), emphasising the negative effects of non-synchronised reform in developing countries and the economic and operational impacts therein.

    This problem is corroborated by the following studies:
    - Nepal and Jamasb (2015) on the governmental, market, and regulatory failure in electricity sector reforms;
    - Zhou and Yang (2015) on China's power industry reform, with the focus on demand-side management;
    - Eshun and Amoako-Tuffour (2016) on the trends in Ghana's power sector;
    - Alpizar-Castro and Rodríguez-Monroy (2016) analyzing Mexico's energy reform in 2013;
    - Qazi (2017) on an institutional framework for the development of a sustainable and competitive power market in Pakistan.

22) **Asset management at the distribution level is underinvested and needs to be emphasised**. Asset management includes logging what assets are in place, what use profile they have been through, such as their age, depreciation, condition, and using this to maintain the system properly. This includes both linear assets (e.g., lines) and point assets (e.g., transformers). This improves a variety of issues around maintenance, capital planning, right of way issues, tunnelling, understanding equipment degradation, and centralised management of large point assets. This is detailed in Schwartz (2010), Schwartz and Sheaffer (2011), and Yarka (2012), including efficiencies and energy savings from robust asset management programs in distribution companies.

    This problem is corroborated by the following studies:

- Schwartz (2010) on strategies for utility distribution systems;
- Schwartz and Sheaffer (2011) consumer energy efficiency and distributed generation in smart grids;
- Yarka (2012) on transmission and distribution investments in next-generation asset management;
- Jiang et al. (2017) on an electrification project for affordable access to electricity with optimal asset management in Singapore;
- Jamasb et al. (2018) on smart electricity distribution networks, business models, and application for developing countries.

23) **Distribution planners need to work closely with infrastructure developers (e.g., ports, rail stations), and with property developers who will have large loads in their network (e.g., campuses, industrials, hotels, schools) to create energy efficiency, and DSM/DR capabilities in load centres**. Cooperation before this infrastructure is built can create opportunities in demand-side management, on-site generation, congestion management, shared/optimised HVAC, and other opportunities. Centralised chillers, combined heat and power units, and large storage units are examples of where infrastructure projects may have a shared load or need with the surrounding built environment and where coordination can be of benefit. Eller (2018) discusses how planning large infrastructure in conjunction with power storage needs is important, and in Volk (2013) the IEA discusses large efficiency gains that can be achieved through proper planning of infrastructure projects.

    This problem is corroborated by the following studies:
    - Bai and Qian (2010) on electricity infrastructure development in China;
    - Kemausuor et al. (2014) on the electrification planning in Ghana;
    - Trebilcock and Rosenstock (2015) on the public–private infrastructure partnerships in developing countries;
    - Mentis et al. (2016) on geospatial planning of electric infrastructure in Ethiopia;
    - Rafique and Rehman (2017) on the current state, future planning, and institutional infrastructure for the national energy scenario of Pakistan.

24) **Effectively managing rapid urbanisation and preventing cluttered and hazardous network planning.** Rapid urbanisation often leads to cluttered, hazardous, and overly costly systems. Dealing with a rapid increase in urban populations is critical for network planners. This can take the form of shanty towns and informal settlements, which are often seen in areas such as sub-Saharan Africa and the Indian subcontinent. Designs and plans to rapidly respond to this increase in urban load are critical. Yazdanie et al. (2017) discuss the economics and operational balances of doing this correctly in growing cities. Keivani (2010) discusses how the safe and well-planned development of distribution infrastructure in synchronised pace with urbanisation is

key to sustainable cities. Shahraki (2017) and the United Nations (UN DESA, 2008) review system stresses and inefficiencies that occur when network planning is out of pace with urbanisation. Reiche et al. (2000), Palit and Chaurey (2011), and Mandelli et al. (2016) discuss how effective design can lower the cost of electrification of newly developing load centres. Shahraki (2017) highlights the negative aspects of poor power distribution planning in urban sprawls.

This problem is corroborated by the following studies:

- Keivani (2010) on how well-planned development of distribution infrastructure in synchronised pace with urbanisation is key to sustainable cities;
- Palit and Chaurey (2011) on the off-grid rural electrification in South Asia;
- Mandelli et al. (2016) on the off-grid systems for rural electrification in developing countries;
- Shahraki (2017) on the negative aspects of poor power distribution planning in urban sprawls;
- Yazdanie et al. (2017) on the economics and operational balances of doing this correctly in growing cities.

25) **Microgrids are underutilised as a tool in network planning in urbanising, developing countries.** Edges of the urban grid and industrials that are not large enough to justify dedicated large generation or power systems can be serviced by microgrids in the near- and mid-terms. Sections of a city, such as a university or a particular district, can be serviced by a microgrid now; and in the future, when the system is upgraded, the microgrid can be absorbed into the broader system and serve as redundancy for the broader system. This is particularly useful as developing countries attempt to scale up power grids yet may not have adequate financing – microgridding one part of the system as a short- and mid-term remedy can delay capital investment and save money. Microgrids involving small-scale electricity generation (10 kW to 10 MW) based on diesel or solar energy may especially benefit small communities in rural areas, such as the one in the island of Mageta, Lake Victoria, Kenya (Pschetz et al., 2018). Torpey (2011) and Siemens (2014a) detail how microgrids can play a critical role in grid support and grid extension, which is central to power planning in urbanising areas.

This problem is corroborated by the following studies:

- Torpey (2011) on the supportive role of microgrids in power planning in urbanising areas;
- Gaona et al. (2015) on rural microgrids and their potential application in Colombia;
- Zhu et al. (2015) on the development of microgrids in China;
- Murenzi and Ustun (2015) on electrifying Sub-Saharan Africa with the aid of

microgrids;

- López-González et al. (2017) on renewable microgrid projects for autonomous small-scale electrification in Andean countries.

26) **As the network is expanding, planners must continually identify medium and large demand response (DR) targets.** As both distribution networks and broader power networks are expanding in developing countries, reliability and outages will be an issue. Working with end users to identify and incentivise meaningfully sized DR targets is important. These can be facilities such as campuses, commercial buildings or rail stations, and they can act by dropping HVAC or non-critical lighting load to accommodate system stress. Single end users can often produce high single-digit or low double-digit MW DR in a matter of minutes, which can prevent system failure. Network planners need to identify these end users and work with them as the network is growing. Line losses and congestion impact the entire system; thus, the impact of effective DR programs is critical to managing growing load centres and power systems. The National Association of Clean Air Agencies (2015) highlights the impacts of this, the ways it can be implemented, and implications for large and growing load centres. The Regulatory Assistance Project notes this as well in Weston (2001), Schwartz (2010), and Schwartz and Sheaffer (2011).

    This problem is corroborated by the following studies:

    - Weston (2001) on the accommodation of distributed resources in wholesale markets;
    - Wang et al. (2010) on the demand response implementation to mitigate the escalating demand for electricity in China;
    - Choi and Thomas (2012) on the electricity generation planning model incorporating demand response;
    - Aghaei and Alizadeh (2013) on demand response in smart electricity grids equipped with renewable energy sources;
    - Monyei and Adewumi (2018) on the integration of demand side and supply side energy management resources for optimal scheduling of demand response loads in South Africa.

27) **Lack of target setting and on-going improvement standards in network operation needs to be addressed.** There are a limited number of developing countries with targets in place for improving access to modern, efficient energy. The problem with this is that target setting is the first step to providing a framework for tracking progress and accountability. Countries are unlikely to achieve their development aspirations unless significant efforts are made to expand the range, quality, and quantity of energy services available to the poor. Legros et al. (2009) display the United Nations' emphasis on target setting amongst other key initiatives in developing countries. Target setting is further emphasised in Leal and Azevedo (2016) and stated as a critical

component of smart cities and sustainability.

This problem is corroborated by the following studies:

- Teera-Achariyakul et al. (2010) on the optimal allocation of maintenance budgets for reliability target setting;
- Ballanca and Garside (2013) on an approach to designing energy delivery models that work for people living in poverty;
- Ahlborg and Hanmar (2014) on drivers and barriers to rural electrification in Tanzania and Mozambique;
- Leal and Azevedo (2016) on setting targets for local energy planning;
- Bisaga et al. (2019) on the potential of performance targets as drivers of energy planning and extending access to off-grid energy in rural Rwanda.

28) **Lack of streamlining and matching network design standards with the demand to develop efficient distribution systems in a timely fashion.** Network planners often apply a 'one-size-fits-all' approach when planning non-urban networks. This often results in applying the same equipment and planning standards to growing townships as in rural agricultural villages. This leaves standards and the power system out of sync with the load because critical issues around voltage, frequency, and distributing quantities of power over different distances are not synchronised. This results in a system that has unnecessary technical losses and requires different equipment and methods to resolve the same issue (such as lack of reactive power at a particular load point). Synchronising designs and standards can result in proactive forecasts of technical losses as cities grow, and management of these issues with minimal distribution and cost. Barnes et al. (1997), Barnes (2011), and Herran and Nakata (2012) focus on electrifying developing countries and how effective design and network standards can ease distribution constraints. Kolokotsa (2016) describes how the standardisation of power distribution and building codes can reduce load and improve energy efficiency. Smith (1995) uses Nepal, Sri Lanka and several South Pacific Islands as examples of where more efficient network design and standards could improve electrification and power distribution. Mandelli et al. (2016) extensively reviewed the development of off-grid, small-scale systems for rural electrification in developing countries in the period between 2000 and 2014, and concluded that using uniform designs in expanding, off-grid townships was critical to meeting growing load with minimal technical losses and cost.

This problem is corroborated by the following studies:

- Barnes et al. (1997) on tackling the rural energy problem in developing countries;
- Barnes (2011) on effective solutions for rural electrification in developing countries;

- Herran and Nakata (2012) on the design of decentralised energy systems for rural electrification in developing countries;
- Kolokotsa (2016) on the role of smart grids in the building sector;
- Mandelli et al. (2016) on off-grid systems for rural electrification in developing countries.

29) **Non-standardisation of both home and industrial electrical equipment and resistance to internationally agreed standards.** Distribution network planners are often reactive in dealing with standards around electrical equipment from as small as household appliances to as large as industrial machinery. Distribution planners need to work with economic and industrial planners to ensure that standards for end-user equipment are set proactively. This can impact a variety of issues from power quality and power factor management to enabling DSM and DR through smart appliances and machines. The IEA (2017) details this and puts forth standards on harmonising machinery from consumer appliances to industrial machines to improve power efficiency. Failures that occur from non-standardisation are detailed in Kershaw (2007). This also relates to an emerging trend in managing waste electrical and electronic equipment (WEEE). A significant proportion of WEEE components ends up in unsanitary and uncontrolled landfill and open dump sites. Integrated WEEE management is a theoretically viable technique in which municipal solid waste and WEEE management systems are standardised and managed according to their characteristics and re-use capabilities. Germany, Sweden, and Italy manage one order of magnitude higher quantities of WEEE compared than countries such as Romania and Bulgaria. China and India have no real systems in places for this. Although prevention and reduction measures are encouraged, all WEEE quantities are continuing to grow. In 2007–2014, developed economies exceeded the annual European collection target of 4 kg WEEE per capita, while collection is still difficult in developing countries. The impacts of not having adequate end-user standards in electronic waste are detailed in Kershaw et al. (2018) and Ikhlayel (2018). WEEE here is included as it represents a subset of the opportunity to standardise equipment and end-user load devices. Critical to this from a technical loss perspective is industrial equipment. There is scope to create standards for end-user devices, which positively impacts both the power distribution system and the growing problem of WEEE at the same time.

    This problem is corroborated by the following studies:

    - Kershaw (2007) on the failures from non-standardisation of international electrical units;
    - Ibanescu et al. (2018) on the assessment of the waste electrical and electronic equipment management systems profile and sustainability in developed and developing European Union countries;

- Ikhlayel (2018) on an integrated approach to establish e-waste management systems for developing countries;
- Simiari et al. (2018) on e-waste management and disposal in Nowshahr, Northern Iran,
- Jayaraman et al. (2019) on e-waste management model from the conviction of individual laptop disposal in Malaysia.

30) **Planners do not sufficiently include resiliency and secure infrastructure in grid planning.** A variety of issues require increased resiliency, such as global warming and unpredictable weather events, terrorism, and more complicated power generation systems. System resilience, security, and rapid recovery from events need to be incorporated in network planning. The number, duration, and severity of weather events have been steadily growing, and the adverse effect on grid reliability is undeniable (Gholami et al., 2016; Panteli et al., 2016; Liu et al., 2017). The most obvious example is Hurricane Maria that hit Puerto Rico in September 2017, causing a near-total power blackout of facilities except the ones running on generators. The causes stemmed from overly bureaucratized and poorly managed Puerto Rico Electric Power Authority to poor system performance as measured by indexes such as SAIDI, SAIFI and CAIDI. Fortifying future resiliency of Puerto Rico's grid will need to include measures such as improving power system operations and dispatch strategies, implementing microgrids, energy storage, and system segmentation, and mitigating infrastructure interdependencies (US DoE, 2018). These issues and the growing risks to developing urban centres from a lack of power system resiliency are further detailed in Collier (2015) and the US DoE (2017).

    This problem is corroborated by the following studies:

    - Gholami et al. (2016) on microgrid scheduling to improve resilience;
    - Panteli et al. (2016) on using defensive islanding to improve power grid resilience to extreme weather events;
    - Liu et al. (2017) on microgrids for enhancing the power grid resilience in extreme conditions;
    - Venizelos et al. (2017) on distribution system resilience enhancement under disastrous conditions by splitting into self-sufficient microgrids;
    - Wang et al. (2017) on robust line hardening strategies for improving the resilience of distribution systems with variable renewable resources.

31) **In order to stay competitive, distribution utilities must transform themselves into more digital enterprises.** Digital infrastructure in a distribution network is critical to retaining low cost, efficiency, and rapid recovery from system events. Planners in developing countries need to find the right means of doing this within their budgets. Collier (2015) regards this as one of the top 10 challenges for distribution utilities.

Barnes et al. (1997) and Fadaeenejad et al. (2014) show this as a key issue in developing countries. Scott (2015) details the risks of rapid urbanisation in developing countries with insufficient distribution planning as well as modernisation and digitisation of power systems. The United Nations (Taipale and Fellini, 2012) review challenges in urbanising areas and power distribution and highlight how digitisation can help this. Schwartz (2010), Schwartz and Sheaffer (2011), and the UN Commission on Science and Technology for Development (2016) describe the importance of smart cities, infrastructure, smart power distribution and digitisation of power. Yasmin and Qamar (2013), the US DoE (2017), Jamasb et al. (2018), and Kauer et al. (2018) discuss the uses of mobile phone data and information technology in improving power distribution. Collier (2015) details how digitisation can lift several of the constraints facing distribution companies. Weichhart et al. (2016) and the US DoE (2017) display how digitisation can lead to greater security and resilience in power distribution.

This problem is corroborated by the following studies:

- Barnes et al. (1997) on tackling the rural energy problem in developing countries;
- Fadaeenejad et al. (2014) on the present and future of smart power grid in developing countries;
- Rashid and Rehmani (2016) on the applications of wireless sensor networks for urban areas;
- Weichhart et al. (2016) on challenges and current developments for sensing, smart and sustainable enterprise systems;
- Jamasb et al. (2018) on smart electricity distribution networks, business models, and application for developing countries.

32) Problems with governance and management are well documented in the developing world and need to be addressed. Standards for safety, efficiency, and sustainability constantly need to be incorporated in system planning. Accounting for and measuring performance against the traditional grid can be a key enabler of smart grid technologies and smart cities. This is detailed in Keivani (2010), Schwartz (2010), and Schwartz and Sheaffer (2011). The importance of emphasising this at the national and local power planning levels is discussed in Ponce-Jara et al. (2017).

This problem is corroborated by the following studies:

- Keivani (2010) on the main challenges to urban sustainability;
- Bifulco et al. (2016) on information and communications technology and sustainability in smart cities management;
- Hajduk (2016) on the concept of a smart city in urban management;
- Meijer and Bolívar (2016) on smart urban governance;
- Ponce-Jara et al. (2017) on the past and present of smart grid in developed and developing countries.

4.2 Excel-Based Tools for Developing Solutions to the EEC

The Excel-based tools and solution framework for the EEC consist of one overall-system scorecard and four sub-scorecards, which were developed from standard engineering texts. These include '*Understanding Electric Power Systems*' (Casazza and Delea, 2010), '*Smart Grid, Fundamentals of Design and Analysis*' (Momoh, 2012), and *Practical Guidance for Designing a Smart Grid Modernisation Strategy'* (Madrigal and Uluski, 2015). These start by ranking the macro energy environment and then focus on four key areas of energy, as they pertain to the research focus areas and knowledge gap (distribution in urbanising, developing countries). The user of the tool starts with the macro environment for energy consumption and general enablers/constraints for the energy industry, and then focuses on four areas which bring the user closer through ranking specific issues and building the foundation of solution development. The scorecards are described below.

4.2.1 Overall-System Scorecard

The overall-system scorecard (**Table 4**) is the starting point to understand the broader power system and supply-and-demand dynamics. This scorecard takes a step back from just distribution problems and looks at the broader power system. The overall-system scorecard consists of eight major topics and 43 subtopics. The major topics are:

- geography,
- demand management and customer engagement,
- renewable energy (RE) integration,
- regulatory and market enablers of smart grid (SG) technology,
- physical enablers of RE and SG,
- local load and local economy,
- system infrastructure and efficiency,
- system reliability.

In the part on geography, the respondent is asked about:

- the share of renewable energy resources in the power market,
- load location and density,
- transmission and distribution characteristics,
- climate impacts on the load and infrastructure.

The part on demand management and customer engagement questions:

- the level of customer participation,
- the extent of economic incentives for participating in energy programs,
- the ability of the system operator to increase demand management programs.

The part on RE integration questions:

- the levels of curtailment,
- economic incentives,
- matching RE resources to load,

- the availability of data on RE resources,
- transmission and distribution fees,
- the methods to support RE producers in power dispatch.

The part on regulatory and market enablers of SG technology questions:

- the regulatory support of renewable energy integration,
- pricing,
- flexible contract structures,
- supporting new entrants in power supply and power services.

The part on physical enablers of RE and SG questions:

- storage,
- grid connection costs,
- the accuracy and data capabilities of metering.

The part on local load and local economy questions:

- the load curve,
- subsidies and tariff elasticity.

The part on system infrastructure and efficiency questions:

- infrastructure at the substation level,
- equipment condition monitoring,
- dynamic equipment rating,
- installation of protective facilities,
- voltage reduction,
- feeder sensors and communication facilities,
- SCADA rule-based VVO,
- FLISR,
- GIS modelling of the distribution system,
- optimal network reconfiguration,
- model-driven VVO,
- switching order management,
- DER management and dynamic volt-VAR control,
- demand response.

Finally, the part on system reliability questions:

- SAIDI,
- SAIFI,
- CAIDI,
- MAIFI,
- standby power.

Table 4. The overall-system scorecard.

Overall System Scorecard			**Enter Scores 0 to 5 in Blue Cells**	
Major Topic	**Subtopic**	**Description**	**Scoring Criteria**	**Score (0-5)**
Geography	Renewable energy resources penetration	The degree of participation from renewable energy in the power market, by installed capacity and by available resources.	Percentage of total, average, peak and trough capacity that is from RE. Curtailment of RE (if any) and amount of underutilised RE resources.	
	Renewable energy resources data available relative to country boundaries	Extent and availability of data on RE resources.	The quantity of total land area that has had RE resources assessed, ease of accessing this data.	
	Load location and density	How focused load is geographically, and distances between major load centres.	What percentage of the load is in the median load centre? How much load is in the top three, five, and ten load centres? What are the distances and approximate costs to connect these load centres? Is pooling load centres possible or prohibitive?	
	Transmission and distribution (T&D) distances and costs	How much distance impact T&D costs and planning, and who can access T&D infrastructure.	Distance from mid- and large-scale generation centres, and major load centres. The extent to which T&D impacts the total cost of power to the ratepayer. The extent to which T&D infrastructure is available to third parties. How much do third parties pay to connect to infrastructure and how close is this to the actual cost to connect.	
	Climate impacts to load	The extent to which temperature impacts load and power infrastructure.	Percentage of the total load that goes into heating and cooling. High and low temperatures, and the number of days per year that heating and air conditioning are in large-scale use. The extent to which weather impacts power sector performance (e.g., high levels of line resistance from high temperatures).	

Demand Management and Customer Engagement	DM system participation	Level of participation in demand management and demand-response systems	Percentage of customers participating in DM & DR systems. The amount of annual load that has been managed through DM & DR systems divided by the total annual load.	
	Incentives for DM	Is there sufficient economic incentive in the full value chain to support successful DM & DR?	Are per unit and full life-cycle costs of participating in DM & DR more attractive than simply selling power for generators, transmission and distribution companies, and retail companies?	
	Increases to DM programs	Can the power system accommodate further DM programs?	Are there underutilised, ramping capacity, storage, or distributed resources? How much load can be shed or curtailed? How responsive are customers to DM programs and how has this impacted the slope of the load curve?	

Renewable Energy Integration	Levels of curtailment	How much RE generation is being rejected or curtailed due to system inefficiency?	Actual RE production (MWh) and estimates of RE potential from existing RE installations (MWh). Quantities of RE being rejected from the grid due to dispatch policy, insufficient T&D infrastructure, etc.	
	FIT and incentives and supporting RE investment	Are feed-in tariffs (FIT) and other economic incentives sufficient to support RE?	What tariffs and incentives are available? Are they sufficient to cover project capex and any grid connection issues? What is the duration of these incentives?	
	Efforts to match RE resource to load	Do FITs and incentives cater to load and RE location?	Are FITs and incentives constructed to encourage RE development nearby load centres or only where resources are high in availability? Do regulations and markets account for geographic gaps between load and RE resources?	
	RE resource data availability	Transparency and availability of data	Is RE data available to all third parties wishing to participate in the power sector at a reasonable price? Was the data collected by an objective third party?	
	T&D fees for RE producers	Ease of connecting RE resources to the grid	Who pays for RE resources to connect to T&D infrastructure? Has net metering been promulgated for small-scale and distributed generators? Is grid connection offered at actual or near-actual cost? Are grid connection costs transparent and are permitting processes transparent and reasonable?	
	Methods to support dispatch and priority for RE producers	Ensuring RE producers realise sufficient grid penetration	Do policies clearly quantify the value of RE power relative to more CO_2-intensive generation? Is a clear system prioritising RE and managing congestion during peak RE periods in place?	

Regulatory and Market Enablers of Smart Grid (SG) Technology	Incentive-based regulation	Do power sector regulations encourage renewable energy integration?	Are flexible generation and ramping associated with balancing load and integrating volatility from RE rewarded? Is the thermal fleet categorised and rewarded by those who can and cannot ramp-up/down quickly? Are power companies only paid for power and availability, or are there incentives for balancing, ramping, and shifting or avoiding load? Is regulation performance based with appropriate rewards and penalties?	
	Pricing	Does pricing encourage energy efficiency and support RE?	Does the system have block pricing, time-of-use pricing, and other mechanisms in place to manage load? Does pricing reward flexible generators? Does power pricing take into account CO_2 per unit of power and environmental costs of generation?	
	Flexible contract structures	Do contract structures support DSM and RE?	Are power consumers encouraged through contracts to avoid or delay load? Do contracts provide incentives for flexible consumption and scheduling load to coincide with RE availability?	
	Access to infrastructure and participation in power services	Do regulations support new entrants into the power supply and power services?	Are regulations clear and transparent for new entrants to participate in power services, and for existing entities to provide new services? How transparent are the processes for small-scale and distributed generators, storage providers, and auxiliary services? What is their cost of the grid or other infrastructure connection relative to the actual cost? Can end users generate their own power? Has net metering been promulgated and is it transparent?	

Physical Enablers of RE and SG	Storage	Is storage available or encouraged, in order to support RE and system balancing?	Are there billable services and a commercial market for storage and system balancing? Do existing hydropower resources have pumped storage? Does the regulator reward system balancing through storage? Are procedures for installing the distribution, retail, and load-level storage transparent?	
	Grid connection costs	Are grid connection costs appropriate and transparent?	How are entities which are not large scale IPPs and not utilities charged for grid connection? Are fees for connecting to the grid close to actual cost and reasonable?	
	Advanced infrared metering	How granular is metering data and is the flow two way?	Is data such as consumption patterns and impacts on power quality collected on individual users? Is data collected on small-scale power producers? Can the system operator utilise metering infrastructure to locate specific needs such as power factor correction and balancing?	

Local Load & Local Economy	Load curve	The slope of the load curve and what impacts it?	What key factors (e.g., weather, consumption habits, industry, seasonality) impact load and slope of the load curve? How well is this understood?	
	Subsidies and tariff elasticity	How affordable is power to the population and industry?	Are large portions of the population or economy subsidised in power and energy? What are power costs as a percentage of mean and median income? Is there scope for raising rates to finance RE and system upgrades?	

System Infrastructure & Efficiency	Substation IEDs	Installation at the substation level of intelligent electronic devices (IEDs), data communications network infrastructure, remote terminal unit (RTU), or data concentrator infrastructure.	The degree to which there is protective relay reliability through self-diagnostics. How much information is available to the grid, including information around distance to faults and overall support of faster service restoration?	
	Equipment condition monitoring	Implementation of analytical software for equipment condition monitoring. Operation and maintenance procedures for condition-based maintenance.	The degree of reduction of routine inspections and maintenance costs. The degree or ability to detect incipient problems. The overall minimisation of repair costs (the ability to fix problems proactively while problems are still small).	
	Dynamic equipment rating	Installation of new sensors (e.g., transformer winding temperature). Develop and implement application software for dynamic rating.	The degree to which the system can improve asset utilisation, defer capital expenditures for capacity additions, and reduce the need for load shedding and overall levels of reliability.	
	Adaptive protection	Installation of protective relay IEDs, substation communication facilities, and software to support automatic setting changes.	The degree of reliability due to having relay setting that matches the operating conditions.	
	Voltage reduction	Any equipment and decrease of labour involved in voltage regulation	The degree to which peak demand is lowered and overall efficiency is improved through voltage reduction.	
	Distribution feeder sensors and communication facilities	Installation and operation of sensors on feeders, and two-way communication facilities. Overall maintenance costs of new distribution feeder sensors and communication equipment.	The extent of communication visibility and communication with feeders and feeder conditions.	
	SCADA rule-based VVO	Install and maintain VVO rules processors, sensors for voltage feedback, two-way communications to all Volt-VAR	The extent to which losses and peak demand are decreased by effective deployment of this equipment. The ability for early detection of capacitor bank and voltage regulator problems. The degree to which the system can	

		control devices, and VVO software.	eliminate routine inspections for capacity banks and voltage regulators.	
	Fault location isolation and service restoration (FLISR)	Install and maintain FLISR processors, automated line switches, fault detectors, two-way communication equipment for FLISR, and software to manage FLISR systems.	The extent to which reliability is improved through rapid service restoration. The extent to which fault investigation times are reduced and made more precise and efficient.	
	As-operated model of the distribution system	Identify and quantify GIS data errors, build and maintain an as operated model.	The extent to which the changing distribution system is accounted for and supported.	
	Optimal network reconfiguration (ONR)	Implement analytical ONR software and train operators and engineers on how to use it.	The extent to which voltage profile, reliability, and electrical losses are improved by load balancing.	
	Model-driven VVO	Implement VVO analytical software, train operators and engineers on its operation.	The extent to which electrical losses are reduced, the voltage profile is improved, peak shaving is supported, and overall efficiency is achieved from VVO. The extent to which the system can adapt to changing feeder conditions, and account for DERs in the VVO control strategy.	
	Switching order management (SOM)	Purchase and implement SOM analytical software and train operators and engineers how to use it.	The extent to which switching efforts are generated faster and more accurately during emergencies. The extent to which outage planning is improved.	
	Enhanced fault location isolation and service restoration (FLISR)	Implement new FLISR software as needed, train staff on the operation.	The extent to which system restoration is improved by utilising available DERs. The extent to which the system adapts to changing feeder conditions.	
	DER management and dynamic Volt-VAR control	Install equipment, software, and communication facilities for monitoring and controlling DERs. Install energy storage, static VAR compensation, and associated controls.	The ability to mitigate adverse consequences of voltage and power swings caused by distributed generators with variable output. The ability for the utility to accommodate more distributed generators on existing feeders. The ability of the utility to deploy microgrids for portions of the grid that are weak or may require this arrangement.	

	Demand response	Purchase and install automatic metering infrastructure (AMI), end-user level displays, end-user level automation networks, and DR hardware and software at critical locations.	The extent to which peak shaving is enabled during critical shortages. The extent to which new generation and transmission facilities can be reduced or delayed.	

System Reliability	SAIDI	System average interruption duration index	Total minutes of sustained customer interruptions vs. total number of customers	
	SAIFI	System average interruption frequency index	Total number of sustained customer interruptions vs. total number of customers	
	CAIDI	Customer average interruption duration index	Total minutes of sustained customer interruptions vs. total number of interruptions	
	MAIFI	Momentary average interruption frequency index	Total minutes of momentary customer interruptions per year vs. total number of customers	
	Standby power	Availability of standby power in the system, and cost of providing this power.	MW of capacity capable of <15-minute ramping – standalone and relative to total capacity in the system and peak load.	

KEY:
5 = Very High
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = Not Applicable

4.2.2 Scorecard 1 – Impacts on the Power System

Scorecard 1 (**Table 5**) asks the interviewee to rank the impacts of the 32 distribution problems (identified in **Section 4.1**, page 67) to 16 areas and functions of the power system, such as stability and scale of the system, losses, and other critical problems.

The 32 problems are shown vertically, and the critical system problems that they might impact are shown horizontally. The interviewee ranks these 0–5 depending on the impact. This scorecard helps the user to understand the 32 distribution problems with a holistic view of the full power system and its key functions, emphasising the broader operations, scalability, and stability of the system. It is used as a starting point in the ranking and scoring sequence, as it addresses critical building blocks of the power system and related planning.

The areas and functions of the power system in this scorecard were based on the textbooks '*Understanding Electric Power Systems: An Overview of Technology, the Marketplace, and Government Regulation'* (Casazza and Delea, 2010), '*Energy Systems and Sustainability: Power for a Sustainable Future*' (Everett et al., 2011), and '*Renewable Energy: Power for a Sustainable Future*' (Peake, 2017). The examples of system stability problems needing consideration include fault prevention, voltage and frequency stability, load balancing, and related issues. The ability to scale up the system refers to meeting growing capacity needs and avoiding bottlenecks. Ramping refers to the ability to meet peak power needs and seasonality, whereas incorporating renewables refers to managing volatile generation from renewables connected at different points in the system. System stress refers to critical equipment that can be damaged or destroyed during peaks and troughs in load, generation, and variation in power quality. Pollution that could have been prevented refers to any inefficient part of the system that results in an increase in CO_2 or other pollutants per unit of power delivered. Lost opportunities in leveraging the built environment refer to inefficiencies or losses that occur from not leveraging infrastructure and buildings that play a role in power system balancing. These are standard components to power sector planning found in the textbooks mentioned earlier, which impact the current and future status and stability of the power system. This scorecard provides a framework for understanding the 32 problems relative to critical areas of power system planning.

Table 5. Scorecard 1 – the master scorecard ranking impacts of the 32 distribution problems to 16 areas and functions of the power system.

Enter scores 0 to 5 in blue cells

Scorecard 1		Impacts:																	
Distribution system planning problems:		**System stability issues**	**Over-build of capacity**	**Flexibility/ability to ramp**	**Ability to incorporate renewables**	**Ability to scale-up**	**Ability to modernise the system**	**Impacts on potential DSM/DR projects**	**Redundant Generation capacity**	**Lost opportunities in managing demand**	**Lost opportunities in data collection**	**Lost opportunities in leveraging the built environment**	**Causes additional system upgrades**	**Pollution that could have been prevented**	**Safety problems or other hazards**	**System stress**	**Lost opportunity to tie in with other utilities and systems**	**Median**	**Total**
1	Over-reliance on simple radial distribution																		
2 . . . 31	. . .																		
32	Problems with governance and management																		
	Median																		

KEY:
5 = Very high
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = None

4.2.3 Scorecard 2 – Impacts to a City's Infrastructure, Utilities, and Inhabitants

With the impacts of the 32 distribution problems ranked by their impacts to critical areas of the power system, we now rank them by their impacts to critical areas of cities and urban planning. Scorecard 2 (**Table 6**) features the 32 distribution problems (identified in **Section 4.1**, page 67) in rows, and nine key areas of a city's infrastructure, including city planners, commercial and residential real estate, utilities, and both average and low-income inhabitants, in columns. From this scorecard, we see who is impacted (e.g., city planners, real estate, industrials, utilities, transport, population) and how much they are impacted.

The areas listed in columns were chosen on the basis of the textbook '*Understanding Electric Power Systems: An Overview of Technology, the Marketplace, and Government Regulation'* (Casazza and Delea, 2010) and the UN's cornerstone document '*Energy for a Sustainable Future: Report and Recommendations*' (AGECC, 2010).

Table 6. Scorecard 2 – scoring nine key areas of a city's infrastructure, utilities, and inhabitants.

Enter scores 0 to 5 in blue cells													
Scorecard 2		**Who is impacted and how much:**											
Distribution system planning problems:		**City planners**	**Commercial real estate**	**Residential real estate**	**Industrials**	**Other utilities (gas, telecom, water)**	**Transportation and major infrastructure (e.g., ports, trains)**	**Critical infrastructure (e.g., hospitals, police, fire)**	**Average population**	**Low-income population**	**Median**	**Total**
1	Over-reliance on simple radial distribution											
2 . . . 31	. . .											
32	Problems with governance and management											
	Median											

KEY:
5 = Very high
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = None

4.2.4 Scorecard 3 – Corrective Measures for Distribution Planning Problems

At this point, we have ranked the 32 problems by their impacts on the power system and related planning as well as on city and urban planning – key elements to the focus areas of the research. The next step is to understand the difficulty of corrective measures to the 32 problems identified in **Section 4.1** (page 67), which is the purpose of Scorecard 3 (**Table 7**). The 32 problems are again shown vertically, while corrective measures (time, investment, and complexity) are shown horizontally. This scorecard helps to rank and provide some measure of importance to managing these problems.

Corrective measures were chosen on the basis of the textbook '*Understanding Electric Power Systems: An Overview of Technology, the Marketplace, and Government Regulation'* (Casazza and Delea, 2010) and the World Bank's guidelines *Practical Guidance for Designing a Smart Grid Modernisation Strategy'* (Madrigal and Uluski, 2015). The scorecard is populated with the scores for the cost of a solution to the problem, the time for the solution to be implemented, and the complexity of that solution. The cost of corrective measures takes into account capital costs such as hardware, software, engineering, and construction services needed to correct a problem or leverage an opportunity in the distribution system and the built environment. Time for the solution to be made and implemented refers to how much time a particular solution requires – this can be as simple as installing software in a substation or requires more time-consuming exercises that include hardware and software at multiple points throughout the system. The complexity of the solution refers to how difficult it is to create and implement the solution, which can be a result of dealing with the incumbent system, bottlenecks, or multiple contingencies required for the implementation of the solution. This scorecard provides a framework for understanding the cost, time, and complexity of corrective measures for the 32 problems.

Table 7. Scorecard 3 – correcting the 32 distribution problems.

enter scores 0 to 5 in blue cells						
Scorecard 3		**Corrective measures for distribution planning problems**				
Distribution system planning problems:		**Cost of a solution**	**Time for a solution to be made and implemented**	**Complexity of a solution**	**Median**	**Total**
1	Over-reliance on simple radial distribution					
2 . . . 31	. . .					
32	Problems with governance and management					
	Median					

KEY:
5 = Very high
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = None

4.2.5 Scorecard 4 – Inhibition of 'New Energy' Products and Services

In addition to some of the 32 problems needing corrective measures, many also inhibit new energy technologies that can benefit system functionality and system efficiency. The final, fourth scorecard (**Table 8**), ranks the 32 problems identified in **Section 4.1** (page 67) by their impacts to or interferences with incorporating new energy products and services into the power system. The 32 problems are shown vertically while the areas to new energy that are possibly impeded are shown horizontally. This scorecard helps us to understand how power system modernisation, and integration of smart technologies, are inhibited by the 32 problems.

The areas being impacted were selected based on the textbooks '*Smart Grid: Fundamentals of Design and Analysis'* (Momoh, 2012), '*Energy Systems and Sustainability: Power for a Sustainable Future*' (Everett et al., 2011), and '*Renewable Energy: Power for a Sustainable Future*' (Peake, 2017), and the World Bank's guidelines '*Practical Guidance for Designing a Smart Grid Modernization Strategy*' (Madrigal and Uluski, 2015). New energy technologies are those that are creating improvement in power system efficiency and more efficient use of electricity through storage, two-way power flow, microgrids, smart cities, and other emerging technologies. The 11 selected areas are featured in the texts mentioned above as the most impactful to the intersect of the distribution system and the built environment. They are critical enablers of renewable energy integration, system balancing, and more flexible, self-healing power systems, which interact with end-users. This scorecard provides a framework for ranking the 32 distribution problems relative to these technologies.

Table 8. Scorecard 4 – ranking technology and new energy products and services that are inhibited by the 32 distribution problems.

Enter scores 0 to 5 in blue cells														
Scorecard 4		**Which 'new energy' products and services are impacted and how much:**												
Distribution system planning problems:		**Data collection for smart grid**	**Advanced metering**	**Microgrid deployment**	**Voltage control and power quality**	**Bi-direction of power flow**	**Mid-scale distributed generation**	**Small-scale distributed generation**	**Deploying electric vehicles**	**Deploying storage**	**DSM/DR**	**Customer interface and new retail products**	**Median**	**Total**
1	Over-reliance on simple radial distribution													
2 . . . 31	. . .													
32	Problems with governance and management													
	Median													

KEY:
5 = Very high
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = None

The first two scorecards rank the 32 distribution problems by their impacts on the focus areas – power system planning and urban planning. These are followed by ranking them by the difficulty of corrective measures, and then by how they impede new, smart grid technologies. The four scorecards together produce a holistic ranking of the 32 problems.

With the 32 problems established and scorecards to measure these problems and their impacts in place, the next phase involved reaching out to seasoned industry professionals on their views. This was critical to confirming the 32 problems, applying the scorecards to the problems, analysing the problems, and creating a foundation for the development of solutions.

4.2.6 Summary of Scorecards

At this point, we are now equipped with:

1) A standard scorecard for the overall power system – understanding the broad characteristics of the area that is undergoing urbanisation.
2) Four scorecards that juxtapose the 32 distribution problems against:
    a) Critical components of the distribution system.
    b) Critical components of cities, and critical infrastructure.
    c) Cost of corrective measures.
    d) Impacts on the implementation of ‘new energy’ technologies.

These together paint a broad-area level, as well as an urban, distribution-system-specific view of critical problems. These are the building blocks of logically creating solutions to these problems and seizing available opportunities for efficiency.

5. RESULTS, Part 2: Example Application of the Assessment Framework

5.1 Endorsement of Methodology and Salient Points from the Expert Interviews

A key issue in addressing a research and knowledge gap was feedback on the overall research and its outputs. The gap, the comparative lack of data and statistics on developing countries versus developed countries, and the fact that power system planning is a complex, non-binary issue, brought the need for feedback and endorsement of the research and its outputs. The interviewees were a means to both obtain detailed, expert views on the research gap, and also to obtain feedback and suggestions on the research. As such, they provided some of the more detailed information on the research gap and a checkpoint in the overall research progress.

The interviewees endorsed the used methodology, including the breadth and depth of the 32 distribution problems, critical problems in urbanising developing countries, as well as the scorecards and overall research process. Below are key conclusions and notes on the endorsement of methodology from these interviews.

1) Interviewees confirmed that the list of critical distribution planning problems is comprehensive. They also confirmed that the research addresses a major deficit in power system planning both globally and within the three focus areas. All felt that problems occur and opportunities are missed due to an insufficient amount of focus in distribution planning versus generation. All three also mentioned observations from the literature review: in their experience, affordable generation was the key focus in power sector planning (Asif and Muneer, 2007; Severance, 2011; Milligan et al., 2015), and distribution planning was simply viewed as physical connectivity to end users with some amount of cost recovery (Hartvigsson et al., 2015).

2) Interviewees also confirmed that these problems lead to disorganised distribution systems, as urban centres often expand rapidly. They confirmed that this presents safety hazards and significant power losses. Their observations and comments matched closely to Kolokotsa (2016) in the efficiency losses and hazards that can occur if the distribution is poorly organised in rapidly growing cities and load centres.

3) Two of the three interviewees stated that microgrids were critical to supporting the growth of distribution systems. Their views were that selecting edges of the grid, critical loads, and sections of cities was an effective management tool for dividing the system into microgrids and later absorbing them into a larger grid. One interviewee stated that microgrids are not critical but helpful, and could be utilised after critical infrastructure was in place. Their views matched with the US DoE (2017) on digitisation and with Torpey (2011) on the use of microgrids.

4) All interviewees felt that DSM and DR were critical to load management, system efficiency, and managing growing cities. All interviewees, however, indicated that these efforts are not typically emphasised sufficiently and, while low-cost, represent a significant means to balance the system and prevent system stresses. Their statements advocated coordination with infrastructure and major loads, similarly to Volk (2013) on efficiency gains and use of DSM and DR for system balancing and efficiency. This is also well noted in Weston (2001), Schwartz (2010), and Schwartz and Sheaff er (2011).

5) Lack of SCADA systems on major loads, primarily industrial entities and factories, was stated as a critical problem by all interviewees. This pertains to automation and control of machinery, and the ease of developing regular reports on activities in major buildings or factories. Requiring or encouraging SCADA systems and communicating their data to utilities was viewed as a major opportunity to increase efficiency. They noted how this was critical to interacting with end users and shaping demand, as stated by Lundmark (2012), and critical to system modelling, as noted by Parshall et al. (2008). They also mentioned how this could be coordinated with asset management, capital efficiency, and efficiencies in system management, similarly to Yarka (2012).

6) All interviewees stated the need for at least minimal metering on any loads and advanced metering on larger loads. Lack of data and the inability to track activity and understand load patterns through effective metering was universally stated as a critical problem. Interviewees reflected Raposo et al. (2017) in the criticality of metering to the success of any smart grid or grid modernisation program.

7) Interviewees confirmed that the research had optimal timing in that many technologies such as metering, control systems, load study software, and equipment to enable distributed generation and load management are now much less expensive than in the past. Interviewees stated that such technologies were generally in the price range that utilities in developing countries would find affordable and should not impact the rate base. Their observations matched Collier (2015) in the importance of embracing now lower cost digital technologies, and The United Nations (Taipale and Fellini, 2012) in the importance of digital tools in coordinating distribution and load.

The interviews were successful in that they provided expert views on the research gap and guidance on the research process. At the conclusion of the interviews, the scorecards, and 32 distribution problems have been endorsed regarding depth and adequacy, and a ranking for the 32 distribution problems has been provided. This now sets the stage for leveraging an assessment of problems, into an analysis that can be used for creating solutions.

5.2 Interview with the Thai Power Company

The Thai power company was kind enough to have a senior executive review the overall process and the four solutions, in an interview on July 30, 2018, at Chit Lom, Bangkok. The senior interviewee mentioned that she and the company well understand the political complexities of decentralising and modernising power systems, and how this impacts the EEC development area. However, it was repeatedly emphasised that a scoring system, with a basis of documented cases studies showing upside and downside to components of solutions, would help award projects to energy companies. Further, the need for organised methods for creating, ranking, and selecting solutions was supported by the interviewee and mentioned multiple times during the interview.

5.2.1 Salient points from the interview

Below are the salient points from the interview. The interview transcript is available in **Appendix F**.

1) The first key point was that power sector transformation is challenging and involves coordination between both government and private sector entities. The interviewee reiterated the overemphasis on generation, and also shared views with Singh et al. (2015) and the IEA (2017) on the need to have coordinated planning throughout the sector, rather than handling just distribution or generation at one particular time.

2) Some of the strongest views were on coordinating with real estate and infrastructure entities. The view was that as urban centres expand, commercial and residential real estate entities often obtain permits, start operations, and later communicate plans to the electric utility. Views expressed were very similar to Chan et al. (2018) on how commercial, residential, and industrial real estate projects shape load in developing countries and are critical to cooperate with. Similar to Tice et al. (2012), it was also emphasised that coordinating with other utilities was a low-cost and easy-to-obtain form of efficiency and information sharing.

3) It was emphasised that energy companies need to engage people more directly and take an active rather than passive role in energy supply and use. Views expressed on the success of smart cities and grid modernisation projects matched Di Maddaloni et al. (2017) in seeing a direct relationship between community involvement and success. Communication with consumers was viewed as an underutilised and low-cost resource. Similar to Gissey et al. (2018), it was noted that interesting technologies like power storage could be considerably more successful if coupled with some ability to shape demand.

4) Microgrids were emphasised as the key enabler of grid modernisation and power system efficiency. Views expressed were that distributed systems are more responsive, efficient,

and resilient than centralised systems, and while these may appear threatening to incumbent players in the power system, they are a critical part of future power systems. Views expressed matched Torpey (2011) and Siemens (2014a) on areas like the EEC where the grid would be expanding, and handling this through a series of microgrids would be most efficient. Similar to Pass et al. (2018), it was noted that that bi-directional power movement needs to be planned for as a norm in future power systems. Comments on the solutions proposed were particularly supportive of a series of digitally connected microgrids to be installed as the EEC area that expand and synchronise as load grows.

5) The interviewee echoed Scott (2015) on the need to digitise the system and collect data before rapid urbanisation in the EEC area takes place, leaving the distribution authority behind in its knowledge of and ability to manage load. Views expressed were that digitisation could be undertaken in large scale and at a lower cost than re-fitting an existing system of substations and feeder lines, especially given the early phase of development in the local power sector. It was also discussed that attracting economic development would require that the grid is both modern and resilient. As one of the goals of the EEC is sustainable employment, the grid's support in providing infrastructure for value-added businesses was emphasised. These views are similar to Weichhart et al. (2016) and the US DoE (2017), who emphasise that digitisation can lead to greater security and resilience in power distribution.

6) The interviewee found the research to be an effective package for developing and ranking solutions for areas under development. The 32 problems, in conjunction with the scorecards and solution development system, was viewed as a comprehensive means to modernise the system with objective backing from case studies and the IEA Framework. It was also expressed that this could be digitised so that others could contribute to the case studies and utilise the scoring system for different ranking and solution development exercises. It was also discussed that such a framework could serve to help make contract awards more objective – having a system of scoring backed by historical data (the 32 problems) and a world-recognised framework (The IEA Framework) could help in complicated situations where several entities propose different solutions.

5.2.2 Scorecard Inputs from the Thai Power Company

Below are the scorecards populated with scores from the Thai Power company for the EEC area. **Table 9** is the overall system scorecard, where they ranked the general system, geography, and conditions of the region. Their scores under '*Renewable Energy Integration*' are fairly positive regarding resources and data, but note that their scores under '*Regulatory and Enablers of Smart Grid (SG) Technology*' imply that improvement is needed. **Tables 9−12** are the four system scorecards, populated with their views on the severity and impact of the 32 distribution problems. Note that problems that are scored above the median are consistently related to points of the distribution system closest to the end-user as well as those that relate to data availability in the planning process. **Table 14** is a simple list of the major infrastructure projects announced by the EEC Commission, which the Thai power company and I then populated with descriptions in terms of load characteristics, opportunities, and challenges in these projects. This provides an overview of the major end users of power and the major infrastructure projects in the region, and key problems to be accounted for in the planning process. Note characteristics of load here and what they mean for ramping the system up and down, and for distributed versus centralised systems. In **Table 15**, after scoring the overall system scorecard and the four individual system scorecards, the Thai power company then distributed the 32 problems into the four categories of the IEA Power System Transformation Framework. This sets scoring and priorities for developing solutions for the EEC area.

Table 9. The overall-system scorecard scored by the Thai power company.

Overall System Scorecard			**Enter Scores 0 to 5 in Blue Cells**	
Major Topic	**Subtopic**	**Description**	**Scoring Criteria**	**Score (0-5)**
Geography	Renewable energy resources penetration	The degree of participation from renewable energy in the power market, by installed capacity and by available resources.	Percentage of total, average, peak, and through capacity that is from RE. Curtailment of RE (if any) and amount of underutilised RE resources.	3
	Renewable energy resources data available relative to country boundaries	Extent and availability of data on RE resources.	The quantity of total land area that has had RE resources assessed, ease of accessing this data.	4
	Load location and density	How focused load is geographically, and distances between major load centres.	What percentage of the load is in the median load centre? How much load is in the top three, five, and ten load centres? What are the distances and approximate costs to connect these load centres? Is Pooling load centres possible or prohibitive?	5
	Transmission and distribution distances and costs	How much distances impact T&D costs and planning, and who can access T&D infrastructure.	Distance from mid- and large-scale generation centres, and major load centres. The extent to which T&D impacts the total cost of power to the ratepayer. The extent to which T&D infrastructure is available to third parties. How much do third parties pay to connect to infrastructure and how close is this to the actual cost to connect.	2

	Climate impacts to load	The extent to which temperature impacts load and power infrastructure.	Percentage of the total load that goes into heating and cooling. High and low temperatures, and the number of days per year that heating and air conditioning are in large-scale use. The extent to which weather impacts power sector performance (e.g., high levels of line resistance from high temperatures).	5
Demand Management & Customer Engagement	DM system participation	Level of participation in demand management and demand response systems	Percentage of customers participating in DM & DR systems. Amount of annual load that has been managed through DM & DR systems divided by the total annual load.	2
	Incentives for DM	Is there sufficient economic incentive in the full value chain to support successful DM & DR?	Are per unit, and full life-cycle costs of participating in DM & DR more attractive than simply selling power for generators, transmission and distribution companies, and retail companies?	1
	Increases to DM programs	Can the power system accommodate further DM programs?	Are there underutilised ramping capacity, storage, or distributed resources? How much load can be shed or curtailed? How responsive are customers to DM programs and how has this impacted the slope of the load curve?	3
Renewable Energy Integration	Levels of curtailment	How much RE generation is being rejected or curtailed due to system inefficiency?	Actual RE production (MWh) and estimates of RE potential from existing RE installations (MWh). Quantities of RE being rejected from the grid due to dispatch policy, insufficient T&D infrastructure, etc.	2
	FIT and incentives and supporting RE investment	Are feed-in tariffs (FIT) and other economic incentives sufficient to support RE?	What tariffs and incentives are available? Are they sufficient to cover project capex and any grid connection issues? What is the duration of these incentives?	3
	Efforts to match RE resource to load	Do FITs and incentives cater to load and RE location?	Are FITs and incentives constructed to encourage RE development nearby load centres or only where resources are high in availability? Do regulations and markets account for geographic gaps between load and RE resources?	3
	RE resource data availability	Transparency and availability of data	Is RE data available to all third parties wishing to participate in the power sector at a reasonable price? Was the data collected by an objective third party?	4

	T&D fees for RE producers	Ease of connecting RE resources to the grid	Who pays for RE resources to connect to T&D infrastructure? Has net metering been promulgated for small-scale and distributed generators? Is grid connection offered at actual cost or nearby-actual cost? Are grid connection costs transparent and are permitting processes transparent and reasonable?	5
	Methods to support dispatch and priority for RE producers	Ensuring RE producers realise sufficient grid penetration	Do policies clearly quantify the value of RE power relative to more CO_2-intensive generation? Is a clear system prioritising RE and managing congestion during peak RE periods in place?	4
Regulatory and Market Enablers of Smart Grid (SG) Technology	Incentive-based regulation	Do power sector regulations encourage renewable energy integration?	Are flexible generation and ramping associated with balancing load and integrating volatility from RE rewarded? Is the thermal fleet categorised and rewarded by those who can and cannot ramp up and down quickly? Are power companies only paid for power and availability, or are there incentives for balancing, ramping, and shifting or avoiding load? Is regulation performance based with appropriate rewards and penalties?	2
	Pricing	Does pricing encourage energy efficiency and support RE?	Does the system have block pricing, time of use pricing, and other mechanisms in place to manage load? Does pricing reward flexible generators? Does power pricing take into account CO_2 per unit of power and environmental costs of generation?	2
	Flexible contract structures	Do contract structures support DSM and RE?	Are power consumers encouraged through contracts to avoid or delay load? Do contracts provide incentives for flexible consumption, and scheduling load to coincide with RE availability?	3
	Access to infrastructure and participation in power services	Do regulations support new entrants into the power supply and power services?	Are regulations clear and permitting transparent for new entrants to participate in power services, and for existing entities to provide new services? How transparent are the processes for small-scale and distributed generators, storage providers, and auxiliary services? What is their cost of the grid or other	3

			infrastructure connection relative to the actual cost? Can end users generate their own power? Has net metering been promulgated and is it transparent?	
Physical Enablers of RE and SG	Storage	Is storage available or encouraged, in order to support RE and system balancing?	Are there billable services and a commercial market for storage and system balancing? Do existing hydropower resources have pumped storage? Does the regulator reward system balancing through storage? Are procedures for installing the distribution-, retail- and load-level storage transparent?	3
	Grid connection costs	Are grid connection costs appropriate and transparent?	How are entities which are not large scale IPPs and not utilities charged for grid connection? Are fees for connecting to the grid close to actual cost and reasonable?	4
	Advanced infrared metering	How granular is metering data and is the flow two way?	Is data collected on individual users such as consumption patterns and impacts on power quality? Is data collected on small-scale power producers? Can the system operator utilise metering infrastructure to locate specific needs such as power factor correction and balancing?	2
Local Load & Local Economy	Load curve	The slope of the load curve and what impacts it?	What key factors (e.g., weather, consumption habits, industry, seasonality) impact load and slope of the load curve? How well is this understood?	5
	Subsidies and tariff elasticity	How affordable is power to the population and industry?	Are large portions of the population or economy subsidised in power and energy? What are power costs as a percentage of mean and median income? Is there scope for raising rates to finance RE and system upgrades?	4
System Infrastructure & Efficiency	Substation IEDs	Installation at the substation level of intelligent electronic devices (IEDs), data communications network infrastructure, remote terminal unit	The degree to which there is protective relay reliability through self-diagnostics. How much information is available to the grid, including information around distance to faults and	2

		(RTU), or data concentrator infrastructure.	overall support of faster service restoration.	
	Equipment condition monitoring	Implementation of analytical software for equipment condition monitoring. Operation and maintenance procedures for condition-based maintenance.	The degree of reduction of routine inspections and maintenance costs. The degree or ability to detect incipient problems. The overall minimisation of repair costs (the ability to fix problems proactively while problems are still small).	2
	Dynamic equipment rating	Installation of new sensors (e.g. transformer winding temperature). Develop and implement application software for dynamic rating.	The degree to which the system can improve asset utilisation, defer capital expenditures for capacity additions, and reduce the need for load shedding and overall levels of reliability.	2
	Adaptive protection	Installation of protective relay IEDs, substation communication facilities, and software to support automatic setting changes.	The degree of reliability due to having relay setting that matches the operating conditions.	2
	Voltage reduction	Any equipment and decrease of labour involved in voltage regulation	The degree to which peak demand is lowered and overall efficiency is improved through voltage reduction.	3
	Distribution feeder sensors and communication facilities	Installation and operation of sensors on feeders, and two-way communication facilities. Overall maintenance costs of new distribution feeder sensors and communication equipment.	The extent of communication visibility and communication with feeders and feeder conditions.	2
	SCADA rule-based VVO	Install and maintain VVO rules processors, sensors for voltage feedback, two-way communications to all Volt-VAR control devices, VVO software.	The extent to which losses and peak demand are decreased by effective deployment of this equipment. The ability for early detection of capacitor bank and voltage regulator problems. The degree to which the system can eliminate routine inspections for capacity banks and voltage regulators.	3
	Fault location isolation and service restoration (FLISR)	Install and maintain FLISR processors, automated line switches, fault detectors, two-way communication equipment for FLISR,	The extent to which reliability is improved through rapid service restoration. The extent to which fault investigation times are reduced and made more precise and efficient.	3

		and software to manage FLISR systems.		
	As-operated model of the distribution system	Identify and quantify GIS data errors, build and maintain an as operated model.	The extent to which the changing distribution system is accounted for and supported.	1
	Optimal network reconfiguration (ONR)	Implement analytical ONR software and train operators and engineers on how to use it.	The extent to which voltage profile, reliability, and electrical losses are improved by load balancing.	1
	Model-driven VVO	Implement VVO analytical software, train operators and engineers on its operation.	The extent to which electrical losses are reduced, voltage profile is improved, peak shaving is supported, and overall efficiency is achieved from VVO. The extent to which the system can adapt to changing feeder conditions, and account for DERs in the VVO control strategy.	2
	Switching order management (SOM)	Purchase and implement SOM analytical software, and train operators and engineers how to use it.	The extent to which switching efforts are generated faster and more accurately during emergencies. The extent to which outage planning is improved.	2
	Enhanced fault location isolation and service restoration (FLISR)	Implement new FLISR software as needed, train staff on the operation.	The extent to which system restoration is improved by utilising available DERs. The extent to which the system adapts to changing feeder conditions.	4
	DER management and dynamic Volt-VAR control	Install equipment, software, communication facilities for monitoring and controlling DERs. Install energy storage, static VAR compensation, and associated controls.	The ability to mitigate adverse consequences of voltage and power swings caused by distributed generators with variable output. The ability for the utility to accommodate more distributed generators on existing feeders. The ability of the utility to deploy microgrids for portions of the grid that are weak or may require this arrangement.	1
	Demand response	Purchase and install automatic metering infrastructure (AMI), end-user level displays, end-user level automation networks, and DR hardware and software at critical locations.	The extent to which peak shaving is enabled during critical shortages. The extent to which new generation and transmission facilities can be reduced or delayed.	1
System Reliability	SAIDI	System average interruption duration index	Total minutes of sustained customer interruptions vs. total number of customers	1

	SAIFI	System average interruption frequency index	Total number of sustained customer interruptions vs. total number of customers	1
	CAIDI	Customer average interruption duration index	Total minutes of sustained customer interruptions vs. total number of interruptions	1
	MAIFI	Momentary average interruption frequency index	Total minutes of momentary customer interruptions per year vs. the total number of customers	1
	Standby power	Availability of standby power in the system, and the cost of providing this power.	MW of capacity capable of <15-minute ramping - standalone and relative to total capacity in the system and peak load.	1

KEY:
5 = Very High
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = Not Applicable

Table 10. Scorecard 1 scored by the Thai power company.

Enter scores 0 to 5 in blue cells																			
Scorecard 1		**Impacts:**																	
Distribution system planning problems:		**System stability issues**	**Over-build of capacity**	**Flexibility/ability to ramp**	**Ability to incorporate renewables**	**Ability to scale up**	**Ability to modernise the system**	**Impacts on potential DSM/DR projects**	**Redundant Generation capacity**	**Lost opportunities in managing demand**	**Lost opportunities in data collection**	**Lost opportunities in leveraging the built environment**	**Causes additional system upgrades**	**Pollution that could have been prevented**	**Safety problems or other hazards**	**System stress**	**Lost opportunity to tie in with other utilities and systems**	**Median**	**Total**
1	Over-reliance on simple radial distribution	5	3	5	5	4	5	4	2	4	5	4	5	3	2	5	5	**4.5**	**66**
2	Insufficient focus and investment on voltage regulation	5	3	3	5	4	5	4	3	5	1	2	5	1	3	5	4	**4**	**58**
3	Lack of development of a medium voltage distribution network	4	3	2	5	5	5	4	2	4	2	2	5	2	1	5	3	**3.5**	**54**
4	Absence of proper accounting and auditing, and lack of distribution level metering	3	2	1	3	3	4	4	3	4	5	4	5	2	0	3	4	**3**	**50**

5	Lack of planning for reactive power at load points	4	3	4	5	5	3	4	2	3	1	4	4	0	2	5	5	**4**	**54**
6	Poor billing practices leading to lack of re-investment in critical parts of the distribution network	4	3	4	5	4	4	5	2	5	5	4	4	1	1	4	5	**4**	**60**
7	Lack of investment in and attention to load flow studies at distribution and retail levels	4	3	3	4	5	5	5	4	5	5	4	5	4	2	4	4	**4**	**66**
8	One-off rather than iterative customer and load mapping in urbanising areas	3	4	3	4	5	5	5	3	5	5	4	5	3	3	4	5	**4**	**66**
9	Insufficient management of theft and disconnection	2	0	0	2	2	3	3	2	2	3	1	4	0	5	3	1	**2**	**33**
10	SCADA systems at the distribution level are typically underinvested, which leads to insufficient data for generating reports on system performance and problems	3	2	4	2	3	5	4	1	4	4	3	4	1	2	3	1	**3**	**46**

11	Insufficient interaction with stakeholders and customers on energy efficiency, pricing signals, and from this, an inability to shape demand	3	3	4	5	4	4	5	1	4	5	4	3	2	0	3	5	**4**	**55**
12	Cross subsidising within the power sector resulting in parts of the industry being left underfunded or insolvent	4	4	3	3	3	5	3	1	3	4	4	3	3	1	2	4	**3**	**50**
13	Knowledge transfer from installation company to operating company, and overall workforce inadequacy.	4	1	2	3	3	4	3	0	2	2	2	2	1	2	3	2	**2**	**36**
14	Insufficient renewable energy resource assessment	1	4	2	5	3	4	3	5	4	3	4	4	4	0	2	4	**4**	**52**
15	Generation, transmission and distribution planning need to be integrated	4	3	4	3	3	4	4	3	1	2	3	5	1	1	4	4	**3**	**49**

16	Poor system balancing due to lack of network area coordination	4	4	4	3	4	4	4	5	4	2	2	5	4	1	4	3	**4**	**57**
17	Bidirectional flow of power and data in distribution system needs to be planned for.	3	2	3	4	4	5	4	5	5	4	5	3	2	1	3	5	**4**	**58**
18	Clear and effective policies need to be enacted to produce, consume, store, delay or augment power at the distribution level	4	4	4	4	4	4	4	3	4	3	4	3	3	1	4	5	**4**	**58**
19	Coordinating with other utilities needs to occur, as this can unlock significant synergies and savings	2	3	3	3	4	4	4	3	5	4	4	3	3	1	4	5	**3.5**	**55**
20	Power sector planners should guide property developers on where urban centres should expand to, rather than attempt to follow and catch-up in network building	4	2	3	4	4	4	4	2	4	4	4	4	2	2	4	5	**4**	**56**

21	Power sector reform and liberalisation should occur at an equal pace from generation through transmission, distribution and retail	3	4	4	3	3	3	3	2	3	2	3	3	3	1	3	2	**3**	**45**
22	Asset management at the distribution level is underinvested and needs to be emphasised	3	4	3	4	2	4	4	2	3	3	3	3	2	5	2	1	**3**	**48**
23	Distribution planners need to work closely with infrastructure developers (e.g., ports, rail stations), and with property developers who will have large loads in their network (e.g., campuses, industrials, hotels, schools) to create energy efficiency, and DSM/DR capabilities in load centres.	4	4	4	3	4	5	5	2	4	4	5	2	2	1	3	5	**4**	**57**
24	Effectively managing rapid urbanisation and preventing cluttered and/ or hazardous network planning	5	4	4	3	4	5	3	2	4	5	3	3	2	4	5	4	**4**	**60**

25	Microgrids are underutilised as a tool in network planning in urbanising, developing countries	4	5	5	5	5	5	5	5	5	4	5	4	2	0	4	5	**5**	**68**
26	As the network is expanding, planners must continually identify medium and large demand response (DR) targets	4	3	4	4	3	4	5	3	5	5	5	4	1	0	5	5	**4**	**60**
27	Lack of target-setting and on-going improvement standards in network operation needs to be addressed	2	2	2	1	3	3	3	1	3	3	3	3	1	3	4	3	**3**	**40**
28	Lack of streamlining, and matching network design standards with demand to develop efficient distribution systems in a timely fashion	5	2	3	3	4	3	3	0	2	2	2	3	0	2	3	2	**2.5**	**39**
29	Non-standardisation of both home and industrial electrical equipment and resistance to	3	0	0	1	2	3	2	0	2	2	3	1	0	5	1	0	**1.5**	**25**

	internationally agreed standards																		
30	Planners do not sufficiently include resiliency and secure infrastructure in grid planning	5	4	4	4	5	5	3	4	4	3	3	3	1	0	4	4	**4**	**56**
31	In order to stay competitive, distribution utilities must transform themselves into more digital enterprises	2	2	5	5	3	5	5	2	5	5	5	2	2	0	4	5	**4.5**	**57**
32	Problems with governance and management	1	2	1	2	2	4	2	1	1	1	3	4	3	4	2	3	**2**	**36**
	Median																		**55**

KEY:
5 = Very high
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = None

Table 11. Scorecard 2 scored by the Thai power company.

Enter scores 0 to 5 in blue cells													
Scorecard 2		**Who impacted and how much:**											
Distribution system planning problems:		**City planners**	**Commercial real estate**	**Residential real estate**	**Industrials**	**Other utilities (gas, telecom, water)**	**Transportation and major infrastructure (e.g. ports and trains)**	**Critical infrastructure, e.g. hospitals, police, fire**	**Average population**	**Low-income population**	**Median**	**Total**
1	Over-reliance on simple radial distribution	5	3	2	4	4	3	5	2	1	**3**	**52**
2	Insufficient focus and investment on voltage regulation	4	4	1	5	5	4	5	1	1	**4**	**53**
3	Lack of development of a medium voltage distribution network	4	4	1	5	3	4	4	1	1	**4**	**48**
4	Absence of proper accounting and auditing, and lack of distribution level metering	5	4	1	5	5	4	2	3	2	**4**	**55**
5	Lack of planning for reactive power at load points	3	4	2	5	4	5	4	1	1	**4**	**52**
6	Poor billing practices leading to lack of re-investment in critical parts of the distribution network	4	2	1	3	3	3	3	2	3	**3**	**43**
7	Lack of investment in and attention to load flow studies at distribution and retail levels	4	3	2	3	4	2	1	2	1	**2**	**39**
8	One-off rather than iterative customer and load mapping in urbanising areas	5	3	2	4	4	4	3	3	3	**3**	**55**

9	Insufficient management of theft and disconnection	3	0	3	1	2	0	0	1	3	**1**	**23**
10	SCADA systems at the distribution level are typically underinvested, which leads to insufficient data for generating reports on system performance and problems	3	2	0	5	3	3	2	0	0	**2**	**32**
11	Insufficient interaction with stakeholders and customers on energy efficiency, pricing signals, and from this, an inability to shape demand	4	2	3	4	4	1	0	2	2	**2**	**39**
12	Cross subsidising within the power sector resulting in parts of the industry being left underfunded or insolvent	4	1	3	3	3	3	2	2	2	**3**	**41**
13	Knowledge transfer from installation company to operating company, and overall workforce inadequacy.	3	1	1	3	2	3	3	1	1	**2**	**32**
14	Insufficient renewable energy resource assessment	5	2	3	3	2	1	0	2	1	**2**	**34**
15	Generation, transmission and distribution planning need to be integrated	4	2	1	4	5	3	2	2	1	**2**	**43**
16	Poor system balancing due to lack of network area coordination	4	2	2	4	3	3	4	2	1	**3**	**44**
17	Bidirectional flow of power and data in distribution system needs to be planned for.	5	2	3	4	3	2	1	2	0	**2**	**39**
18	Clear and effective policies need to be enacted to produce, consume, store, delay or augment power at the distribution level	5	4	5	4	4	4	1	4	3	**4**	**60**
19	Coordinating with other utilities needs to occur, as this can unlock significant synergies and savings	5	4	4	4	5	4	2	3	2	**4**	**59**

20	Power sector planners should guide property developers on where urban centres should expand to, rather than attempt to follow and catch-up in network building	4	4	4	2	4	3	1	2	2	**3**	**46**
21	Power sector reform and liberalisation should occur at an equal pace from generation through transmission, distribution and retail	3	1	1	3	3	1	0	1	1	**1**	**25**
22	Asset management at the distribution level is underinvested and needs to be emphasised	4	3	3	3	3	3	5	1	0	**3**	**44**
23	Distribution planners need to work closely with infrastructure developers (e.g., ports, rail stations), and with property developers who will have large loads in their network (e.g., campuses, industrials, hotels, schools) to create energy efficiency, and DSM/DR capabilities in load centres.	5	5	4	4	4	4	2	3	0	**4**	**55**
24	Effectively managing rapid urbanisation and preventing cluttered and/or hazardous network planning	5	3	4	1	4	3	0	2	2	**3**	**43**
25	Microgrids are underutilised as a tool in network planning in urbanising, developing countries	4	5	3	5	5	5	5	1	1	**5**	**60**
26	As the network is expanding, planners must continually identify medium and large demand response (DR) targets	4	4	3	5	5	3	3	1	1	**3**	**52**
27	Lack of target-setting and on-going improvement standards in network operation needs to be addressed	3	0	0	2	2	2	2	1	1	**2**	**23**
28	Lack of streamlining, and matching network design standards with the demand to develop efficient distribution systems in a timely fashion	3	2	2	3	3	3	3	1	1	**3**	**37**
29	Non-standardisation of both home and industrial electrical equipment and resistance to internationally agreed standards	3	2	2	2	1	1	2	1	1	**2**	**27**

30	Planners do not sufficiently include resiliency and secure infrastructure in grid planning	4	2	2	3	4	3	4	1	1	**3**	**43**
31	In order to stay competitive, distribution utilities must transform themselves into more digital enterprises	4	4	4	5	5	5	2	3	2	**4**	**60**
32	Problems with governance and management	3	1	1	1	3	3	2	1	1	**1**	**28**
	Median											**43**

KEY:
5 = Very high
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = None

Table 12. Scorecard 3 scored by the Thai power company.

Enter scores 0 to 5 in blue cells						
Scorecard 3		**Corrective measures for distribution planning problems:**				
Distribution system planning problems:		**Cost of a solution**	**Time for a solution to be made and implemented**	**Complexity of a solution**	**Median**	**Total**
1	Over-reliance on simple radial distribution	4	4	3	**4**	**59**
2	Insufficient focus and investment on voltage regulation	5	3	4	**4**	**64**
3	Lack of development of a medium voltage distribution network	4	4	3	**4**	**59**
4	Absence of proper accounting and auditing, and lack of distribution level metering	2	2	2	**2**	**32**
5	Lack of planning for reactive power at load points	4	3	3	**3**	**53**
6	Poor billing practices leading to lack of re-investment in critical parts of the distribution network	2	2	2	**2**	**32**
7	Lack of investment in and attention to load flow studies at distribution and retail levels	1	1	1	**1**	**16**
8	One-off rather than iterative customer and load mapping in urbanising areas	1	1	1	**1**	**16**
9	Insufficient management of theft and disconnection	1	1	0	**1**	**11**
10	SCADA systems at the distribution level are typically underinvested, which leads to insufficient data for generating reports on system performance and problems	2	3	2	**2**	**37**
11	Insufficient interaction with stakeholders and customers on energy efficiency, pricing signals, and from this, an inability to shape demand	2	4	3	**3**	**48**
12	Cross subsidising within the power sector resulting in parts of the industry being left underfunded or insolvent	1	3	3	**3**	**37**
13	Knowledge transfer from installation company to operating company, and overall workforce inadequacy.	1	3	2	**2**	**32**

14	Insufficient renewable energy resource assessment	1	3	1	**1**	**27**
15	Generation, transmission and distribution planning need to be integrated	1	2	4	**2**	**37**
16	Poor system balancing due to lack of network area coordination	5	3	4	**4**	**64**
17	Bidirectional flow of power and data in the distribution system needs to be planned for.	3	3	5	**3**	**59**
18	Clear and effective policies need to be enacted to produce, consume, store, delay or augment power at the distribution level	1	3	4	**3**	**43**
19	Coordinating with other utilities needs to occur, as this can unlock significant synergies and savings	1	2	4	**2**	**37**
20	Power sector planners should guide property developers on where urban centres should expand to, rather than attempt to follow and catch-up in network building	1	3	3	**3**	**37**
21	Power sector reform and liberalisation should occur at an equal pace from generation through transmission, distribution and retail	0	3	3	**3**	**32**
22	Asset management at the distribution level is underinvested and needs to be emphasised	2	3	3	**3**	**43**
23	Distribution planners need to work closely with infrastructure developers (e.g., ports, rail stations), and with property developers who will have large loads in their network (e.g., campuses, industrials, hotels, schools) to create energy efficiency, and DSM/DR capabilities in load centres.	3	3	5	**3**	**59**
24	Effectively managing rapid urbanisation and preventing cluttered and/or hazardous network planning	2	1	1	**1**	**21**
25	Microgrids are underutilised as a tool in network planning in urbanising, developing countries	3	3	3	**3**	**48**

26	As the network is expanding, planners must continually identify medium and large demand response (DR) targets	2	2	4	**2**	**43**
27	Lack of target-setting and on-going improvement standards in network operation needs to be addressed	0	1	0	**0**	**5**
28	Lack of streamlining, and matching network design standards with the demand to develop efficient distribution systems in a timely fashion	1	1	1	**1**	**16**
29	Non-standardisation of both home and industrial electrical equipment and resistance to internationally agreed standards	0	1	0	**0**	**5**
30	Planners do not sufficiently include resiliency and secure infrastructure in grid planning	4	3	4	**4**	**59**
31	In order to stay competitive, distribution utilities must transform themselves into more digital enterprises	3	3	5	**3**	**59**
32	Problems with governance and management	0	1	1	**1**	**11**
	Median					**37**

KEY:
5 = Very high
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = None

Table 13. Scorecard 4 scored by the Thai power company.

Enter scores 0 to 5 in blue cells														
Scorecard 4		**Which 'new energy' products and services are impacted and how much:**												
Distribution system planning problems:		**Data collection for smart grid**	**Advanced metering**	**Microgrid deployment**	**Voltage control and power quality**	**Bi-direction of power flow**	**Mid-scale distributed generation**	**Small-scale distributed generation**	**Deploying electric vehicles**	**Deploying storage**	**DSM/DR**	**Customer interface and new retail products**	**Median**	**Total**
1	Over-reliance on simple radial distribution	4	5	5	4	4	4	4	3	4	4	4	**4**	**65**
2	Insufficient focus and investment on voltage regulation	3	3	4	5	5	4	5	2	3	3	2	**3**	**57**
3	Lack of development of a medium voltage distribution network	3	2	1	2	3	3	1	1	3	1	1	**2**	**31**
4	Absence of proper accounting and auditing, and lack of distribution level metering	4	4	2	1	2	1	3	3	2	3	4	**3**	**42**
5	Lack of planning for reactive power at load points	3	2	1	4	3	3	3	1	1	1	2	**2**	**35**
6	Poor billing practices leading to lack of re-investment in critical parts of the distribution network	4	4	1	2	1	2	3	1	2	3	2	**2**	**36**
7	Lack of investment in and attention to load flow studies at distribution and retail levels	5	4	3	3	4	4	5	4	5	4	4	**4**	**65**
8	One-off rather than iterative customer and load mapping in urbanising areas	5	4	3	3	3	4	5	5	5	5	5	**5**	**68**

9	Insufficient management of theft and disconnection	3	3	1	2	1	0	1	0	1	2	1	**1**	**22**
10	SCADA systems at the distribution level are typically underinvested, which leads to insufficient data for generating reports on system performance and problems	5	5	3	2	2	3	2	1	2	4	3	**3**	**47**
11	Insufficient interaction with stakeholders and customers on energy efficiency, pricing signals, and from this, an inability to shape demand	5	5	4	1	1	1	4	2	4	5	5	**4**	**54**
12	Cross-subsidising within the power sector resulting in parts of the industry being left underfunded or insolvent	4	4	2	3	3	3	3	3	3	3	3	**3**	**49**
13	Knowledge transfer from installation company to operating company, and overall workforce inadequacy.	3	2	2	3	2	0	3	1	3	2	2	**2**	**33**
14	Insufficient renewable energy resource assessment	5	3	3	1	2	5	5	0	4	1	2	**3**	**45**
15	Generation, transmission and distribution planning need to be integrated	4	3	1	1	1	4	4	3	3	3	3	**3**	**44**
16	Poor system balancing due to lack of network area coordination	5	3	3	3	2	4	3	1	5	5	2	**3**	**52**
17	Bidirectional flow of power and data in distribution system needs to be planned for.	5	5	5	3	5	2	4	4	4	3	2	**4**	**61**
18	Clear and effective policies need to be enacted to produce, consume, store, delay or augment power at the distribution level	5	5	3	2	3	3	5	3	5	5	4	**4**	**63**
19	Coordinating with other utilities needs to occur, as this can unlock significant synergies and savings	5	5	4	1	2	2	1	0	3	3	1	**2**	**39**

20	Power sector planners should guide property developers on where urban centres should expand to, rather than attempt to follow and catch-up in network building	5	5	5	3	4	4	4	3	4	5	2	**4**	**64**
21	Power sector reform and liberalisation should occur at an equal pace from generation through transmission, distribution and retail	3	3	2	1	1	1	3	2	3	2	2	**2**	**33**
22	Asset management at the distribution level is underinvested and needs to be emphasised	5	5	2	2	3	2	3	3	2	2	1	**2**	**44**
23	Distribution planners need to work closely with infrastructure developers (e.g., ports, rail stations), and with property developers who will have large loads in their network (e.g., campuses, industrials, hotels, schools) to create energy efficiency, and DSM/DR capabilities in load centres.	5	5	5	3	3	3	3	3	4	5	4	**4**	**63**
24	Effectively managing rapid urbanisation and preventing cluttered and/or hazardous network planning	3	3	2	2	2	1	3	2	2	2	2	**2**	**35**
25	Microgrids are underutilised as a tool in network planning in urbanising, developing countries	5	5	5	3	4	4	5	3	4	4	3	**4**	**65**
26	As the network is expanding, planners must continually identify medium and large demand response (DR) targets	5	5	5	4	3	3	3	2	4	5	3	**4**	**61**
27	Lack of target-setting and on-going improvement standards in network operation needs to be addressed	4	3	1	1	1	2	2	1	1	3	2	**2**	**31**

28	Lack of streamlining, and matching network design standards with demand to develop efficient distribution systems in a timely fashion	3	3	2	2	1	1	3	3	2	1	1	**2**	**32**
29	Non-standardisation of both home and industrial electrical equipment and resistance to internationally agreed standards	3	3	0	2	0	0	1	2	0	1	2	**1**	**20**
30	Planners do not sufficiently include resiliency and secure infrastructure in grid planning	4	2	3	2	2	3	3	0	4	2	0	**2**	**36**
31	In order to stay competitive, distribution utilities must transform themselves into more digital enterprises	5	5	5	5	5	3	4	5	5	5	5	**5**	**76**
32	Problems with governance and management	2	2	0	1	0	0	1	0	1	1	1	**1**	**13**
	Median													**44**

KEY:
5 = Very high
4 = High
3 = Neutral
2 = Medium
1 = Low
0 = None

Table 14. The location characteristics table filled-in by the Thai power company.

EEC Infrastructure to be Built	Load Characteristics	Opportunities	Challenges
Airports, Hospitals and Critical Loads	Need high-quality power and highly resilient systems with redundancy. The load is confined to finite areas with consistent demand patterns. Large users of water, gas, heat, and steam.	Highly resilient microgrids. On-site renewables. Large-scale battery storage to back up the critical load and provide grid support services. May need on-site CHP for steam (hospitals). May have dedicated substation which can then also create a medium-voltage network for nearby communities. Could have to share infrastructure with water, gas, and power utilities. Will need on-site chillers, which can also provide cooling for adjacent communities.	On-site renewables and any battery will require permitting and communication equipment for data sharing with the surrounding grid. Currently, no laws in place for a battery to provide support to the grid that would help economically justify the battery storage. A medium-voltage mesh network would be helpful for nearby communities (versus linear network) to reduce outages and maintenance but requires planning. Need to coordinate with other utilities (e.g., gas, water). The chiller can also provide for local communities, but this needs to be coordinated in planning.
Commercial Real Estate	A series of clusters of load in commercial buildings, such as shopping malls. Seasonal and having ramping and reactive power from air conditioning, elevators, and other machinery. Large cooling requirements. Non-critical loads with some seasonality and more daytime load than evening load.	On-site (rooftop photovoltaics and small wind) generation. Battery storage for easing ramping-up of loads and providing Volt/VAR, and frequency regulation. Opportunity for centralised chillers. Opportunity for CHP for hot water needs. Stability can be achieved through an extensive medium-voltage mesh network. Commercial real estate represents large-scale DSM opportunities and customer engagement.	Need to work with the distribution company on the distribution network. Specifically, any DG (distributed generation) or storage will require two-way inverters and data sharing to coordinate with grid and eliminate stability issues. SCADA and advanced metering will be needed for large loads (e.g., hotels, shopping malls) and should be required by law. District cooling and coordination with other utilities need to be coordinated. Increased air conditioning use and seasonality will challenge the system's ability to ramp and to manage reactive power. Electric vehicle charging stations for buses or car fleets require coordination with the distribution company. DSM and customer engagement needs to be coordinated.

Residential Real Estate	Spread-out housing developments with low initial low, but which is likely to increase with time and increased penetration of appliances and air conditioning. Demand seasonal due to air conditioning. Evening load and daytime load somewhat balanced. Small and mid-sized clusters of cooling requirements.	On-site (rooftop photovoltaics and small wind) generation. Opportunity for CHP for hot water needs. Stability can be achieved through an extensive medium-voltage mesh network. Residential real estate represents large-scale DSM opportunities and customer engagement.	Need to work with the distribution company on the distribution network. Specifically, any DG and electric vehicles will require two-way inverters and data sharing to coordinate with the grid and eliminate stability issues. Building a medium- and low-voltage network in a mesh fashion will help manage stability and event ride-through. DSM and customer engagement needs to be coordinated.
Light industry industrial parks	Low seasonality to demand, looking for low-cost power and renewables where possible. Power quality is required, but redundancy requirements are not major. Some cooling and heat or steam needs.	On-site DG - small wind, rooftop solar, CHP. Microgrids and battery storage can help provide redundancy but can easily have the capacity to support the grid. May need on-site chillers that can support nearby housing. Opportunity to coordinate with other utilities, e.g., gas, telecom, water. Possible charging of electric vehicle trucks bringing goods in and out of facilities. Likely to need dedicated substation that can support a medium-voltage mesh network for nearby commercial, industrial and residential entities. SCADA, data and communications with the grid can greatly enhance system stability and balancing. These can be major assets in DSM and system balancing efforts.	Need to coordinate with other utilities and with the distribution company on substations. No rules in place for supporting the industrial park to sell power or power services to the grid – this needs to be addressed. Need to coordinate how to make DSM into a product for industrial entities. SCADA and advanced metering need to be in place to manage the system relative to their load. Their storage or microgrid is potentially a major asset for supporting the grid, but there will need to be communication and coordination for sizing it and making sense of economics. Electrical vehicle fleets will require coordination as well.

Chemicals industry and high tech industrial parks	Need high-quality power and resilient systems with redundancy. The load is confined to finite areas with consistent demand patterns. Need heat, steam, cooling, power quality, and energy management services	On-site DG – small wind, rooftop solar, CHP. Microgrids and battery storage can help provide redundancy but will need much of their capacity dedicated to redundancy for the industrial park. Will need on-site heat and steam, which can be coordinated with local industries that are nearby. Opportunity to coordinate with other utilities, e.g., gas, telecom, water. Possible to charge electrical vehicle trucks bringing goods in and out of facilities. Will need a dedicated substation. SCADA, data and communications with the grid can greatly enhance system stability and balancing. These can be major assets in DSM and system balancing efforts.	Need to coordinate with other utilities, and with distribution company on substations. No rules in place for supporting the industrial park to sell power or power services to the grid – this needs to be addressed. Need to coordinate how to make DSM into a product for industrial entities. SCADA and advanced metering need to be in place to manage the system relative to their load. Their storage or microgrid is potentially a major asset for supporting the grid, but there will need to be communication and coordination for sizing it and making sense of economics. Electrical vehicle fleets will require coordination as well.
Data Centres	24/7 need for high-quality power with significant redundancy. Large-scale cooling needs. Likely to occur in a few small clusters on confined properties. May have adjacent IT parks with a daytime load which is somewhat flexible.	On-site (rooftop photovoltaics and small wind) generation. Battery storage will be mid- to large-scale but dedicated to the site with little capability. Large-scale air conditioning will be needed, as will water access. Can serve an adjacent IT park with these facilities. Can possibly use a large battery for black-starts or emergencies. Large water needs present an opportunity to coordinate with the water utility.	These are large loads that are very demanding for stability, so the distribution company will need to coordinate closely. Water for cooling will be a major need, so coordinating with the water utility will be critical. Gas reciprocating engines are a likely backup power source, so how this is coordinated is critical. Telecom fibre needs to be laid, so working together on this will be important. These can potentially black-start the grid but need contracts and incentives for this.

High-speed rail, bus stations, taxi fleets, and other transportation	Fleets (trains, buses, taxis) that will require fuelling at one point and will travel short to medium distances (between Bangkok and Trat). Most will take place during day hours, with some in the early evening (not a 24/7 load). Some seasonality. Must of the logistics infrastructure will follow a predominantly north-south line, following commercial and residential real estate. Loads are potentially high for high bus fleets and train stations, and scattered and small-sized for taxi fleets.	The electric train line will create a significant path of right-of-way, which can be shared with power, telecom and other lines. Train stations have large, yet very predictable loads. Train stations can serve to charge batteries on trains, and the medium voltage electric line servicing the main high-speed train line can complement nearby loads. Significant infrastructure can be shared. There is a large opportunity for storage alongside train stations or the lines powering the train. Bus fleets can be electrified with charging stations having a shared substation with the distribution system, and to provide power storage to absorb evening RE loads, and discharge when not in use. Taxi fleets can be electrified and can feed into low-voltage charging stations around commercial real estate such as shopping malls. These have a high potential for communicating with customers on other energy products as they involve masses of people who work or live in that area.	Coordination needs to begin early to plan for the placement of lines and substations. There is a large potential for power storage, but this will require sizing of storage and matching this to load and location. Right-of-way and any tunnelling or cabling that takes place should be utilised for other utilities. Data collection needs to be installed and coordinated inside these transportation systems for power system efficiency to materialise.
Other Utilities (water, gas telecom)	Water utilities will have large loads at water processing plants, and medium loads at pumping stations to move water through infrastructure and real estate. This will be a critical, 24/7 load. Gas and telecom will not be large loads but can share infrastructure.	Can share right-of-way with gas, water, and telecom infrastructure. Water processing plants can utilise sludge for producing power and steam, and provide a means of disposal. Water processing plants and pumping stations will have medium sized loads and can have power storage intertwined in their assets. Right-of-way can be shared with gas pipes and telecom infrastructure as well. Gas can be utilised in small reciprocating engines for backup power. Telecom infrastructure can be used for data support. Water can be a utility to join with communicating DSM opportunities.	Some water loads are critical (fire stations, hospitals), some are less critical (homes can be asked to reduce use at some times), but the network is shared in many places. Seasonality of rainfall impacts water inputs into the system. Pumping systems represent infrastructure that is embedded in load centres and can be utilised for other things, but the water and power utility needs to be aligned for this. Most locations do not have incentives in place for cooperation across utilities.

Table 15. Solutions-developing input sheet filled-in by the Thai power company.

Enter problems 1 to 32 in blue cells																
Step 1: Use the IEA Framework for grouping problems and opportunities		List of problems distributed here: Cluster list of 32 problems into these four groups by the IEA Framework														
Aspect	**Description and Relevance**															
1. Markets and Operations	The structure of electricity markets and how they are operated, both at the wholesale and retail levels, is a key driver of power system transformation. Emerging market frameworks and improved system operations can help cost-effectively manage electricity delivery infrastructure with greater shares of VRE resources; changes to retail rate structures and regulatory paradigms can help to activate and engage demand-side resources to contribute to the system.	4	6	7	8	9	10	11	12	16	17	18	19	20	23	26
2. Planning and Infrastructure	Power system planning determines the future architecture of the power generation, transmission and distribution systems. Emerging, integrated approaches to power system planning and grid expansion can facilitate an efficient transformation of the power system, while maintaining affordability and reliability; it can also prepare electricity grids for the effective integration of greater technological innovation.	1	2	3	7	13	14	16	17	18	19	20	21	22	23	26
3. Uptake of Innovative Technology	An array of emerging innovative technologies, including smart technologies, flexible resources, and system-friendly VRE, can enable a more flexible, reliable and affordable power system.	1	2	5	8	10	14	16	17	18	19	23	24	25	26	31
4. Efficiency and Sector Coupling	Greater energy efficiency in the power sector can help reduce costs both at the system and customer level. Electrification across the transport, and heating and cooling sectors, in combination with the broader trend of cross-sector integration of the demand-side into electricity markets, can compound the benefits of clean energy deployment and hasten the transition to a low-carbon power system.	2	8	11	16	17	18	19	21	23	25	26	30	31	24	20

5.3 Solutions Framework for Distribution System Problems

In cooperation with the Thai power company, the scorecards were leveraged to develop solutions specific to the EEC area. The overall system scorecard outlined macro-level constraints and enablers of the system, the four system scorecards prioritised issues within the IEA framework, and the EEC infrastructure to be built (Table 14) provided local context for these two. The below four solutions are outputs from the research methodology and tools, specific to the EEC area.

5.3.1 IEA Category 1: Markets and Operations

The inputs from the Thai power company on the problems of the EEC area falling in this category are shown in **Figure 22** and the solution summary in **Figure 23**.

Aspect 1: Markets and Operations								
System Impact Scorecard					Corrective Measure Costs			
Low scores	04	10	09		09	07	08	***Low scores***
12	23	16	20		12	19	20	04
11	17	26	06		11	17	18	06
19	18	07	08		16	23	26	10
High Scores								
12	04	19	18		08	07	18	12
17	26	23	08		23	20	26	10
11	20	16	06		16	11	17	04
Low scores	07	10	09		09	06	19	***Low scores***
Other Industries Impacted					Impacts to New Energy			

Figure 22. The distribution of scores in IEA Category 1: Markets and Operations.

Research on the 32 problems and the scorecard together have pointed the user toward what to emphasise in developing a solution. From this framework, we can see that decentralising assets and opening market structures are critical to solutions in the *Markets and Operations* category. The engineer now uses his or her expert knowledge, along with guidance from the research and framework, to develop specific solutions. With the high priority given to problems 8, 17, 18, 23 and others in **Figures 22** and **23**, a solution was built emphasising the opening up of demand-side measures features and distributed assets.

Aspect	Solution Description
1	A reduction in dependance on centralized generation, and opening of the market to small-scale and distributed generation in addition to storage. The core solution involves a distributed energy resource system spread throughout the EEC area and enables a rapid build-up of renewable energy and localized generation. The storage complements this and provides stability and redundancy for the system. The two together also provide a platform for greater end-user participation. This core solution is optimized via data analysis on renewable energy resources and customer mapping, simple network upgrades, and expanding energy market products and services to include DSM, storage, and FiTs for local generation.

	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii	xiii	xiv	xv		Total	Multiplier	Total Score	Solution Score
1. Markets and Operations	14	11	18	23	26	8	17										117	1	117	121
2. Planning and Infrastructure	3																3	1.25	4	
3. Uptake of innovative technology																	-	1.25	0	
4. Efficiency and sector coupling																	-	1.25	0	

Figure 23. The solution and the score summary for IEA Category 1: Markets and Operations.

As demonstrated by **Figure 23**, the solution includes the following problems from the list of the 32 problems:

- 3 – *Lack of development of a medium-voltage distribution network*;
- 8 – *One-off rather than iterative customer and load mapping in urbanising areas*;
- 11 – *Insufficient interaction with stakeholders and customers on energy efficiency, pricing signals, and from this, an inability to shape demand*;
- 14 – *Insufficient renewable energy resource assessment*;
- 17 – *Bidirectional flow of power and data in the distribution system needs to be planned for*;
- 18 – *Clear and effective policies need to be enacted to produce, consume, store, delay, or augment power at the distribution level*;
- 23 – *Distribution planners need to work closely with infrastructure developers (e.g., ports, rail stations), and with property developers who will have large loads in their network (e.g., campuses, industrials, hotels, schools) to create energy efficiency, and DSM/DR capabilities in load centres*;
- and 26 – *As the network is expanding, planners must continually identify medium and large demand response (DR) targets*.

5.3.1.1 Solution Overview

Thailand's energy markets structure is highly centralised, with EGAT as the core buyer (**Figure 17**) purchasing power from centralised, large-scale, largely thermal generators. This IEA category refers to power system transformation through wholesale and retail market development, which supports greater shares of VRE and demand-side management. In Thailand's centralised model, two key structural problems need to be supported to change this:

1) Distributed energy resources (DER) – Small-scale, decentralised production of renewable energy at the home or building level. This provides power to the system distributed throughout the network, which can aid the management of volatility of renewable energy and can serve as a platform for the inhabitants or owners of the DER system to participate more actively in energy markets.
2) Energy storage systems (ESS) – These would focus on distribution- and retail-level storage to increase the share of VRE in power markets, provide system balancing for the system operator, and support DSM-related energy products.

The core solution for IEA Category 1 involves DER and ESS being incorporated into the system throughout the EEC area. The core solution is supported and optimised by sufficient data collection and analysis to plan and optimise the DER and ESS systems, network upgrades to ensure these systems function optimally, and market mechanisms to support customer involvement and the economic viability of the DER and ESS systems.

5.3.1.2 Core Solution: Distributed Energy Resources (DER)

Distributed energy resources are power generation resources sited at the point of use. They present an alternative approach to improving the efficiency of traditional energy generation. The following lists technologies commonly found in the current DER systems:

- Combined heat and power (CHP) [cogeneration],
- Combined cooling, heat, and power (CCHP) [tri-generation],
- Fuel cells,
- Microturbines,
- Photovoltaic solar cells,
- Wind turbines,
- Reciprocating engines,
- Battery energy storage,
- Thermal storage tanks.

By incorporating multiple DER technologies (technological hybridisation) in a gridded area to produce and supply energy within each suburb of an urbanising or growing area, energy system efficiency is improved, and the loss due to long-distance energy transmission and distribution is mitigated. This is the start of a microgrid, and, depending on its level of integration with information technology, a smart city.

Distributed energy resources in a grid for each suburb within a new city are proposed to integrate CCHP technologies, photovoltaic (PV) solar cells, and battery energy storage systems. This will enable multiple participants in power production and trading, and reduce technical losses from centralised generators and extensive transmission and distribution systems.

5.3.1.3 Core Solution: Energy Storage Systems (ESS)

Distributed energy resources will promote a significant amount of localised, renewable energy production, which is clean but volatile. Creating a market for energy storage services, and installing energy storage systems at various points in the distribution system is critical to smoothening volatile renewable energy (VRE), balancing the system, and reducing curtailment (in cases such as evening or off-peak wind power generation). Energy storage systems are a key balancer of DER. Opening energy markets and physically installing these systems in parallel to one another is critical. Energy storage systems plus DER together are essentially a cornerstone of a microgrid or a smart city.

Energy storage systems consist of batteries, inverters, and control systems that enable energy generated from renewable energy systems to be stored and delivered at other times. Application of this technology can improve the power generation and distribution efficiency. Such systems also support discontinuities in renewable energy generation, as renewable energy resources are climate-dependent. Energy storage also provides reliability for both the business district and general housing in the smart microgrid. The main energy storage technology proposed for the smart microgrid is a battery system.

For each local grid, its energy storage system would be installed in the same area as the CCHP system to store the excess energy generated and to supply stored energy to the loads when energy generation is insufficient. This provides a balance between energy demand and supply to the local grid. Energy storage equipment should be installed in such a way that the storage capacity is increased in proportion to the increasing energy generation capacity as the city is being developed.

5.3.1.4 Solution Optimisation

The solution optimisation has three components: 1) data, 2) network requirements, 3) expanding the existing market for auxiliary services and energy products.

The solution optimisation begins with ensuring that sufficient information is available on renewable energy resources, and on customer mapping and load flow in these areas. These two data sets will be critical to DER planning and fine-tuning the attributes of the ESS system.

To support both the DER and ESS systems, a medium-voltage network in cities and towns will be important, as will be bidirectional power flows. This can be done by standard installations of transformers and inverters, placed in the network in coordination with the DER and ESS planning.

To enable the DER and ESS systems, the following pricing and communications programs will be needed:

1) Stakeholder and end-user outreach to inform on pricing signals and the opportunity to be involved in energy markets (e.g., by DSM programs, purchasing and installing PV panels, batteries),
2) Formally creating a market mechanism for distributed energy production and power sales (e.g., FiTs),
3) Formally making a market mechanism for power storage (e.g., a standby, system balancing, or another standardised energy service), and
4) Formally making a mechanism for DSM (e.g., consumer savings for reducing or delaying power use) with a focus on major loads such as campuses, infrastructure, and commercial real estate.

5.3.1.5 Solution Summary

For this IEA category, the centralised structure of the Thai power market was addressed. A quick means of gaining additional renewable energy penetration into this area is through DER – where multiple owners of homes, offices, commercial buildings, industrial complexes, and power companies can install local generation. In addition, the geography of the area was also taken into consideration. The EEC area (**Figure 7**) spans a long northwest–southeast portion of Thailand rather than one square-grid-like urban area. With this, a series of DERs along the EEC corridor manages load at the appropriate scale and voltage throughout towns and small cities in the EEC area.

One benefit of this lies in solar PV being a convenient option given high irradiance in Thailand and its correspondence with air conditioning loads. Another benefit is that in spreading multiple VRE and other generation throughout multiple small load centres, the volatility of generation is spread throughout the system and can be managed through a series of ESS installations. These ESS systems also provide redundancy to the system.

The core DER and ESS solutions also provide a platform for end users to interact with the power system through their own generation, demand-side management, and time-of-use schemes that the system operator can introduce with the help of storage. This was supported by data to plan the DER and ESS attributes, network upgrades to support their installation and operation, and market mechanisms to make these commercially viable.

5.3.2 IEA Category 2: Planning and Infrastructure

The inputs from the Thai power company on the problems of the EEC area falling in this category are shown in **Figure 24** and the solution summary in **Figure 25**.

Aspect 2: Planning and Infrastructure								
System Impact Scorecard					Corrective Measure Costs			
Low scores	22	21	13		07	14	13	*Low scores*
14	23	16	20		18	22	26	21
03	02	26	18		17	23	01	19
19	17	01	07		16	02	03	20
				High Scores				
16	26	19	18		07	01	18	14
17	01	23	02		23	20	26	22
07	03	20	22		16	02	17	19
Low scores	14	13	21		03	13	21	*Low scores*
Other Industries Impacted					Impacts to New Energy			

Figure 24. The distribution of scores in IEA Category 2: Planning and Infrastructure.

The engineer can view the historical problems and missed opportunities that impact the *Planning and Infrastructure* category, subdivided and ranked under the four sub-scorecards. At this point, expertise is utilised along with the framework to develop solutions that capture as much of the problems and missed opportunities as possible.

Aspect	Solution Description
2	Power planning and infrastrucutre will focus on developing a series of microgrids along the EEC area. These will be connected to the grid, connected to one another, and designed to provide maximum renewable energy integration.These microgrids will be able balance the broader system and will help in managing urbanization and growing power demand.

	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii	xiii	xiv	xv		Total	Multiplier	Total Score	Solution Score
1. Markets and Operations																	-	1.25	0	95
2. Planning and Infrastructure	3	23															26	1	26	
3. Uptake of innovative technology	25																25	1.25	31	
4. Efficiency and sector coupling	30																30	1.25	38	

Figure 25. The solution and the score summary for IEA Category 2: Planning and Infrastructure.

As demonstrated by **Figure 25**, the solution includes the following problems from the list of the 32 problems:

- 3 – *Lack of development of a medium-voltage distribution network*;
- 23 – *Distribution planners need to work closely with infrastructure developers (e.g., ports, rail stations), and with property developers who will have large loads in their network (e.g., campuses, industrials, hotels, schools) to create energy efficiency, and DSM/DR capabilities in load centres*;
- 25 – *Microgrids are underutilised as a tool in network planning in urbanising, developing countries*;
- and 30 – *Planners do not sufficiently include resiliency and secure infrastructure in grid planning*.

5.3.2.1 Solution Overview

Because of the geographic reach of the EEC, and because of it consisting of a series of small and medium-sized towns and cities, the optimal infrastructure will consist of a series of microgrids to function both independently and when needed, as individual units in a broader grid. This will best address the distribution system constraints in a rapidly urbanising area. It will also allow EGAT to incorporate individual microgrids into its larger grid when urbanisation and population increases and the corresponding expansion of power needs requires this. This is a modular solution with high flexibility in meeting local loads, yet which easily coordinates as a single large unit when needed. The four components of the microgrid infrastructure include the following:

1) <u>Microgrid system development plan</u> – Microgrids are finite areas of varying size, functioning as independent or semi-independent grids regarding their power supply and demand. In the case of the solution, these will have significant generation from renewable energy, will be able to balance themselves, and will be able to interact with the main grid.

2) <u>Power transmission and distribution development plan</u> – The microgrids in this solution will interact with, give, and receive power from the main grid. This will provide stability to the microgrid and will provide a support service to the main grid.

3) <u>Power distribution within a smart microgrid</u> – Distribution within each microgrid will be optimised in order to maximise renewable energy in the microgrid, ensure stability and

high-quality power, and service any loads within the microgrid (e.g., industrials, large chillers, steam production).

The core solution is optimised through power transmission between microgrids for stability and trading power. Microgridded towns and cities will be connected directly to one another, not just to the main grid. This will provide an additional layer of resiliency and support traded power and expansion of the larger grid system.

5.3.2.2 Core Solution: Microgrid System Development Plan

A microgrid is a low-voltage or medium-voltage electrical system that integrates distributed energy resources, energy consumption loads, information and communication systems, and energy control system. Smart microgrids can operate in conjunction with the main grid or independently in island mode, separately from the main grid. The key focus of a smart microgrid is to balance power generation with the power demand within the microgrid, and the connection to the main grid is provided to improve system reliability (**Figure 26**).

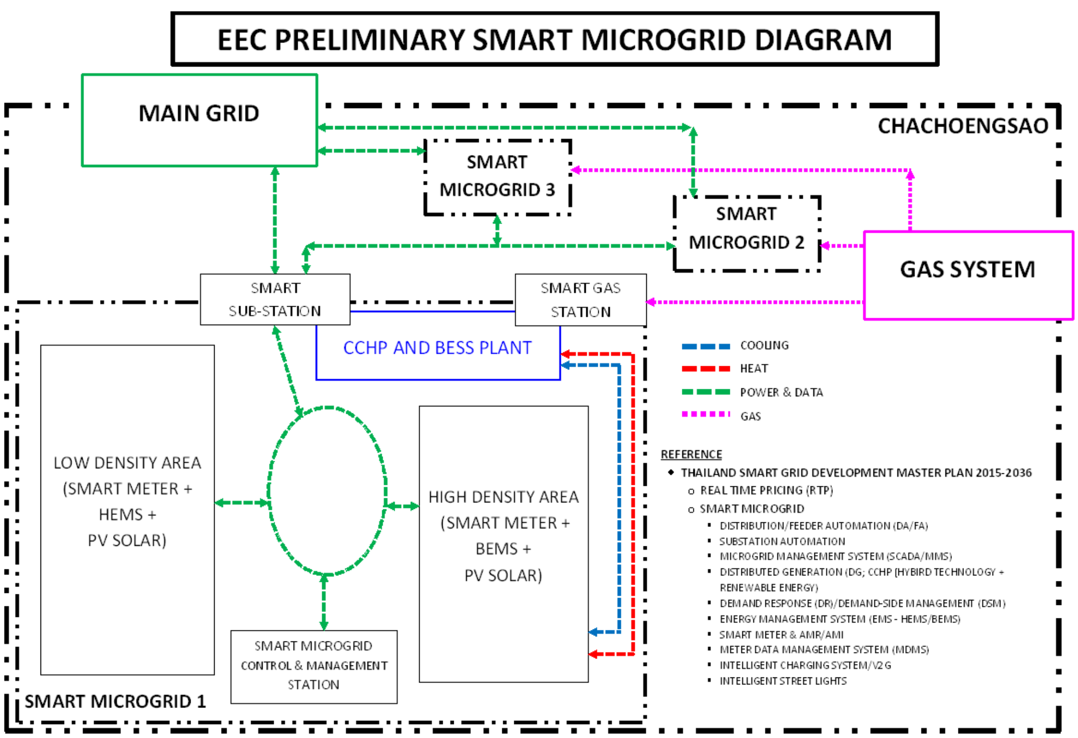


Figure 26. A schematic of a microgrid (source: Momoh, 2012).

From the concept that a new smart city is consisting of smaller suburbs, each suburb should develop its own smart microgrid system. Each suburb's smart microgrid would then be linked through the power transmission and communication system. The city's central control system would then manage power transmission and distribution between the smart microgrids within the city (**Figure 26**). When completely developed, a smart microgrid of each suburb in the EEC would have a balanced demand vs. supply as shown below (**Figure 27**).

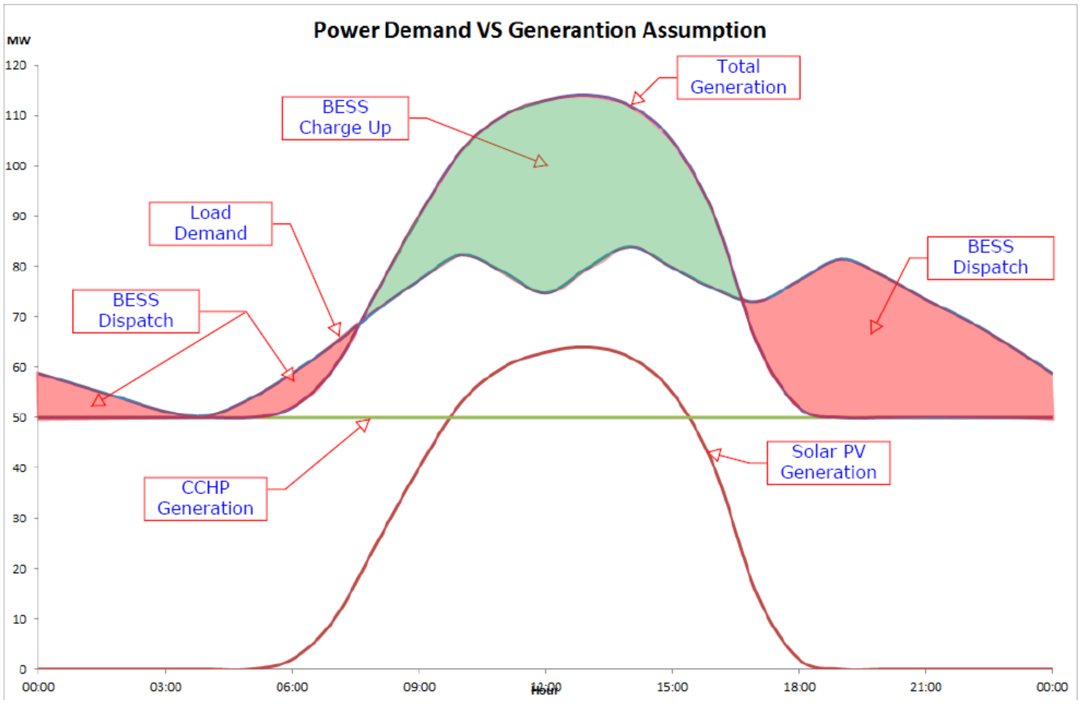


Figure 27. Load balancing with renewable energy in a microgrid system (source: Momoh, 2012).

5.3.2.3 Core Solution: Power Transmission and Distribution Development Plan

As each microgrid must be capable of connecting to the main grid, the current power transmission and distribution systems used by PEA and EGAT must be considered.

Integration of multiple microgrids also enables optimisation of the utilisation of each microgrid and an overall enhanced level of reliability and resilience through the utilisation of multiple interconnected systems.

5.3.2.4 Core Solution: Power Distribution within a Smart Microgrid

For each microgrid, the power distribution is proposed to be at the voltage level of 22 kV, which is currently used by both PEA and EGAT. Within a smart microgrid, a substation would be installed to receive power from the transmission lines and transform voltage from 115 kV to 22 kV as illustrated below (**Figure 28**).

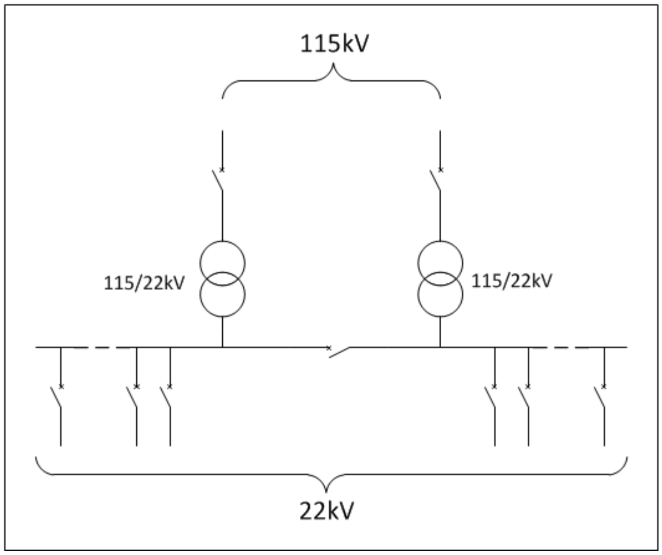


Figure 28. Interconnect between the microgrid and the grid (source: Casazza and Delea, 2010).

Within a microgrid, power could be distributed using overhead (or spaced aerial) cables, underground cables, or a combination of both. To distribute power at 22 kV and 8 MVA with the maximum voltage drop of 5%, overhead cables can distribute power up to 15 km, whereas underground cables can only distribute power up to 2 km. Thus, in general areas, overhead cables should be considered as the means for power distribution. However, for areas requiring tidiness and orderliness or areas subjected to severe weather, underground cables should be considered.

The power distribution system can be arranged in a loop configuration, a radial configuration, or a combination of both. The two configurations are illustrated below. Loop configuration is more reliable and provides better continuity in power distribution than radial configuration. However, it is more expensive and distributes power over a shorter distance in comparison to the radial configuration. Hence, loop configuration should be considered in the centre of the suburb or areas with high population density.

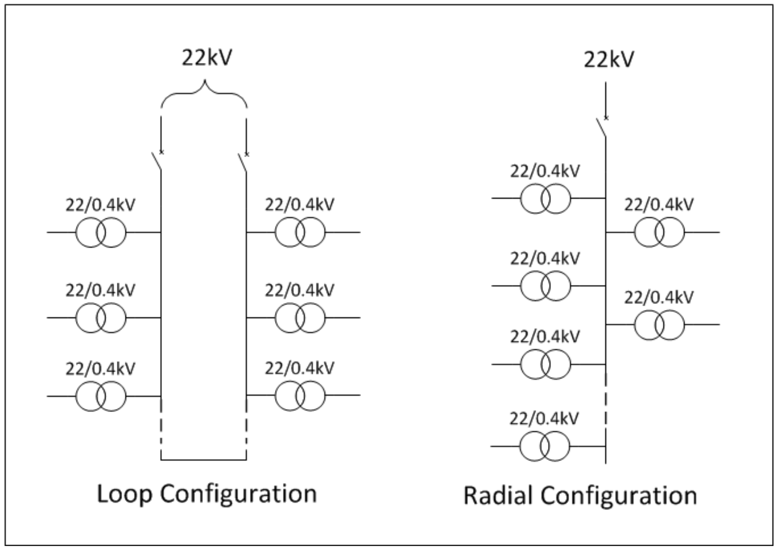


Figure 29. A schematic of the power distribution in a microgrid – loop vs. radial configuration (source: Casazza and Delea, 2010).

5.3.2.5 Solution Optimisation

The optimisation will consist of power transmission between smart microgrids. Power transmission between microgrids is proposed to be at the voltage level of 115 kV, which is currently used by both PEA and EGAT. Overhead transmission lines should be considered and should be located in areas with low population density. This is because overhead transmission lines are more economical and easier to maintain. Currently, the right-of-way for 115 kV overhead transmission lines is 12–25 m from the centre of the transmission towers. Connecting the microgrids both to the main grid and to one another will maximise the resiliency and system balancing benefits of the microgrids, and significantly reduce system losses.

5.3.2.6 Solution Summary

Building out power supply and demand in a series of small yet growing towns and cities will be most effectively managed in a modular, yet connected series of microgrids. The research pointed to significant problems around urban sprawls, cluttered networks, and suboptimal distribution systems that do not keep pace with urbanisation. Microgridding the length of the EEC and expanding these microgrids as needed is a means to address this. Digitising a modular approach like microgrids in an urbanising area also means that EGAT, or any other system operator, can essentially absorb a series of microgrids into its broader grid when operating conditions require.

5.3.3 IEA Category 3: Uptake of Innovative Technology

The inputs from the Thai power company on the problems of the EEC area falling in this category are shown in **Figure 30** and the solution summary in **Figure 31**.

Aspect 3: Uptake of Innovative Technology								
System Impact Scorecard					Corrective Measure Costs			
Low scores	05	14	10		08	24	14	*Low scores*
19	17	02	31		26	25	05	10
16	18	01	26		23	31	01	19
23	24	08	25		16	02	17	18
High Scores								
01	23	25	31		31	08	23	16
16	08	18	19		01	25	18	10
24	02	26	05		02	17	26	14
Low scores	17	14	10		05	24	19	*Low scores*
Other Industries Impacted					Impacts to New Energy			

Figure 30. The distribution of scores in IEA Category 3: Uptake of Innovative Technology.

The emphasis on item 31 and the corresponding high score are especially visible in the *Uptake of Innovative Technology* category, followed by DSM and system balancing. These also interplay well with *Planning and Infrastructure* (Scorecard 2), as data can be collected in the infrastructure of high use (problem 31 – digitising the system) and can be utilised to balance supply and demand via DSM measures and coordinated dispatch of VRE. At this point, expertise is utilised in conjunction with the research and framework to develop solutions, as detailed below.

Aspect	Solution Description
3	A microgrid controller system will be installed at each individual microgrid and in a centralized locaiton. This will allow for local-level optimization of microgirds and for the microgrids to function as one larger grid, in a fully digital fashion. It will underpin offering new products and services to end-users, and to market participants such as battery storage companies and small-scale power producers. A digitized system will allow real-time balancing and and addressing problems in the system. This will also be critical in integrating VRE into the grid.

	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii	xiii	xiv	xv		Total	Multiplier	Total Score	Solution Score
1. Markets and Operations																	-	1.25	0	83
2. Planning and Infrastructure																	-	1.25	0	
3. Uptake of innovative technology	10	16	26	31													83	1	83	
4. Efficiency and sector coupling																	-	1.25	0	

Figure 31. The solution and the score summary for IEA Category 3: Uptake of Innovative Technology.

As demonstrated by **Figure 31**, the solution includes the following problems from the list of the 32 problems:

- 10 – *SCADA systems at the distribution level are typically underinvested, which leads to insufficient data for generating reports on system performance and problems*;
- 16 – *Poor system balancing due to lack of network area coordination*;
- 26 – *As the network is expanding, planners must continually identify medium and large demand response (DR) targets*;
- and 31 – *In order to stay competitive, distribution utilities must transform themselves into more digital enterprises*.

5.3.3.1 Core Solution Overview

This IEA category refers to power system transformation through wholesale and retail market development, which supports greater shares of VRE and demand-side management. In Thailand's centralised model, two key structural problems need to be supported to change this:

1) Microgrid controller

This is a software system with a hardware interface that optimises and controls the supply and demand for energy and energy services in an individual microgrid unit.

The solution is optimised first at the local level through SCADA and other systems for industrials, large HVAC units such as centralised chillers, and other major loads so that each microgrid has information on its local major loads.

It will be further optimised through a digital platform for microgrid and load management – this is a platform for connecting all of the individual microgrid controllers. This allows them to function in an order or relation as a grid, or in moving power between individual microgrids. This digital component is what allows for true scalability in microgrids, which are on a standalone basis, modular infrastructure units. This also allows DSM to occur within a microgrid or a series of microgrids, and trade power between microgrids and between microgrids and the broader grid for resiliency and system balancing. This will mean that the microgrids can function fully independently or as one large connected grid all along the EEC area, operated from a fully digital control function.

2) Microgrid Information, Communication, and Energy Control System Development Plan

Each smart microgrid would have a microgrid controller to coordinate the inputs and outputs of the various DER systems, power transmission and distribution systems, and information and communication systems. The purpose of the controller is to balance the demand and supply of power within the microgrid and to ensure efficient interaction with the main grid.

For each smart microgrid, its microgrid controller would be located in the same area as the CCHP system. For a new smart city, one of its microgrid controllers would then act as a central controller to manage the energy resources of all microgrids within the city.

Information and communication technologies that are important in energy management include:

1) Analytical system to estimate power demand within a microgrid using statistics and the history of power consumption, as well as communication links to various instruments and measuring devices.
2) Analytical system to estimate renewable energy generation from power generation information, weather information, geographic information system (GIS), and relevant statistics as well as communication links to weather stations and other data monitoring stations.
3) Analytical system to evaluate fault occurrence trends in power generation and distribution systems.
4) Data storage system.
5) Data monitoring system.
6) Communication within smart microgrids and to the main grid.

Other than information and communication technologies, the key components of the energy management system include:

1) Smart meter or electrical meter that is capable of providing a detailed power consumption profile and automatically notifying the controller of any fault such as a blackout. A smart meter can communicate directly with the microgrid controller through various communication links including optical port communication, internet, and standard RS485.
2) Control logic to manage energy generation, energy storage, and energy distribution.
3) Fault detection and monitoring system. The electrical protection scheme should be designed to allow bi-directional power flow throughout the entire distribution system.
4) Analytical system to evaluate the performance and reliability of DER systems and power distribution system.

The diagram below (**Figure 32**) summarises the above concept of information, communication, and energy control system for each smart microgrid.

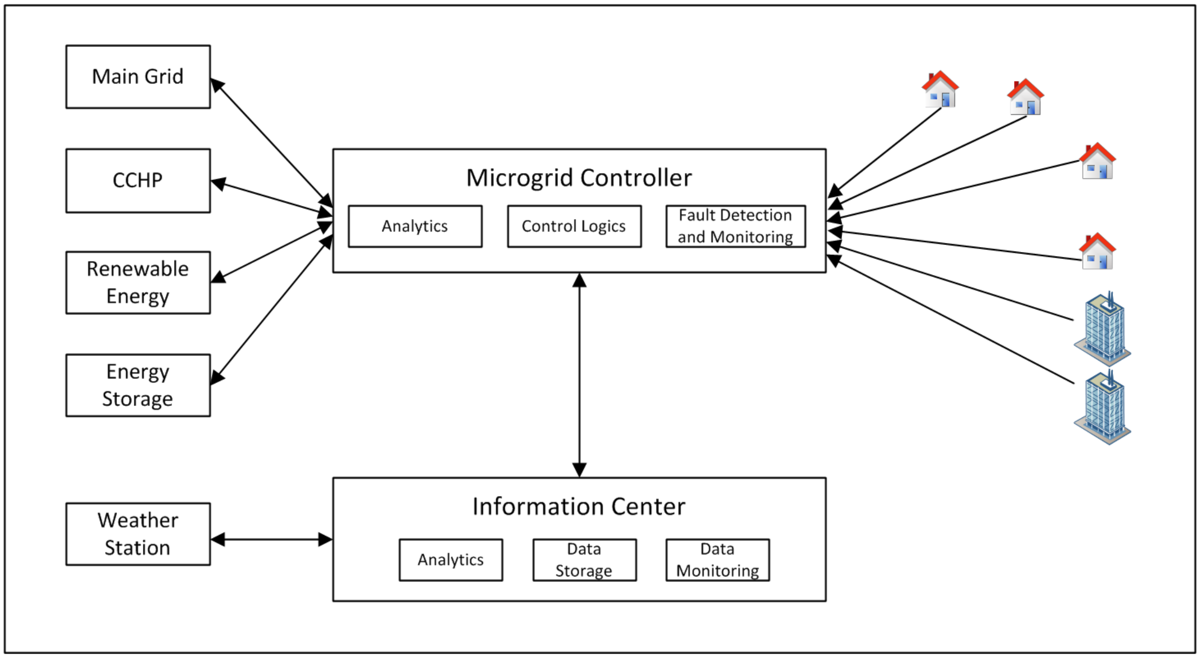


Figure 32. A schematic of a microgrid controller system (source: Momoh, 2012).

For end-users such as commercial buildings, local businesses, and general residential buildings, building energy management systems should be included in the initial building development plan to support demand response management.

Cybersecurity systems should also be provided in each smart microgrid to protect the grid from cyber threats that come with technological advancements, as per practices that are now becoming standard in the power systems of developed countries.

5.3.3.2 Solution Optimisation

The optimisation will consist of data collection from major loads within each microgrid, and a digitisation program to assist the microgrids in acting in conjunction with one another and with the main grid throughout the EEC area.

Individual microgrids can provide services to commercial and industrial loads, such as heating, cooling (or power for these units), and power quality regulation. They can also assist in industrials incorporating SCADA and other data collection into their facilities so that their load can interact and be optimised with the microgrid system. This will optimise power supply and demand within major loads in microgrids.

The microgrids individually and collectively will run from a digital platform. This will mean that they can assist tenants of the microgrids in interacting with DSM programs. It will also mean that microgrids can fully “island” (run independently), support one another, or support the broader grid. Building out power supply and demand in a series of small yet growing towns and cities will be most effectively managed in a modular yet connected series of microgrids.

5.3.3.3 Solution Summary

Microgrids in and of themselves are an infrastructure-oriented solution, servicing loads in a particular area. When they are optimised through a microgrid controller, they can increase VRE integration, and reduce losses on the microgrid site. When they are further integrated with the broader grid and with each other in a series of digitally controlled microgrids, they can react in real time to a variety of system problems and opportunities for cleaner, less expensive power. They can be significant providers of resiliency and system balancing and continue in a coordinated yet modular fashion to expand with an urbanising population. The digital element ties together a series of microgrids underpins their efficiency and resiliency.

5.3.4 IEA Category 4: Efficiency and Sector Coupling

The inputs from the Thai power company on the problems of the EEC area falling in this category are shown in **Figure 33** and the solution summary in **Figure 34**.

Aspect 4: Efficiency and Sector Coupling								
System Impact Scorecard					Corrective Measure Costs			
Low scores	19	11	21		08	24	21	*Low scores*
20	02	31	23		26	11	25	19
30	17	26	24		30	31	17	20
16	18	08	25		16	02	23	18
				High Scores				
16	23	25	31		31	08	23	11
30	08	18	19		20	25	18	16
24	02	26	20		02	17	26	19
Low scores	17	11	21		21	24	30	*Low scores*
Other Industries Impacted					Impacts to New Energy			

Figure 33. The distribution of scores in IEA Category 4: Efficiency and Sector Coupling.

The Efficiency and Sector Coupling has direct interplay with *Planning and Infrastructure* (Scorecard 2) but also *Uptake of Innovative Technology* (Scorecard 3) as information and digitising the matching of supply and demand underpins many solutions oriented towards efficiency and system balancing. At this point, expertise is utilised to develop a solution, which here leverages DSM and efficient energy (cooling, heating, and power) assets and coordinates them with digitally enabled dynamic balancing.

Aspect	Solution Description
4	Combined cooling, heating, and power (CCHP) units are a highly efficient way to produce cooling, hot water and steam, and power. One major unit will be in each major town and urban center in the EEC to maximize efficiency. This will serve as a cornerstone utility for these growing regions. In the planning phase of the CCHP unit, other utilities (e.g., water and telecom) will be involved to maximize capital and any infrastructure in place. Property companies will also be consulted to ensure that utility-property coordination occurs and that utilities are brought to people in an efficient fashion. To optimize this solution, an electronic sytsem will be installed for managing disconnection and theft, for asset management, and for billing.

	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii	xiii	xiv	xv		Total	Multiplier	Total Score	Solution Score
1. Markets and Operations	6	9	11														26	1.25	33	99
2. Planning and Infrastructure	22																22	1.25	28	
3. Uptake of innovative technology																	-	1.25	0	
4. Efficiency and sector coupling	19	20															39	1	39	

Figure 34. The solution and the score summary for IEA Category 4: Efficiency and Sector Coupling.

As demonstrated by **Figure 23**, the solution includes the following problems from the list of the 32 problems:

- 6 – *Poor billing practices leading to lack of re-investment in critical parts of the distribution network*;
- 9 – *Insufficient management of theft and disconnection*;
- 11 – *Insufficient interaction with stakeholders and customers on energy efficiency, pricing signals, and from this, an inability to shape demand*;
- 19 – *Coordinating with other utilities needs to occur, as this can unlock significant synergies and savings*;
- 20 – *Power sector planners should guide property developers on where urban centres should expand to, rather than attempt to follow and catch-up in network building*;
- and 22 – Asset management at the distribution level is underinvested and needs to be emphasised.

5.3.4.1 Core Solution Overview

The EEC region is and will continue to consist of a variety of towns and small cities with growing needs for utilities. The core of this solution involves a central utility unit in each major town or city, which produces power, cooling, and heating in a highly effective way. The planning and operation of this unit will involve coordination and optimisation with other utilities.

One combined cooling, heating, and power CCHP unit will be placed in each major town or city in the EEC region. When running at continuous load, this is a highly efficient means to produce energy, cooling, and heating. Centralising cooling (especially in hot climates) and hot water production in growing urban centres reduce the reliance on single-wall units and produce tremendous savings. These will be designed to be able to scale-up as needed. The CCHP unit will serve as a cornerstone utility in that town or city and will benchmark efficiency in providing utilities to people.

The solution will be optimised by its planning phase and its operations. In planning, close coordination will occur with other utilities to maximise infrastructure, energy use, and invested capital, and with property companies to ensure that major properties are developed within the constraints of the CCHP unit and its distribution capabilities. The CCHP unit will be installed with a billing and disconnection system, and an asset management system, which other utilities will utilise as well.

The purpose of the CCHP system is to produce energy efficiently for its service region and loads. The CCHP systems can use natural gas and biomass to generate electricity, and the exhaust heat from electricity generation is then used to produce heat (steam or hot water) and cooling (chilled water) energy. The CCHP systems achieve maximum efficiency and economic return when continuously running at nearly full load.

The CCHP system is proposed to be developed on a dedicated area of approximately 80,000 m^3 or 20 acres. This area is proposed to be shared between the CCHP, microgrid controller, substation, gas station, and energy storage system. The area is proposed to be located close to the suburb centre where the energy demand is the highest. During the initial city development phases when the energy demand is relatively small, the CCHP would be made up of smaller power generating units, such as 1–5 MW reciprocating engines, installed one by one to meet the growing demand. In these early stages, the CCHP system would likely be producing electricity only as the demands for heat and cooling energy are small.

As the city development progresses into its intermediate stages, approximately after ten years of development, the demands for electricity, heat, and cooling energy would grow to the point where the CCHP system is required to expand. Larger power generating units would be installed, such as 5–20 MW gas turbines, steam turbines, absorption chillers, and heat exchangers to deliver a complete CCHP system as depicted below (**Figure 35**).

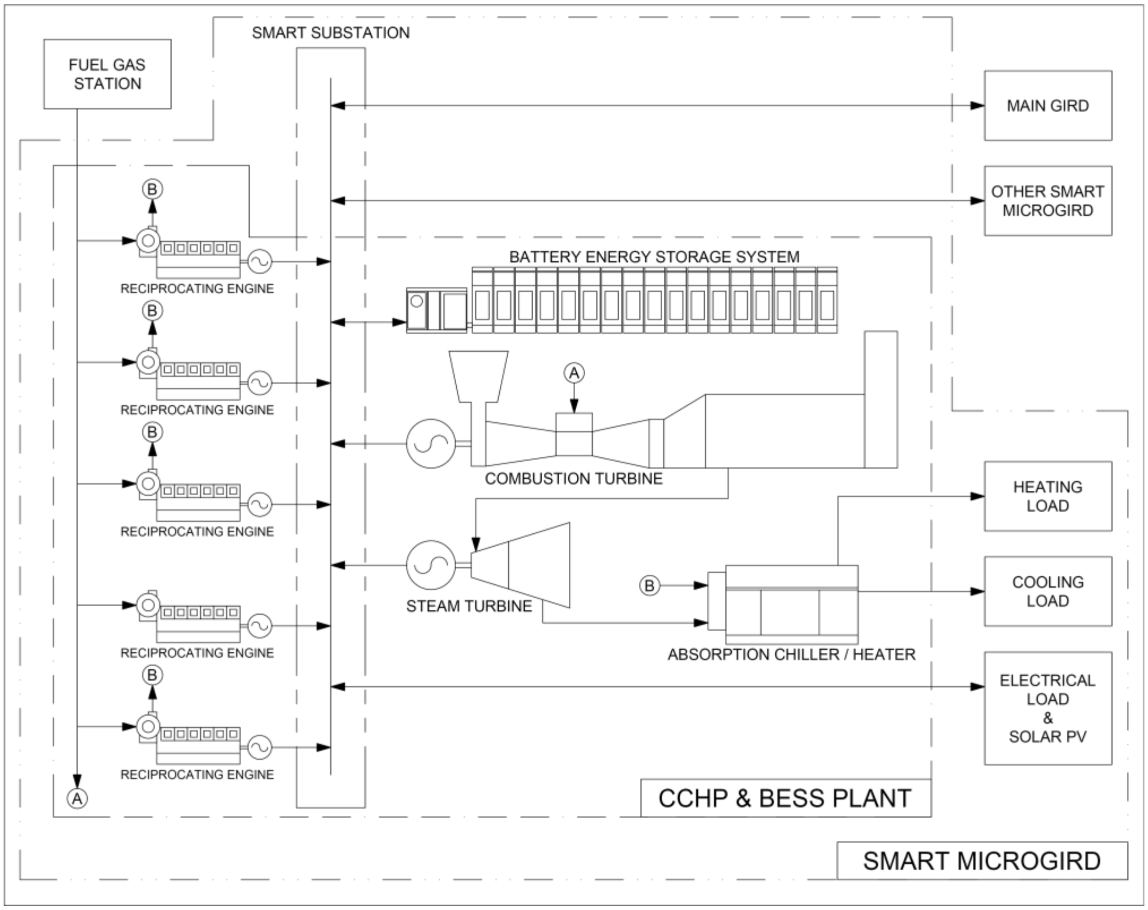


Figure 35. A schematic of a combined cooling, heat, and power (CCHP) system (source: Momoh, 2012).

When the CCHP system is fully developed, the system is estimated to be able to supply 70% of the estimated peak demand. That is, approximately 50 MW of power is produced by the CCHP for each suburb.

5.3.4.2 Solution Optimisation

Solution optimisation will first occur in the planning phase. Property companies will be consulted on where they anticipate building new developments, quantities of inhabitants, and other needs. The same will occur with public and private sector infrastructure developments. Coordination with these entities will occur so that they are aware of the CCHP unit's operating and distribution limits, and so that utilities are brought to new developments safely and effectively. Other utilities (e.g., telecom, gas, water) will also be involved in the coordination exercise so that the infrastructure and public works (e.g., tunnelling) can be maximised, the right-of-way in any construction is clear and abided by, the infrastructure is shared and optimised wherever possible, and the capital invested in utilities is maximised. The planning coordination will serve as a model for how other towns and cities should optimise the development of the built environment and utilities.

In the installation of the solution, an electronic suite will be installed with two simple functions. One will be billing and disconnection. This platform can be shared amongst other utilities so that the residents of the EEC can have simplified procedures for paying utility bills. Utility companies will have enhanced information on their customers and can manage billing and disconnection more easily. Also in this suite will be an asset management function. This functions to log and make a record of linear assets (e.g., pipes, power lines, water lines) and point assets (e.g., transformers, pumps, capacitor banks). An asset management suite is critical to making a clear and accurate record of the many utility assets and equipment installed in the field, predict and optimise maintenance, ensure safety, and save money. Many asset management systems are paper-based in developing countries, while software for this has significantly declined in price. The software in the optimisation of this solution will be shared amongst other utilities for their benefit as well.

5.3.4.3 Solution Summary

The solution relies on putting a core utility – a CCHP unit – at each town or city, knowing that it will expand needing power, cooling, and hot water, and that centralised units can perform this most effectively. The design for this CCHP unit can be standardised so that purchasing, installation, and maintenance in the many CCHP units installed along the EEC area can be simplified and efficient. The optimisation of the solution is where critical cross-utility coordination and coordination with property and infrastructure developers takes place. This will be complemented by a simple software solution for billing and obtaining customer data and for cross-utility asset management. This software can be standardised as well so that the planning, CCHP unit, and accompanying software can occur in a packaged process within all towns and cities in the EEC.

5.3.5 Summary of Solutions and Scores

The solution for IEA Category 1 (*Markets and Operations*) starts by breaking down the traditional centralised utility paradigm, allowing for small-scale, local generation, new products such as storage and DSM, and greater participation from end users and non-power companies. This is a critical starting point to power system modernisation. IEA Category 2 (*Infrastructure and Planning*) requires critical infrastructure in place. The key solution here focuses on a standard microgrid design for towns and small cities to meet demand in a flexible, modular fashion. Further complementing this is the solution to IEA Category 3 (*Uptake of Innovative Technology*), which digitises the microgrids and maximises their functionality. This is with the ability to function independently as one microgrid or in concert with other microgrids and the broader grid in the EEC region. This facilitates system balancing, resiliency, and integration of volatile renewables. Finally, the solution to IEA Category 4 (*Efficiency and Sector Coupling*) focuses on a highly efficient means of meeting critical loads (power, cooling, hot water) in this area through highly efficient CCHP units, through coordination with both property and infrastructure developers, and with other utilities. The core solutions address the local EEC needs and the definitions of the IEA categories (**Figure 36**), while the scores and the outputs of the solutions are enhanced through the solution optimisation, which is produced by iterating within the scorecard (**Figure 37**). According to research on the 32 problems, expert interviews with experience in multiple energy projects in developing countries, and the overall research methodology, these four key solutions together should provide a significant energy backbone to the EEC region.

Aspect 1: Markets and Operations								
System Impact Scorecard					Corrective Measure Costs			
Low scores	04	10	09		09	07	08	*Low scores*
12	23	16	20		12	19	20	04
11	17	26	06		11	17	18	06
19	18	07	08		16	23	26	10
High Scores								
12	04	19	18		08	07	18	12
17	26	23	08		23	20	26	10
11	20	16	06		16	11	17	04
Low scores	07	10	09		09	06	19	*Low scores*
Other Industries Impacted					Impacts to New Energy			

Aspect 3: Uptake of Innovative Technology								
System Impact Scorecard					Corrective Measure Costs			
Low scores	05	14	10		08	24	14	*Low scores*
19	17	02	31		26	25	05	10
16	18	01	26		23	31	01	19
23	24	08	25		16	02	17	18
High Scores								
01	23	25	31		31	08	23	16
16	08	18	19		01	25	18	10
24	02	26	05		02	17	26	14
Low scores	17	14	10		05	24	19	*Low scores*
Other Industries Impacted					Impacts to New Energy			

Aspect 2: Planning and Infrastructure								
System Impact Scorecard					Corrective Measure Costs			
Low scores	22	21	13		07	14	13	*Low scores*
14	23	16	20		18	22	26	21
03	02	26	18		17	23	01	19
19	17	01	07		16	02	03	20
High Scores								
16	26	19	18		07	01	18	14
17	01	23	02		23	20	26	22
07	03	20	22		16	02	17	19
Low scores	14	13	21		03	13	21	*Low scores*
Other Industries Impacted					Impacts to New Energy			

Aspect 4: Efficiency and Sector Coupling								
System Impact Scorecard					Corrective Measure Costs			
Low scores	19	11	21		08	24	21	*Low scores*
20	02	31	23		26	11	25	19
30	17	26	24		30	31	17	20
16	18	08	25		16	02	23	18
High Scores								
16	23	25	31		31	08	23	11
30	08	18	19		20	25	18	16
24	02	26	20		02	17	26	19
Low scores	17	11	21		21	24	30	*Low scores*
Other Industries Impacted					Impacts to New Energy			

Figure 36. A summary of score distributions in the four IEA categories.

Step 3: Create solutions in blue cells below, tally scores of solutions | **Step 4: Select issues that each solution addresses** | **Results**

Aspect	Solution Description	Issue								Total	Multiplier	Total Score	Solution Score	Rank
1	A reduction in dependance on centralized generation, and opening of the market to small-scale and distributed generation in addition to storage. The core solution involves a distributed energy resource system spread throughout the EEC area and enables a rapid build-up of renewable energy and localized generation. The storage complements this and provides stability and redundancy for the system. The two together also provide a platform for greater end-user participation. This core solution is optimized via data analysis on renewable energy resources and customer mapping, simple network upgrades, and expanding energy market products and services to include DSM, storage, and FiTs for local generation.	1. Markets and Operations	14	11	18	23	26	8	17	117	1	117	121	1
		2. Planning and Infrastructure	3							3	1.25	4		
		3. Uptake of Innovative Technology								-	1.25	0		
		4. Efficiency and Sector Coupling								-	1.25	0		
2	Power planning and infrastrucutre will focus on developing a series of microgrids along the EEC area. These will be connected to the grid, connected to one another, and designed to provide maximum renewable energy integration.These microgrids will be able balance the broader system and will help in managing urbanization and growing power demand.	1. Markets and Operations								-	1.25	0	95	3
		2. Planning and Infrastructure	3	23						26	1	26		
		3. Uptake of Innovative Technology	25							25	1.25	31		
		4. Efficiency and Sector Coupling	30							30	1.25	38		
3	A microgrid controller system will be installed at each individual microgrid and in a centralized locaiton. This will allow for local-level optimization of microgirds and for the microgrids to function as one larger grid, in a fully digital fashion. It will underpin offering new products and services to end-users, and to market participants such as battery storage companies and small-scale power producers. A digitized system will allow real-time balancing and and addressing problems in the system. This will also be critical in integrating VRE into the grid.	1. Markets and Operations								-	1.25	0	83	4
		2. Planning and Infrastructure								-	1.25	0		
		3. Uptake of Innovative Technology	10	16	26	31				83	1	83		
		4. Efficiency and Sector Coupling								-	1.25	0		
4	Combined cooling, heating, and power (CCHP) units are a highly efficient way to produce cooling, hot water and steam, and power. One major unit will be in each major town and urban center in the EEC to maximize efficiency. This will serve as a cornerstone utility for these growing regions. In the planning phase of the CCHP unit, other utilities (e.g., water and telecom) will be involved to maximize capital and any infrastructure in place. Property companies will also be consulted to ensure that utility-property coordination occurs and that utilities are brought to people in an efficient fashion. To optimize this solution, an electronic sytsem will be installed for managing disconnection and theft, for asset management, and for billing.	1. Markets and Operations	6	9	11					26	1.25	33	99	2
		2. Planning and Infrastructure	22							22	1.25	28		
		3. Uptake of Innovative Technology								-	1.25	0		
		4. Efficiency and Sector Coupling	19	20						39	1	39		

Figure 37. Score summary of solutions for IEA Categories 1–4.

6. DISCUSSION

Urbanisation and development of infrastructure and the built environment represent a crucial driver of recurring energy demand in developing countries. This will result in continued growth in energy demand as people come to cities and live a life of higher energy intensity. Growing urban centres in developing countries, which represent the largest new sources of energy demand in the world, need to be critical areas of focus of future infrastructure planning. Coming from a low base in infrastructure, these areas can potentially insert best-in-class planning practices and technologies as they develop. Power generation generally involves single, large capital projects and is clearly the starting point of the power value chain. Recently, as renewable energy generation technology has improved, power generation came into increased focus not just due to its scale and size of assets, but due to it being the easiest single point to reduce CO_2 per unit of power capacity.

Several authors (The World Energy Council, 2014; Bosco et al., 2016) note the role of generation in energy sector development in developing countries. Further, how generation is supported and enabled by fiscal, monetary, and financing issues, are noted by Brew-Hammond (2010) and Winkler et al. (2012). The academic community and universities have played a critical role in developing renewable energy generation technology and in supporting the government and the private sector in materialising these improvements in power systems globally. Existing research on energy in developing countries is, understandably, highly focused on generation and policy and economics that enable this, but this falls short of addressing the full list of what urbanization means in terms of energy demand (Thavasi and Ramakrishna, 2009; Lin et al., 2017; Mirjat et al., 2017). To enable the full value chain of energy, it is critical to finance and regulate generation. However, these are essentially static issues that pertain to a single asset being constructed and operated, rather than to addressing the multitude of issues around long-term energy demand – for example, how people manage transportation, food, heating, and cooking, how they are employed, and where they live, and how these issues change with time. Financing energy projects, while difficult, is essentially a binary issue – can a generation plant be funded or not? Distribution systems in dynamic, growing urban centres are not binary in nature, and solutions to distribution systems in urban centres need to be expanded and enhanced as time passes.

Due to these factors, distribution has been relatively underemphasized in both academic research and capital deployment. Distribution represents the closest point to the consumer, it is an enabler of data exchange, and it is interwoven in the built environment, which represents a key location where energy and resources are consumed. These three areas together – urban centres in developing countries, power distribution, and the built environment – are critical to focus on in the search for energy efficiency.

Authors note that distribution has a series of issues from safety (Keivani, 2010), to efficiency (Kolokotsa, 2016), to capital planning (Brew-Hammond, 2010). However, the existing research literature is limited insofar as it points to quantitative, granular issues in single-line diagrams and local-level planning, rather than addressing the system-planning level (Jha et al., 2002). Distribution is also the point where the consumer and the power system potentially exchange information and communicate (Raposo et al., 2017; Pau et al., 2018) and represents a critical point to shape supply and demand dynamics. As digital technologies and information exchange capabilities increase, opportunities to interact with end-users of energy open new possibilities for enhancements to energy. End-users do not have direct interaction with large-scale generation plants or transmission systems – the interaction between end-users and the power system takes place where the distribution system enters the built environment inhabited and used by people.

An objective tool with the capacity to identify problems and rank potential solution to issues of distribution is absent from decision-making processes. Decision-making on large capital assets can be highly unstructured – open to subjectivity, bribery, and can involve committing to unsure or untested technologies. This is an area where academia and research can truly benefit real-world applications by providing an objective means for bringing structure to unstructured problems. Individuals researching and working in this area have the opportunity to shape positive future outcomes by producing tools for developing solutions for unstructured problems in these critical areas of energy planning.

Authors note that urbanisation is one of the greatest driving forces in energy demand and stress on cities (Sadorsky, 2013; Zinaman et al., 2015), and developing countries will be the centre of this (Muhammad and Lean, 2011; Allouhi et al., 2015). While they do note the magnitude and materiality of the impacts of urbanisation on energy and the environment, a clear connection to system planning, and specifically distribution planning, is missing (World Energy Council, 2014; Bosco et al., 2016). The literature review displayed a significant knowledge gap in the field of distribution planning in rapidly urbanising, developing countries – as well as a lack of structure in how to develop solutions and more effectively plan for these areas. In exploring this knowledge gap, several key outcomes were accomplished. This included five key findings as well as a further five indirect but important broader themes. These are detailed below.

6.1 Overview of the Research Outcomes

The first questions asked were whether or not portions of the power system are underserved by academic, government, and private sector companies in developing countries. It was displayed that generation is heavily emphasised over distribution and that this is problematic in developing countries where urbanisation is taking place (**Section 2.2.2**, page 26). Following this, problems were discovered and documented through research (**Section 4.1**, page 67). These problems and their impacts were reviewed and scored in interviews with professionals who work on power systems in developing countries. The next challenge is how to connect these problems to solutions. After completing this, the solutions were tested by applying them to a case study in a developing country where load density is increasing, and interviewing local power authorities on their views of the impact of the proposed solutions.

The overall objective of this research was to address a significant gap in academic research and create a tool which can contribute to efficient power planning in developing countries. The starting point was understanding power demand in developing countries and identifying and understanding its key drivers. Urbanisation was identified as a key driver. From here, research was conducted to understand if this driver of load is adequately reflected in power planning across the academic, public, and private sectors. It was determined from this that distribution planning, and distribution planning in conjunction with urbanisation and the built environment, were highly underemphasised.

A list of problems was developed arising from insufficient planning in the focus areas, and a repository of case studies on these areas was created. In order to understand the impacts of these problems, an Excel-based tool was made to rank and score the problems and set a framework for developing solutions. Based on standard engineering texts, scorecards were then developed to rank the severity of impacts of the problems on the system. This tool – the list of problems, the repository of case studies, and the scorecards – were endorsed by three interviews with industry experts. The tool was then combined with the IEA Framework for organising and classifying efforts in power system modernisation. The scorecards were organised to feed inputs into the framework and produce clusters of problems of focus for developing solutions.

A live example– an urbanising area along the Thailand–Cambodia border – was utilised as a case study. The tool was utilised to work with a local power company to develop solutions for the case study area. The solutions developed from the tools were reviewed and endorsed by a senior manager of the Thai power company. Verification by industry experts and the Thai power company provided interesting insights into the practical problems around planning and implementing plans in complex environments with multiple stakeholders. Several interesting points were noted around the struggles between the broader government in a developing country, power sector regulators, energy companies, and industry. Particularly of interest was the notion that distributed generation is now being promoted by the energy industry as an advanced and efficient solution, yet it represents a loss of political power and sits at the core of what many regulators are worried about and, in some cases, seek to block or hinder.

The ending point of this research is 1) a tool which can serve as an objective means for developing and ranking solutions; 2) background, framework and explanation of power distribution problems in developing-nation urban centres; and 3) a repository with case studies on the 32 distribution problems. This process and its outputs were solidified by the use of case studies, a recognised IEA Framework, and endorsed by multiple interviews from senior industry professionals. At the closure of the final interview, the research, methodology, tool, and outputs of the tool have all been endorsed. The conclusion of this is that areas for improvement have been successfully identified and a suitable methodology for creating solutions has been developed. This marks a successful combination of academic research, industry experience, and framework from international organisations to create actionable solutions for major energy problems. The outputs of the research can be stored on a USB drive and utilised by an engineer in an aid agency or other private or public sector body while in the field and planning power systems in developing countries.

6.2 The Five Key Findings

There are five key points which were consistently encountered in the research and interview processes, and are important outcomes of the research as it pertains directly to the research gap and focus areas:

1) <u>Generation is clearly overemphasised versus distribution in power system planning</u>, as displayed in **Sections 2.2.1** (page 22) and **2.2.2** (page 26) and Tables 1 and 2. Furthermore, a problem outside of the scope of this research, is the apparent human tendency to search for a single large solution to energy and pollution problems (e.g. install a large solar PV plant) versus a series of more complex solutions (an improved configuration in the low and medium voltage distribution network in a city). This exists even though the latter may have greater or equal outcomes at lower or equal costs. While generation is the starting point of the electrical value chain, and one solution is easier to grasp than a combination of solutions, this tendency leaves distribution significantly lower funded and less emphasised. The public and private sectors have spent an unbalanced amount of time and effort emphasising affordable generation versus the growing problem of distribution systems in urbanising, developing countries (Asif and Muneer, 2007; Severance, 2011; Milligan et al., 2015).

2) <u>Urbanising areas in developing countries need to be a critical area for focus and emphasis on energy efficiency</u>. This problem deserves increased attention from both the public and private sectors. Urbanisation rates (see **Section 2.1.3**, page 19) emphasise the scale of this problem. **Section 2.1.4** (page 19) highlights a variety of problems that are occurring in these areas and the criticality of addressing them. A bright point, however, is that a lack of existing infrastructure can be an advantage in creating solutions. A developing country

often has less burden from legacy systems, and in effect can utilise the latest technologies available and 'leapfrog' other places in system planning where significant infrastructure already exists (Sadorsky, 2013; US DoE, 2017).

3) Urban planning and power system planning in developing countries need significant improvement in coordination (Lin and Li, 2014). Coordination with real estate developers and utilities such as water, gas, and telecom are often absent or substandard (Costa et al., 2017). Planning and developing efficiency through load matching, infrastructure synergies, end-user communications, and other methods are not capital intensive and should be viewed as one of the lowest cost ways to reduce losses, CO_2, and pollution. Again, the relative lack of infrastructure in developing countries often means that addressing these problems in the early phases of planning a city can lead to significant synergies and savings.

4) From both case-study research (**Section 5**, page 113) and expert interviews (**Appendices C–E**), a relatively short list of power distribution system components was noted as critical enablers of efficiency and renewable energy integration:

   a) Power storage – there have been significant cost declines in this area, and this is a critical component to increasing the share of VRE in the generation mix.

   b) Metering, load studies, and forecasting – these systems have seen significant cost declines. Detailed data on consumption, and utilising this data to plan, and to shape demand via communications with end users, is critical to modernising utilities.

   c) Modular distributed generation systems, and corresponding digital management systems – these have also reduced in price and are available from a variety of vendors. Distributed systems allow for low-cost redundancy and a reduction in line losses versus centralised systems. Modular systems provide ease of installation and maintenance and significant cost reductions. Digitally managing these means that the system can both predict and adapt to change.

   d) Customer outreach and interactive power systems – these are critical to shaping demand and making the power system dynamic. Participation across stakeholders and from various types of end users is critical to a flexible power system and over the long term, a reduction in consumption and losses.

5) Case-study research (**Section 5**, page 113) and expert interviews (**Appendices C–E**) both highlighted difficulties in quantifying and ranking distribution planning solutions. Dollars per megawatt of generation capacity, annual uptime and plant life, and CO_2 per megawatt of generation are some of the more commonly used metrics for generation, but distribution systems require a more detailed ranking system. An engineer in The Thai power company

commented on figure 39 which is the scorecard summary of the solutions for the EEC area. It was stated that the distribution of scores was appropriate (ranging from 83 to 121) and that the IEA framework and quantitative scoring system appropriately valued solutions by their depth per IEA category and their ability to incorporate problems in multiple IEA categories. A conclusion confirmed from research and interviews is that there is a clear deficit of systems and tools for creating and ranking solutions for power distribution systems in developing countries.

The discovery-based approach and corresponding endorsement by expert interviewees created the ability to hone in on critical aspects and quantify what problems are most important. These were more frequently encountered problems in case studies, more frequently discussed problems in interviews, and problems which received high scores in the scorecard exercises. Effective planning, the need to measure and rank distribution system proposals, the need for a digitised, flexible, and distributed power system, all were consistently encountered. Also consistently encountered, was urgency and need for change in how we address power systems in burgeoning cities in the developing world.

The solutions were developed using documented problems in the focus areas, an internationally recognised framework, and some localisation of these tools by the overall system scorecard and the basic location characteristics. As a result, these solutions are tailored to the EEC area but draw from information and framework on the broader research gap. The IEA framework ensures that the systems are holistic – covering markets, infrastructure, technology, and efficiency. The EEC solutions have interplay and interconnection primarily by connected distribution infrastructure and a series of distributed load servicing assets which are optimised across the urban centre and are digitally connected.

6.3 Five Broader Themes

In addition to the five key findings highlighted above, five broader themes were found as an indirect result of the research. While not directly pertaining to the research questions addressed in this thesis, they are interesting and could form the basis of further investigation:

1) Leapfrogging is discussed by global non-profits such as the World Bank (Kojima et al., 2010; Bacon and Kojima, 2011) as a means for developing countries to quickly improve technology and infrastructure. This occurs where the country does not have to go through a series of iterative trial and error or research-focused improvements, but can rather simply obtain best-in-class technology and replace or upgrade its existing system. This means skipping or leapfrogging several generations of less optimal technology and immediately enjoying the benefits of best-in-class capabilities and functions. The World Bank (Kojima et al., 2010; Bacon and Kojima, 2011) notes that Africa and other developing regions are

positioned to make some of the largest gains in infrastructure and technology from their existing low bases by simply making wise decisions on acquiring and building new infrastructure and technologies. Industrial leapfrogging and how specifically this can be carried out – not conceptually, but in specific urban centres and large assets – is more complicated. Some authors (Sauters and Watson, 2008) have noted the potential in leapfrogging strategy for specific industries, but a practical approach to this is lacking. Nevertheless, the leapfrogging issues point to the quantum of change that can take place in developing countries.

2) Understanding the implications of decentralising energy systems of an industry for stakeholders and government. Decentralisation of the power industry from traditional centralised, large-scale assets and planning, to decentralised, local level was repeatedly identified as an important step by the interviewees (**Section 5**, page 113) and in the academic literature (Stephens et al., 2015; Burke and Stephens, 2018). It is, however, worth noting that this raises issues of ownership and control of new decentralised assets, and what happens to the legacy, centralised system. Herran and Nakata (2012), Nepal and Jamasb (2015), and Ponce-Jara et al. (2017) all note the importance of power sector decentralisation, yet all note the political struggle that is going on as a result of it. In the Easter Economic Corridor case study, the Thai government owns and has financed the existing transmission and distribution system and much of the generation system. The legacy assets in this area are of varying lifespans and could have drastically different operating and economic profiles if the area, or broader Thai power industry, became decentralised. While of interest to end-users and planners, who have the environment as their top concern, parties with a vested interest in the legacy system are less interested in decentralisation and may be motivated to stymie its progress.

3) Decision-making on large capital assets is a process riddled with corruption, subjectivism, and lack of long-term planning. These are all present in major infrastructure projects in urban centres. Multiple authors show the need for ranking, benchmarking, judging, and selecting projects in an organised, objective fashion (e.g., The Australian Academy of Technology and Engineering, 2016; Davies and Slade, 2017). Also at play are deep-seated behavioural characteristics. The psychologist Daniel Kahneman notes the tendency for decision-makers to make instinctive heuristic decisions, preferring what appear to be simple solutions rather than more complex ones (Kahneman, 2013). In the context of decarbonising energy systems, this might mean choosing to install numerous wind turbines rather than the complex task of planning for how the distribution system will interact with the built environment. It was found through interviews and the research in general that while distribution systems may unlock as much or, in some cases, more efficiency and environmental gains than adding more 'green' generation, the latter is easier

to grasp and may be preferred even if less effective. Both of these two issues – the need for ranking and objective decision making as well as decision-making biases – point to the need for more decision-making tools and structures in large infrastructure projects.

4) Databases and integrated planning tools for the research focus areas similar to the case studies on the 32 and excel tool in this research are in early phases of development. IRENA FlexTool (IRENA, 2019) and the ENERGYDATA.INFO platform (The World Bank Group, 2019) were widely supported by the interviewees as helpful, but few in numbers and depth. The Thai power company also stated how such databases and connected tools could take significant subjectivity and problems from the planning and project award criteria process.

5) The academic community is well-positioned to make a significant impact on planning processes and project award criteria. This was stated by the Thai power company and noted throughout the research. Academia is perceived as having the: (i) necessary access to databases on planning problems, (ii) the structures and research capacity to develop solutions, and (iii) apparent neutrality – not having a profit motive in planning or selecting a particular design. The lack of an objective and neutral means to plan and compare the merits of infrastructure projects was identified and addressed in the outcomes of the research, and is a key benefit of the research and tool developed. This is an area where the academic community could significantly support government and aid organisation in judging the merit of proposed projects they finance or support. The academic community could carry out this structure (create a database of planning problems, rank problems, create a structure for linking problems to solutions) in a variety of industries (such as transport, healthcare, or energy).

6.4 Shortcomings and Limitations of This Research

Several difficulties were encountered during the research. Where possible, they were appropriately addressed, or a pragmatic workaround was identified. An initial limitation was the lack of published research and case studies on the focus areas. While this gap in the literature indicated the potential to make a useful contribution to academic research and the improvement in energy efficiency, it also meant that finding case studies on the focus areas was difficult.

Data on distribution systems are not typically publicly available. Conversely, data on large generation units are routinely publicly available. It is relatively easy to find their capacity, location, year of commissioning, and other high-level information. Distribution systems are more heterogeneous and atomised (i.e. a greater number of small- and medium-sized assets) Information is often not gathered in one place and frequently not available to the public for a variety of reasons, including safety and security. This limits the quantification of problems and solutions.

The lack of availabile data on developing countries was both a limiting factor and a reason that an opportunity for high-impact solutions is present. The availability of data in the English language, publicly available data (in any language), and the amount of public, private, and academic institutions publishing research in developing countries were all be limiting factors.

A final limitation was getting access to potential interviews. The nature of the research did not call for a questionnaire approach with a large number of target interviewees, but rather a small number of in-depth interviews with highly qualified industry professionals. It was challenging to obtain many interviews of such qualified people and thus also a limiting factor in the research. However, the three interviewees and the Thai company gave excellent feedback and details on the focus areas.

6.5 Future Research

The focus areas of this research involved growing cities, in developing countries, where existing infrastructure is limited but increasing, and where energy needs and overall consumption are due to rise. The research successfully identified a gap in current research effort, specifically the intersect of the distribution system and the built environment, or urbanisation, in developing countries. The research also displayed how the significance of this gap to global energy and the environment is material. The gap and its magnitude are indeed meaningful to academic research and knowledge; the development of a sustainable energy industry; and sustainable cities. A list of 32 recurring problems was revealed, summarised, and saved into a repository.

It is important to grasp that decision processes and planning for distribution systems, involve the construction and commissioning of major capital assets, which will serve people and consume resources over the years or decades to come. The key question, therefore, is not whose technology is best. This is a temporary issue and can pertain to point problems and opportunities (the best battery, the best inverter and so on), rather than to a city, which is an amalgamation of various technologies, hardware, and software. The key question is, therefore, whose design, which is an amalgamation of hardware, software, infrastructure, and other items, is best? Who makes structured decisions, rather than arbitrary ones, on large designs that do not have one single point of efficiency to quantify or measure? How does one eliminate subjectivity and bias from this? How does one ensure that an appropriately rounded set of guidelines are used to judge designs and award contracts? All infrastructure starts with a planning process, which involves different options on how to achieve the desired outcome. However, this process is inherently flawed by: (i) human subjectivity, (ii) the lack of an objective appraisal tool for a highly dynamic area such as distribution systems in developing countries, and (iii) is subject to impact by bribery and other political problems. A novel outcome of the research is an assessment tool, which groups and guides problems into solutions, directly addresses the notion of developing plans and judging the quality of plans, for large capital assets, and large infrastructure assets. Without such a tool, decisions are likely to remain largely subjective, with a correspondingly high impact due to their scale and lifespan.

The research then structured the 32 problems via an internationally recognised public sector organisation (The IEA), which together helps to address the inherent flaws in selecting options for infrastructure design. The IEA framework was further developed into the Excel-based tool, containing historically documented problems in the distribution planning process, expert views on the research gap, and an internationally recognised framework for organising power system modernisation. The creation of the tool and the process to group and organise the 32 problems into a solution development process was a successful outcome of the research. This provides a means to link documented problems into solutions applicable to live scenarios. There is an opportunity for academia to explore long-range planning processes by utilising such a framework – this can apply to various sectors such as transportation, healthcare, and others. This could give the research community a role in how funds for renewable energy, urban development, healthcare, education, and other such areas are prioritised. Academia and researchers acting as a non-public and non-private sector source of guidance for solution development could be of tremendous benefit to the complicated process of selecting designs for long-term infrastructure development across many industries. Planning and judging plans for long-life, capital-intensive assets that are a part of the built environment, is of major impact to growing urban centres, and is an area where the academic community can play a role through the research framework and similar structures.

In sum, the research was successful in displaying a gap in the focus areas, and it displayed that the gap is meaningful in magnitude and impact, and is worthy of further academic, public, and private sector research and emphasis. The gap was successfully articulated further into a detailed explanation of 32 commonly occurring items that occur in the focus areas of the gap, and a repository of studies showing these 32 issues. A tool was then made with a view of progressing documented problems into solutions, through a framework that is widely recognised and accepted in the energy and academic communities. The process was reviewed by expert interviews and by application to a live scenario, together with providing endorsement for the research outcomes and goals. An unintended and somewhat novel side-effect is that academia can use the same process – detail problems in the planning process, interview experts on their impact and importance, develop a tool to bridge problems into solutions – in other industries and other focus areas.

7. CONCLUSIONS

Various authors and researchers have debated the causes, effects, benefits and problems of urbanisation. Much of this literature looks back on this as a historical process; however, more than half of the world, particularly the developing world, is still rapidly urbanising. Consequently, methodologies for planning and meeting energy needs are of material impact to the 21st century and decades to come. How society makes investment decisions about large capital assets in these rapidly developing and rapidly urbanising countries, and the power systems therein, has a significant impact across the developing world and the environment.

The general context of this research has been the rapidly growing cities in the developing countries of Southeast Asia. These are places where infrastructure is increasing rapidly but from a low base, as well as where energy consumption is rising to new and permanently higher levels. This is driven by the complex interplay of changing demographics, lifestyles, and aspirations for the future. This rapid change is exposing shortcomings in existing research and knowledge. This is apparent in the growing need for effective planning at the intersect of energy distribution systems and the built environment. In particular, there is a need to bring objectivity into decision-making processes for major infrastructure investments. This gap is significant in terms of meeting changing global energy needs and addressing climate change. Addressing this challenge will require significant input from the research community. The new knowledge created by this research has the potential to stimulate a sustainable energy industry as well as delivering more sustainable cities.

It is important to stress how decision-making on energy infrastructure impacts the construction and commissioning of major capital assets, which will serve people and consume resources over years or decades. Understanding and making decisions on how to plan infrastructure and optimal systems are complicated. Finding an objective means of making these decisions is both urgent and challenging. This is complicated by the way that generation capacity and distribution systems are perceived differently in existing planning processes. Generation is often perceived as a ‘single asset’ to analyse and is often judged by single static metrics (e.g., CO_2 per unit of energy produced). Distribution systems, how they interact with the built environment and end users, and how this changes with time, are highly dynamic and lack a single static metric. Adding more renewable generation capacity may seem like an ‘obvious’ solution to meeting demand; however, reaching for this ‘obvious’ solution may often ignore significant opportunities in planning better distribution systems.

The key question is not – *whose technology is best?* In many respects, technology is a temporary issue that pertains to point problems and opportunities: i.e. the best battery, the best inverter, and so on. A city-wide distribution network is a system comprised of various technologies – hardware and software. What is more, its composition and its energy profile change over time. The key question is, therefore – *whose design is best?* Design is the process of combining hardware, software, infrastructure, and other items. How should one make structured decisions, rather than arbitrary ones, on large designs that do not have one single point of efficiency to quantify or measure? How does one eliminate subjectivity and bias from this? How does one ensure that an appropriately rounded set of guidelines are used to judge designs and award contracts? What historical studies and information and what internationally recognised structures can be used in this process, and what role can researchers and the academic community play in this process?

All infrastructure starts with a planning process, which involves different options on how to achieve the desired outcome of the infrastructure in focus. However, existing decision-making processes are flawed and appear to be subjective, open to bias and influence. This applies to various infrastructure – civil, social, energy, and others. A novel outcome of the research presented here is a tool that groups and guides problems into solutions, directly addresses the notion of developing plans, and judges the quality of plans for large capital assets and large infrastructure assets. This is important because flawed decision-making can have a high impact due to the scale and lifespan of the investments being made. The academic community has an important role to play helping improve such decision making, by developing appropriate assessment tools.

To date, the academic community has been a significant force in developing and supporting the implementation of both renewable energy generation and energy efficiency technologies. Going forward, there is an emerging opportunity for academia to play a greater role in long-range planning processes. Academia is well-placed to identify knowledge gaps in other industries and infrastructures, develop databases (on commonly occurring problems and missed opportunities), and create frameworks to take problems and opportunities through the process of solution development. There is a strong need for unbiased non-public and non-private sector, guidance, and solution development. This could be of tremendous benefit in the complicated process of selecting designs for long-term infrastructure development. Planning and judging plans for long-life, capital-intensive assets that are part of the built environment is of major impact to growing urban centres. This is an area where the academic community can play a significant role.

The research was successful in identifying a knowledge gap in the key focus areas. This gap is meaningful in magnitude and impact and is worthy of further academic, public, and private sector research and emphasis. A decision-making framework has been articulated which should be a platform for future academic research as well as delivering improved objectivity in real-world planning.

8. REFLECTION ON CHALLENGES, STRENGTHS AND WEAKNESSES OF THE PRESENTED WORK

The dissertation has been a challenging and interesting process. One challenge was starting with proving or finding evidence for lack of something – finding a way to display that distribution, versus generation, is underemphasised in planning. It was challenging to display this lack of emphasis, and it was at times challenging to find strong literary sources for the focus areas of the research.

While I have spent significant time designing and building projects in Asia, sub-Saharan Africa and the Middle East, the research brought further detail and perspective to the complexities of energy in developing countries. Every situation or case study has its own issues around governments, policies, subsidies, economics, socio-political issues, and other local-level issues. Isolating energy from these non-energy complexities can be difficult at times. It is also important to note that information on generation capacity is generally publicly available, but data on distribution systems in many cases are not. Finding granular data requires permission from the local utility, which can make research in this area difficult.

There were two human, politically-oriented issues that were encountered consistently. The first is in the conflict of electricity authorities generally agreeing that decentralised and distributed systems can be more resilient, accommodative to change, and positive for end-user participation. However, this brings the notion or threat of less power in the hands of the distribution authority. Distribution authorities for a variety of reasons do not favour a rapid shift towards multiple, end-user-oriented solutions, as they perceive this as diminishing their control over the network. A second issue was that while digital solutions to manage networks are now lower-cost and widely available from numerous vendors, selecting a technology or system is still difficult. The regulators and power companies who were encountered during this research were generally flooded with information, proposals, and propositions from a variety of technology companies. In some cases, they found decision making very difficult, despite lower prices and the wider availability of technology. In a sense, however, this could mean that we need more objective tools for making decisions and selecting solutions to implement.

I would have liked to have done more site visits and interviews during the research, as this adds interesting insights that are often not found in published research. I benefitted from this during my working career but was somewhat budget-constrained during my PhD research. I would have liked to spend more time in sub-Saharan Africa, which, according to research, will be home to many of the world's new megacities. I would have liked to spend more time in India, which is now developing a power ancillary services market against a grid which struggles with stability in many provinces, as it attempts to attract high-tech businesses with energy quality needs. Another issue would be to gain access to the load mapping and system balancing software that are now becoming available, and see them in a real application. I have researched these, but would like to see them applied to actual power systems to enhance my knowledge.

I have enjoyed this research and was delighted to find that many organisations are seeking to raise awareness of the focus areas; many are seeking solutions and believe that the outputs of this research and the tool developed are applicable and highly useful. I look forward to executing myself or participating in some way in the following future work on this topic:

1) Digitise the research, 32 distribution problems, case study repository, and Excel-based scorecard. I will explore options for how to do this and how to make it an open platform that others can contribute to.
2) I will attempt to work with the IMF, World Bank, or other financing entity to see if capital and operating expenses can be collected on software and hardware that are involved in the problems and solutions of this tool. If high-level estimates could be compiled into a database, the tool could be extended to have a basic cost-benefit analysis in the scoring and ranking system, and a means to prioritise the deployment of funds into grid modernisation projects.
3) I would like to work with the IEA or a similar body to develop an open-source tool and case study library for regulators to use in judging bids. Regulators award various contracts for developing and improving power systems, and the process of selecting the best configuration can be challenging. I would like to work with an internationally known body on making dynamic solution development and scoring systems to guide power system development in the future.

I do believe that I achieved what I set out to do, which was to make a system for NGOs, aid agencies, and similar, to improve distribution planning in developing countries. This can be in a USB drive with a summary of this study, the case studies on the distribution problems, and the Excel tool – a planner in an aid agency could work with this on a notebook computer while on assignment. This could be improved over time by digitising the tools and research database. I would like to make an app where users can add to the database of case studies and leverage and manipulate the Excel tool. I am hoping that after the completion of my PhD, I can find funding for digitising this research database and tool.

9. ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr Sandy Kerr, for his patience and guidance throughout my research. I would also like to thank Dr Wolf Fruh for his support and kindness.

I would like to thank the Thai power company and the interviewees who participated in this research. Their feedback and endorsement was a key component to making this applicable to the world and, hopefully, of impact on energy and the environment.

The long hours dedicated to this work were inspired by my wife, Mariapia, and our sons, Christian, Pasquale, and Emanuele.

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Appendix A

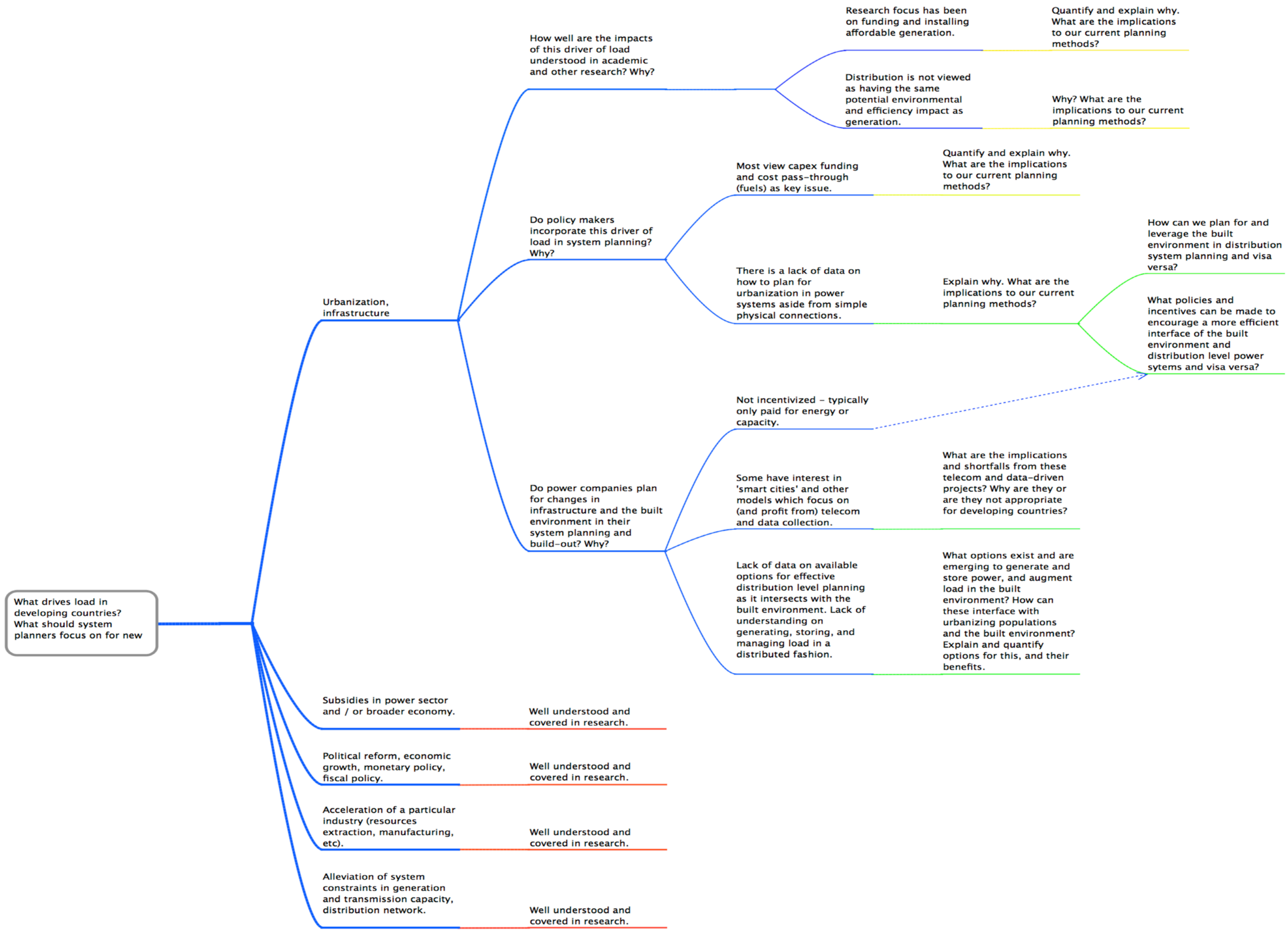

Figure A1. Examining drivers of load in developing countries.

Appendix B

School of Energy, Geoscience, Infrastructure and Society

Research Ethical Guidelines, Procedure and Form

In keeping with directives from the European Union and from the UK Government, universities are required to put in place ethics procedures and guidelines for research. In addition, research councils including EPSRC ask for formal ethics approval of proposals in some of their funded programmes.

Heriot-Watt University has a University Ethics Committee to guide schools, monitor procedures and ensure appropriate ethical issues are being considered. In addition, a small ethics sub-committee of the school's Research Committee has been formed to deal with ethical approval procedures for research undertaken in EGIS.

The University Ethics Committee has agreed an application form and procedure for considering ethical approval of research projects, and these have been adopted by PME for use in all Schools and Institutes.

This note outlines the context and general principles for ethical considerations in research, and provides the standard application form and protocol for ethics approval. The protocol will apply to all research in the school including research Masters and PhD work.

The form must be completed and returned to the Research & Knowledge Exchange Support Team egis-research-admin@hw.ac.uk. If the form is completed for PGR student research, it must be returned to egis-pgr-students@hw.ac.uk. If the form is completed for MSc/MRes student research, it must be returned to the Learning & Teaching team egis-pgt@hw.ac.uk. If you have any queries about the form or procedure please contact James Morgan (**james.morgan@hw.ac.uk**).

General Ethical Principles

- No field of human activity can be considered exempt from ethical concerns. Increased accountability has led to systems of research governance to ensure that research methods and information are open to public scrutiny and can be seen to be subject to the highest ethical standards.
- Research should conform to generally accepted moral and scientific principles. There are:

a) Obligations to society:- i.e. conforming with responsible, moral and legal practice; maintenance of high scientific standards and impartial assessment and dissemination of findings.

b) Obligations to funders and employers:- the relationship between researchers, funders, and employer should be clear and balanced without compromise to morality, the law or professional integrity.

c) Obligations to colleagues:- the maintenance of standards and appropriate professional behaviour with methods, procedures and findings open to review.

- Breaches of these principles include areas of research misconduct such as fabrication, falsification and plagiarism.
- The well being of all involved in research is of central concern in ethical considerations. All staff are therefore obliged to comply with health and safety guidelines and to carry out a risk assessment of the research whatever its nature (e.g. laboratory work, field work, testing subjects etc). Further advice and **documentation on risk assessment** can be found by following the hyperlink above.

Ethical principles for research involving human subjects

One major obligation of researchers which is not included in the above list is to the subjects who are involved in research. Social researchers must strive to protect subjects from undue harm arising as a consequence of their participation in research. This requires that subjects' participation should be voluntary, and as fully informed as possible. At the same time, no group should be disadvantaged by routinely being excluded from consideration. Subjects should also be aware of their entitlement to refuse to participate at any stage for whatever reason, and to withdraw data just supplied. Special considerations should be given to studies requiring informed consent from vulnerable participants. Such groups include children, those with an intellectual disability and those in a dependent relationship to the researcher or commissioning body (e.g. students in college or patients in a hospital).

a) For interviews / focus groups:

- All subjects to be fully informed of the nature of the research and to give informed consent prior to interview.
    - Subjects to be given a plain language statement of the nature and purpose of the research.
    - It is generally preferable not to identify individual subjects but, if the identification of subjects is necessary, subjects must be informed of this.
    - No interview should be recorded without the permission of the subject.
    - Interviews by telephone must meet the same conditions as face-to-face interviews.
    - Written parental consent is required for interviews with subjects under 18 (16 in Scotland), unless such interviews take place in the presence of a parent or guardian or in an institutional setting were the institutional consent has been given).

b) Questionnaires: All written questionnaires must have an opening statement informing the subject of the nature and purpose of the research. Completion of the forms shall indicate evidence of informed consent.

c) Observational methods: Where behaviour patterns are observed without the subjects' knowledge, researchers should take care not to infringe the privacy of an individual or group. Where practical, an attempt should be made to obtain consent post hoc. Cultural variations in what constitutes public and private space should be acknowledged.

d) Photography: of human subjects in publicly accessible spaces is a legitimate research tool. However; if prejudicial to the subjects' interests or reputation, identifying features of the subject must be obscured.

e) Experimental or field testing of subjects: Ethical requirements for this situation are the same as for those applying to subject interviews.

More detailed reference documents are available which provide useful further guidance on these issues, notably, the Social Research Association's *Ethical Guidelines* (**http://www.the-sra.org.uk/documents/pdfs/ethics03.pdf**).

Ethical considerations include taking into account issues related to personal data collection, use and management. This is regulated by the Data Protection Act. The Act states that anyone who processes personal information must comply with eight principles, which make sure that personal information is:

- Fairly and lawfully processed
- Processed for limited purposes
- Adequate, relevant and not excessive
- Accurate and up to date
- Not kept for longer than is necessary
- Processed in line with your rights
- Secure
- Not transferred to other countries without adequate protection

Guidance on the Data Protection Act can be found at **http://www.ico.gov.uk/Home/for_organisations/data_protection_guide.aspx**

Heriot-Watt University Code of Practice governing recruitment of research participants
All research that seeks to recruit research participants through printed material or electronic communication, either within the University or outside it, must meet the requirements of this Code. All applications for ethical approval made to School/Institute Ethics Committees must confirm that this Code will be followed when participants are recruited. The EGIS application form for ethical approval contains a question that allows such confirmation.

The Heriot-Watt University Code of Practice governing recruitment of research participants can be found by following the hyperlink above.

Protocol for consideration of ethical issues in EGIS research

1. For **all** research projects in the School undertaken by staff and/or postgraduate research students the **staff member responsible for the research (PI or research supervisor)** needs to complete and sign the ethics approval form. **For postgraduate research, the student undertaking the research also needs to sign the form**.
2. For research in taught postgraduate and undergraduate courses the supervisor is responsible for determining whether there are any ethical concerns which warrant completion of the form and for completing the form should that be the case. Both the supervisor and the student need to sign the form.
3. The completed form must be submitted to the Research Administrator (or PG Research Assistant in the case of postgraduate student research) before the research goes ahead. If the project requires completion of an RPC form, the ethics form must be completed at the time of completing the RPC form.
4. **All** forms must have questions 1 to 7 completed and be signed. If the research does not involve human participants or living animals in any way no further parts need to be completed.
5. If the research **does** involve human participants or living animals in any way, then Sections B & C, which ask questions regarding ethical procedures and considerations, need to be completed.
6. If Sections B & C **do not** raise ethical concerns, Section D is **not** to be completed. The form is then submitted to the Research Administrator, who will then refer it to the Chair of the Ethics Subcommittee for noting and approval.
7. If Sections B or C **do** raise any ethical concerns, then Section D must be completed. The form is then submitted to the Research Administrator, who will refer it to the Chair of the Ethics Subcommittee. The Chair will submit the proposal to the full EGIS Ethics Sub-committee for consideration and approval. If there is any doubt from even one member of the sub-committee about a particular research proposal, this will be referred to the appropriate external body (Animals (Scientific Procedures) Committee, Lothian Region Ethics Committee or the University Ethics Committee) for further scrutiny and a final decision. In some cases the member of staff responsible for the research may also wish to suggest up to two staff members with appropriate expertise to review the submission and report to the EGIS Ethics Sub-committee if they think this is appropriate and helpful. Such suggestions may be made using section E.

Type of approval

- **In Principle** applies when the project design does not have full details of the methodology. An In Principle application should specify when Full approval would be sought.

- **Full** applies when the project design includes full details of the methodology.

- **Resubmission** applies when ethical approval has not been granted in a previous application, or when there have been sufficient changes in a project to warrant a new ethical approval application.

Postgraduate research students will normally be expected to apply for **In Principle** approval when they start their PG research, and for **Full** approval at the time of their First Year Report, when they are expected to have a fully defined research methodology.

HERIOT-WATT UNIVERSITY

APPLICATION TO SCHOOL ETHICS COMMITTEE FOR ETHICAL APPROVAL FOR A RESEARCH PROJECT

Click on the grey boxes to insert text

Section A: Project Overview

1. Project Title: **Improving the Intersect of the Power Distribution System and the Built Environment in Developing Countries**

2. Approval sought: Full approval ☒ Re-Submission ☐ In principle ☐
If 'In principle', when will full approval be sought?

Contact Information

3. Responsible Staff Member / Supervisor of student research:

a) Name: Sandy Kerr...

b) Telephone...

c) Email: s.kerr@hw.ac.uk ....

4. Investigator (if different from Responsible Staff Member) / Student:

a) Name ....

b) Telephone...

c) Email ....

5. Duration of Proposed Project: March 12 2018 – August 15 2018. (5 months)

6. Anticipated Start Date: March 12 2018 ....

7. Does the proposed research involve human participants or living animals in any way? Yes ☒ No ☐

Note: Involvement of human participants includes obtaining information from people through methods such as experiments, observation, surveys or interview, or any use of previously obtained personal data, or any use of human tissue samples.

If your answer to Question 7 is 'yes' complete the rest of the form; if it is 'no', simply sign the declaration in section F at the end of the form.

8. Please provide a brief summary of the proposed study (if possible, in less than 300 words. Include an overview of the design, variables, and other ethically-pertinent considerations). Feel free to attach a document if convenient.

My research focuses on power distribution in developing countries that are undergoing urbanization. I have a list of commonly found problems in these areas, and a series of score cards to rank and measure these problems. The interviews I would like to conduct are with 3 professionals with long experience in these areas. I would like to ask their feedback on the problem list and scoring methodology, and ask how they have found solutions for these issues in their previous and current work. The interviews will be conducted via email and phone.

Section B: Administration

		Yes	No
1.	Will participants be appropriately informed of: the aims of the study; their ethical rights; their expected contribution; and their subsequent debrief? For example, their right to withdraw, any deception employed or potential consequences of the study.	☒	☐
2.	Will consent be obtained from all appropriate parties?	☒	☐
3.	Will the Heriot-Watt University Code of Practice governing recruitment of research participants be followed? (Code of Practice available at Code of Practice governing recruitment of research participants)	☒	☐

Section C: Ethical Considerations

		Yes	No
1.	Will the study require participants to potentially experience stressful or unpleasant situations?	☐	☒
2.	Will the data collection and management (storage & disposal) potentially compromise the interests of the participants? For example, body fluids, tissue samples or other personally identifiable materials, such as, visual, auditory or other data?	☐	☒
3.	Will payment or non-payment of participants have potentially negative implications in the study?	☐	☒
4.	Are there potential negative outcomes from the study for the participant? For example, compromise to or damage of, their physical, psychological, financial or social wellbeing.	☐	☒
5.	Are there any other potential negative outcomes from the study? For example, damage to property or risk of criminal or civil liability.	☐	☒
6.	Would you identify any other issues that may have potential ethical implications for your study?	☐	☒

If you responded 'No' to any questions in section B, or 'Yes' to any questions in section C, please now complete section D & E. Otherwise, proceed to section F.

Section D: Further Information Regarding Ethical Considerations

If you responded ’No’ to any questions in section B, or ‘Yes’ to any questions in Section C, please provide further information, indicating how you would address this issue. Please be as comprehensive as possible, as this will speed the process for the referees and may avoid the need to contact you for further information or clarification.

Section E: Potential Referees

If you have completed Section D, this form and any appended information will be reviewed by the full EGIS Ethics Sub-committee. In addition, if you think it may be helpful for the review, you can suggest up to two staff members with appropriate expertise to review the submission.

1. Name .... Contact ....

2. Name .... Contact ....

Section F: DECLARATION

The information in this form is accurate to the best of my knowledge

Signature of Responsible Staff Member (PI or research supervisor)

Date15 March 2018

Signature of Student (if applicable) ....

Date: March 8 2018 ....

Once completed this form should be returned to the Research & Knowledge Exchange Team egis-research-admin@hw.ac.uk. If the form is completed for PGR student research, it must be returned to egis-pgr-students@hw.ac.uk. If the form is completed for MSc/MRes student research, it must be returned to the Learning & Teaching Team egis-pgt@hw.ac.uk.

APPROVAL OF SECTIONS A.8, B, C & D (if completed)
I am satisfied that the researcher has properly considered the ethical implications of the intended study and has taken the appropriate action.

(Chair of EGIS Ethics Sub-committee or delegated representative) ....

Date................................

FINAL APPROVAL
I am satisfied that the researcher has properly considered the ethical implications of the intended study and has taken the appropriate action.

(Head of School / Director of Research)..

Date................................

Appendix C

Interview with Expert Interviewee 1: Managing Director of power delivery for a US engineering firm. He is an Indian national now based in the US, with much of his work focused on sub-Saharan Africa and developing Asia.

Did you receive the ethics guidelines for the Heriot-Watt University that were e-mailed to you?
Yes.

The purpose of this research is to identify problems seen in 1) <u>power distribution planning</u> in 2) <u>developing countries</u> that are 3) <u>urbanising.</u> These three elements together are the focus areas of the research. Are you clear on the research topic and comfortable with participating in this interview?
Yes.

Did you receive by e-mail the Word document describing common problems and missed opportunities in the focus areas, as well as the Excel document to rank and quantify these problems?
Yes.

Do you believe that the attached Word document adequately covers key problems in the focus areas? If not, what problems were missed?
Yes, the list covers key areas, and these problems receive less attention generation. This is an under-represented area in power planning and one where many potential synergies are lost.

Can you share examples of problems or missed opportunities in distribution planning in developing countries?
I am working on a project in West Africa right now where there is actually excess generation capacity, with some units sitting idle in a developing country with some homes still not electrified. The regulators financed a large-scale generation project and did not do sufficient studies into distribution planning, and they now have a situation where some homes and commercial entities are underserved in power due to lack of or poor connection to the distribution system, yet generation capacity is underutilised. The generation plant is also somewhat oversized as their customer mapping and studies were done poorly. So you have underutilised generation and an oversized unit, and unmet demand at the same time because the planning emphasis was overwhelmingly on the generation side and network planning was minimal. Now the regulator is looking to either attract industrials to locate in or around that city or will look to electrify nearby villages to absorb generation capacity. This is suboptimal, to say the least.

What problems have you seen in the planning, development, and operation of distribution systems that could be improved?

Large generation projects will get big bank funding and will often be managed by a national level, empowered person, or team. Distribution planning and operations are usually the opposite – they are left to local authorities that are typically less equipped and have less funding. They have less access to technology, people, and funding in the planning process and typically struggle. They also often know in the planning phases that their ability to recover capital through the rate base will be limited – most of this will go to generation capital recovery and to fuel or operating expense recovery. They often know ahead of time that power delivery and distribution networks are not something people want to pay for, and governments making decisions around power prices are concerned with election cycles, job creation, and generally want cheap energy. Unfortunately, from planning through operations, power distribution is underfunded and not well-planned. This can result in lack of metering, not managing theft, safety issues, unmet needs, severely under- or overutilised equipment, and a regular flow of unnecessary construction around fixing, updating, or adapting the network that was previously installed.

Items 2 and 5 in the word document that you were sent cover voltage regulation and reactive power at key load points. What are your views on the criticality of this?

The question you are asking is essentially one about a village or a small town versus a developing city, and where we draw this line. I would say that in a village, town, or small but rapidly developing city, the key issue is to simply connect end users to power. Planning the network, putting in distribution lines as the city grows, installing meters, ensuring that power is delivered safely to end users is the first priority. In these smaller load centres, simply focus on safe power connections to end users and metering – voltage can vary by 5%, and it will not be critical to the typical end users at this phase. I would say that voltage regulation, reactive power, and power factor correction are issues to tackle when a city is more developed, and the load is more complicated. This is an issue when you have more developed commercial and residential real estate, and industrial entities – this does exist in developing countries, but only after cities and their economies have developed to a certain level. Big cities like Jakarta do need reactive power at load points and voltage support in the centre of the city and on the edges of the grid. But go outside of Jakarta to a place which is a large town developing into a small city, and I would classify safe power connections and metering as critical, and voltage support as something that can be done at a later phase.

What problems or missed opportunities have you seen in distribution planning and customer mapping?

Developed countries have good geographic information system (GIS) mapping for distribution networks, gas networks, and utilities in general. These provide a major advantage in planning *systems, forecasting load, etc. The trend is spreading – I am working on a project in Kenya at the moment on this. Funding is not so much the constraint here. For the project in Nairobi, it will be in the single-digit million American dollars for the initial GIS system and distribution network planning. After this, the annual upkeep and continued forecasting are likely $1–2 million per year. Spread over the residents of Nairobi over several years of utilities billing and recovery, and being able to use this system in other cities in Kenya, the impact to the end user is really nil. The issue is that its seen as secondary to other more important things in the power system like generation for the grid and then substations and supporting for large infrastructure like ports. These are important but in reality, GIS-based distribution planning is now quite standardised and low-cost, it is software- not hardware-intensive, and it potentially saves a tremendous amount in terms of fixing improper distribution systems, managing disruptions and system failures, and enabling residential electrification.*

One interesting issue that I wanted to mention, as much of my work right now is in sub-Saharan Africa, is around China's Belt and Road program. This is a shift in paradigm in terms of distribution planning in urbanising areas. Essentially 'China Incorporated' is building entire cities – housing, commercial real estate, train lines, factories, and the power backbone to all of this – in developing parts of Africa. I do not know the socioeconomic or political implications of this, but when the same large body that builds the city also builds the power infrastructure, there can be some optimisation taking place. I am not sure that this is their focus in these projects, but in building the city and the city's power infrastructure under one entity, we can potentially have power systems installed in alignment with the city's physical infrastructure, rather than the typical situation of the distribution utility trying to catch-up with a sprawling city. Whether or not this is actually happening remains to be seen, but it is an area of potential coordination in the focus areas of your research.

What problems or missed opportunities have you seen in demand response (DR) and demand-side management (DSM)?

I have worked on projects in South Africa where there is a power pool in places that allows for DR amongst big industrials. Basically, Eskom, the South Africa power utility, can request and provide incentives to industrial entities for delaying power consumption typically during very hot weather times or when there are system failures. Again, this depends on the level of development in the city or country you are talking about. DSM or DR at the retail level for individual homes is not effective in developing countries. You would have a lot of infrastructure in place at the individual residential level for homes that do not consume that much power as compared to the US or Europe. You would have a lot of equipment and systems that cannot actually augment that much load. You would need clusters of industrials or large commercial real estate like shopping malls. So in the markets I work in sub-Saharan Africa, these opportunities are present in South Africa, Nigeria, and to some extent Kenya, but in less *developed places like Mozambique and Uganda where there are not enough large clusters of load for effective DSM and DR.*

What is your view on item 25 in the attached Word document and the problem of using microgrids to support the development of distribution systems?
Again this brings up the issue of what phase of development is the city or town in, and what are we classifying as mission critical to the power system. Microgrids have three key benefits for developing countries:

1) *Microgrids are good for resiliency and critical loads. If you have an industrial who perhaps could hire a large amount of people and needs a stable power supply that the local grid cannot provide, this could be addressed by microgridding their property. This also applies to critical loads like hospitals and airports. But if a country or city is less developed, your only critical load might be a hospital. You do not need a microgrid for just a hospital – this is too fancy of a solution where a simple back-up diesel generator would do.*
2) *If you have towns or satellite cities around a main city, and sending power to these satellite locations from a centralised facility incurs a lot of technical losses, then you can microgrid these areas and save on system losses and building transmission and distribution lines.*
3) *As urbanisation continues and continues in big cities like Jakarta, you can take the sprawling edges of the city and microgrid these growing districts. You might find this easier than having crews do tunnelling and cabling in a crowded city, obtaining permits and right-of-way, and other issues around installing new distribution lines in a big city like Jakarta. You might be better off designating the edges of the city sprawl into microgrids and managing the extension of the main Jakarta grid by microgridding the edges of the Jakarta grid.*

So essentially mission number 1 is to safely connect the population to power, ensure meters are in place, and ensure generation capacity is matching your load studies and customer maps. After this, microgrids are either not needed versus a backup generator if the area is not very developed, or they can be useful for grid extension in city sprawls or supporting the development of industrials that need power quality. So it is not a one-size-fits-all solution, the use case needs to be analysed.

Thank you for your time. Are you able to participate in additional research?
Yes.

Appendix D

Interview with Expert Interviewee 2: Director of power systems for a global-scale energy company. He is a US national based in Saudi Arabia, with a background in Middle East power projects.

Did you receive the ethics guidelines for the Heriot-Watt University that were e-mailed to you?
Yes.

The purpose of this research is to identify problems seen in 1) power distribution planning in 2) developing countries that are 3) urbanising. These three elements together are the theme I am pursuing. Are you clear on the research topic and comfortable with participating in this interview?
Yes.

Do you believe that the attached Word document adequately covers key problems in the focus areas? If not, what problems were missed?
The list is comprehensive. Unfortunately, it is not popular in power companies and in governments to propose a series of distribution-oriented solutions versus one or a few large generation or clean generation solutions. This leaves many developing countries with many lost opportunities as cities and load centres develop.

Can you describe key challenges in power distribution in developing countries?
The first issue is simply economics. Developing countries need to deliver power to people with low incomes, who will be sensitive to changes in power prices over time. The generation component usually involves a large state-sponsored financing package and gets the most attention and emphasis. But, it is important to note that after this comes what is really the larger challenge: planning and building the distribution network. This involves delivering power to people, network planning, dealing with remote areas or edges of cities where voltage control can be difficult. In many cases, as these cities are developing and are fed by a single unit or small generation fleet, the real cost of delivered power to someone at the edge of the grid can be quite costly. So economics is the first major issue, generation usually has the most focus within this but is actually not the most complicated issue. Other important issues pertain to how developed the power system is, is there redundancy, is it a linear system or a network, and how rapidly is the load centre growing.

Often times people in poor countries can from their income pay for the generation portion of power, but the distribution of power, especially to edges of the grid or remote towns and small *cities, is not something that they can pay for. Countries like the United States had specific programs around rural electrification which involved funding distribution networks.*

Can you describe more how distribution can be handled effectively?

There have been major cost declines and efficiency improvements in small- to mid-scale renewable energy generation, power storage, and microgrids. Microgrids are basically packaged sets of on-site or localised power generation, sometimes storage, and distribution to loads. These are not at the large, centralised scale, but at the local scale for campuses, clusters of apartment blocks, edges of cities, or small and growing cities. These are usually built around solar PV, small- to medium-sized wind and/or biomass feedstock for combined heat and power facilities functioning as core generation. They typically then have a storage component if needed or if affordable, usually a lithium-ion battery, some kind of hydrocarbon – typically a diesel generator for back-up or secondary power, and then a send-out or small distribution system. Some key issues around this are that the operating costs are reduced with having a large renewable energy component, there is no transmission, and the distribution system is shorter and localised.

This plays into a bigger picture issue that the global power sector is facing: We have to move away from thinking only about big centralised facilities. It is much more effective to break large power grids down into smaller decentralised parts. This can be distributed generation, microgrids, and other arrangements. This removes transmission altogether in some cases, reduces distribution costs by managing power connections and power quality and voltage management locally, and uses renewable energy and small- to mid-scale generation, which is increasingly cost-competitive.

What are the key problems to power companies and regulators embracing this change?

Power companies have to start thinking of modular designs – not ones which are hinged on justifying large generation and large centralised facilities, but smaller grids with an ability to scale-up and which can leverage cost declines in renewable power generation and microgrids. Both power companies and regulators need better decision-making processes. Single large generation projects, followed by simple linear transmission and distribution networks, are inefficient but have very focused decision making and require fewer decision makers. As soon as you go into microgrids, modular designs, distributed generation, and local distribution networks, you have multiple assets rather than one or a few larger ones. This requires delegating power and responsibility to more people. In many cases, regulators are not comfortable with this, and power companies do not have the depth of management and teamwork to run power systems that are amalgamations of multiple small units. So very key to making cities more efficient is not looking at them as cities, but as collections or clusters of load that might be better served by localised solutions. But this requires a big shift in behaviour for power companies and regulators, and also in how we finance these efforts.

Please note the problems in the attached Word document which highlight demand-side management (DSM) and demand response (DR). Have you been able to utilise this in managing power systems?
Yes and no. SCADA is not available on all industrial facilities – many simply run without SCADA, so we have no way of seeing what is going on inside the industrial facility and no way of communicating with the operators. So in many cases, real-time data is not something we are working with in developing countries. SCADA system in industrials is critical as it helps us to understand larger loads.

Metering is improving, but in the past, it has been an issue. Either meters are often times not present in developing countries at every point of consumption, or they are present but are in the wrong places in the network to obtain useful information. Metering overall in developing countries is being improved and is helping us locate where and how we can address distribution issues. We are in the process of checking large industrials, and large commercial and residential complexes to ensure they have up-to-date meters. We have been able to work with a few industrials who have more advanced metering systems on time-of-use (TOU) pricing where from analysing meter and other data, we provide pricing packages which encourage the industrial to run certain processes at certain times of the day.

What other problems in the attached Word document are in your mind most critical?
You show here cross-subsidising – this takes place in every developing country I have worked in. Typically, industry is charged more to subsidise residential. This simply does not work, and subsidising power does not encourage people to use power efficiently. It also can result in parts of the power system under-recovering capital.

On DSM, DR, and metering, we have worked with the local government to require that all new power connections need to be checked for appropriate metering equipment – now you cannot get power connected until we have confirmed you have a working meter and it is feeding us the information we need. We have also worked with the government on requiring that all new power connections for loads over a certain amount have advanced meters in place, which allow us to do TOU pricing and an ability to work with the tenant on DSM. So new shopping malls that are being developed and will feature high air con loads are in direct contact with us on their power use from day one. This makes a huge difference in managing their load, voltage control and power factor correction, and the distribution network around them.

Thank you for your time. Are you able to participate in additional research?
Yes. Thanks.

Appendix E

Interview with Expert Interviewee 3: Director, electrical engineer in a major distribution company in Asia. He has worked on distributing power through Manila and the greater Philippines.

Did you receive the ethics guidelines for the Heriot-Watt University that were e-mailed to you?
Yes.

The purpose of this research is to identify problems seen in 1) power distribution planning in 2) developing countries that are 3) urbanising. These three elements together are the theme I am pursuing. Are you clear on the research topic and comfortable with participating in this interview?
Yes.

Do you believe that the attached Word document adequately covers key problems in the focus areas? If not, what problems were missed?
The list covers the issues that we have been working with over the years and is comprehensive, although I would point out that the relative importance of the issues varies with time and level of development of the distribution system. Sometimes we and other similar distribution companies are very focused on metering or theft, or trying to get the government to promulgate rules that make the real estate sector work more closely with us. But yes, it covers the critical areas that we have formally and informally focused our efforts on.

Can you describe the key challenges in power distribution in developing countries?
A critical issue is that we are seen as an afterthought to raising the money for a generation project, which is viewed as feeding the masses the energy that they need. We are viewed as simply standard sets of send-out lines, very static and non-dynamic, no options around optimisation, and simply delivering what the big generation project has accomplished. In some ways this is valid – getting an export credit agency or a large bank to finance a big power station and then oversee the multi-year engineering, procurement, and construction process is a complex undertaking. Running the plant well is also a major undertaking. But overemphasis on this in operational importance and economic importance leaves power distribution ill-equipped to seize efficiencies, communicate with end users, and make the downstream portion of the power system efficient. Over the years I have been working in this industry, we have generally not had adequate resources or support to pursue real efficiency gains in distribution, and, I would add, customer interface.

Another issue is around the 'rate base'. This is the pool of expenses for power distribution that we incur, both capital and operating expenses, that get spread on a unit basis over the power consumed in the Philippines. It is basically a large cost pool that everyone shares in their power bills. Number one, the process of applying for things to be included in the rate base is very difficult. If I have a technology or tool of some kind which can improve system efficiency, and I would like to deploy it through our network, it is a very complicated process to include the expenditure for this in the rate base, even when the impact, spread over the full population, is minimal. The rate base and the process of adding things to it is also very highly correlated to the political cycle – do not expect to get any expenditures approved unless absolutely mission- critical – in an election year.

So one issue is the amount of cash being put in the rate base, and another issue is the contents of the rate base in terms of products and services. Trying to propose the inclusion of new inverters, new software, new voltage control equipment, is just simply met with scepticism and the question of 'Why are you not using what was approved in the last capital budgeting cycle?'

I would say that at low cost, we could be working with a whole lot more data. Property companies, government bureaus, infrastructure builders – no one has to tell us what they intend to build or do. They simply tell us where they will be building capacity and what they expect from us in terms of a power connection, typically when that capacity is already permitted. We could be working with more metered data, simple software to map urbanisation, load growth, and other issues. Our asset management went from paper to Excel in the mid-2000s, and we now in 2018 moving from Excel to a dedicated asset management software. We are easily ten years behind developed countries and not for lack of budget, but for lack of budget allocation to what we are doing.

Can you describe more how distribution can be handled effectively?

There are several points around planning. One issue is simply customer registering with us their projected and actual loads. Commercial and industrial entities are slowly being required to do this, but this is in early phases. Shopping malls, hotels, office towers, train stations and other major power consumers are only just starting to be required to share more granular information with us, register with us before their projects are developed, and overall work with us. Without this sharing of data, whether it is via advanced meters at their premises or whether is via communicating what activities are taking place on-site, we are trying to manage or networks sections of nodes in a highly reactive fashion. There could be more required sharing of data, and more SCADA and other interfaces to manage this.

Also around planning, if you look at Metro Manila, it has expanded in every direction, and we have essentially played catch-up. Satellite, GIS, and other data can help in knowing where demand will be and mapping the best ways to meet that demand. Better means to obtain, *analyse, and utilise data can help us in both planning new assets and maintaining existing assets, both of which have a major cost and energy implication.*

Our execution methodology has several of the issues mentioned in your document. We utilise linear distribution planning systems until a threshold has been exceeded, at which point we determine the place to be a city or dense-enough load centre to shift to network or mesh planning. This threshold is too high – we lose synergies and have system failures, crowded lines, and technical losses from over-utilising linear planning.

We are late in starting to utilise microgrids in grid extension and reliability assurance. As cities grow, microgridding a growing part of the network can save significant money versus adding onto crowded nodes of lines and networks. We have started to microgrid critical loads like hospitals but are also using them to handle the power needs of growing parts of the edge of a city, and later to incorporate it into the greater metro grid. Microgrids are an effective tool that we are just starting to utilise – we could adopt this faster and in more instances.

On the issue of the rate base, we do not have a means for allowing new competitive distribution technologies to take part in the system. Our rate base system does not allow us to open problems or opportunities to vendors who might be able to solve problems with new solutions – it is focused on justifying why we should use existing solutions now rather than later in time. Many new technologies can solve distribution problems at competitive prices, but we do not have a system of approving new costs that allows new ideas to come into operations.

Please note the problems in the attached Word document that highlight demand-side management (DSM) and demand response (DR). Have you been able to utilise this in managing power systems?

We lack platforms for reaching out to customers and are just now developing these. We utilise pre-paid power purchase programs, which allow people to buy power for the next month for their home or their workplace, which then come with some information on usage incentives. This is slowly helping us to communicate the value of shifting or reducing demand, but we lack an effective means to communicate with key stakeholders and individual consumers. We are developing this now, but DR and DSM are key areas we are trying to develop. We have already quantified the benefits of DR and DSM versus new generation and system upgrades and are trying to roll out effective programs for these.

What other problems in the attached Word document are in your mind most critical?

The removal of cross-subsidy thinking from regulators' mindset is crucial. The view is funding generation and hopefully having distribution break even and provide a non-dynamic service. This has put distribution entities on the verge of bankruptcy or significant technical losses that can be avoided. Advanced metering, data management, and digitisation of operations are *areas that we and other countries need to focus on in distribution planning. Again, we are taking these on, but are in early phases of planning and executing this.*

Thank you for your time. Are you able to participate in additional research?
Yes. Thanks.

Appendix F

Interview with the Thai Power Company

Did you receive the ethics guidelines for the Heriot-Watt University that were e-mailed to you?
Yes.

The purpose of this research is to identify problems seen in 1) power distribution planning in 2) developing countries that are 3) urbanising. These three elements together are the focus areas of the research. Are you clear on the research topic and comfortable with participating in this interview?
Yes.

Did you receive by e-mail the Word document describing common problems and missed opportunities in the focus areas, as well as the Excel document to rank and quantify these problems?
Yes.

Do you believe that the attached Word document adequately covers key problems in the focus areas? If not, what problems were missed?
I think you have covered the key areas. I reviewed this, and I think you have shown what goes wrong and where we can seek opportunities.

Of all of the issues in that document, the two that are perhaps highest potential for me are planning with infrastructure, real estate and other large load entities, and utilising microgrids, which follows the trend of breaking down generation and distribution into smaller components and linking them digitally – this is the direction that the power industry is going. These two are areas that I think can unlock significant efficiencies.

Can you share examples of problems or missed opportunities in distribution planning in Thailand or neighbouring countries?
The first is that we are constantly dealing with an underfunded distribution system – here in Thailand, Cambodia, Laos, Vietnam, and any of our neighbours. Distribution is seen as mechanical delivery of generation, which is viewed as big capital and highly complex. In reality, this is not the case – the whole system is complex, and our planning efforts and investment should not be so centred around generation. We lose lots of efficiencies past transmission in megacities like Bangkok, which are constantly growing. Big names like IFC and Asian Development Bank are involved in financing for big generation units, and when

these are commissioned, we are relieved that the capital and equipment got in place, and many feel like the job is done there. In reality, we are not taking stock of losses through our distribution system – technical losses, theft, and simple efficiency solutions that would be found if we had load- studying tools. So, distribution, I would say, is under-emphasised and underfunded, which leaves us solving problems after they occur, rather than proactively creating efficiencies.

Urbanisation can be very rapid – look at Bangkok, Yangon, and Phnom Penh. These have always been urban areas, but really in the 1970s onward they steadily expanded in population and in power demand. Governments always stress job creation for people in these cities, which is positive, but that immediately creates power demand from their employment and also from increases to wealth as they buy appliances and improve standards of living. So, not only does power demand increase rapidly in these urban areas, but so does the slope of the load curve.

Another issue is that we are basically told to distribute power into buildings and infrastructure during some phase of their construction. We have minimal or no consultation at all during their planning phases. A big missed opportunity is in working with urban planners and real estate companies on infrastructure before it is built. If we were involved in the short-, medium-, and long-term planning of cities, we could make a major difference.

We also don't have many means to interact directly with end users. Commercial and industrial entities are not really encouraged or required to tell us about their load, when they operate, what kinds of systems they have in place – like heating, cooling, water, and other types of demand. We have some incentives for them that we try to create, but these are limited in impact. If there was a mandate on communicating consumption, or funding for some type of tool to know how and when major commercial and industrial entities use power and optimise this usage with them, we could see a lot of savings in terms of system balancing and voltage control.

What problems have you seen in the planning, development, and operation of distribution systems that could be improved?

A question that always comes up is maintain and expand existing infrastructure, replace parts of existing infrastructure, or do a comprehensive overhaul. It is a very difficult decision-making process and involves capital expenditure, all or some of which is covered through some amount of rate increase and/or subsidies. One of the reasons I liked your Excel tool is that it has scoring system before making any vendor or cash decisions – it simply looks at what is strategically and technically best for the system based on historical issues and adjusted to local conditions. What size of commitment we make to distribution planning, and how we layer-in investments in improvements over time are important and difficult to plan.

An issue in operating distribution systems is communication with the consumer – what are you doing with your energy, can you delay or augment it, can you participate in markets. This is now being enabled by smart devices and even at the simplest level via smartphones. Google's

Nest home control system is very interesting, although I think we need an adaptation of this for large commercial and industrial entities. Two-way information sharing, them telling us what energy they need and when, and us communicating back options and prices and other information would be a major improvement. Operating power systems will definitely be improved as smart devices allow us to communicate with end users.

Breaking the larger grid into smaller grids or microgrids, and automating these functions is also a key tool that spans planning, development, and operating of power systems. It breaks down planning and capital, supply and demand of energy, and how we operate those systems into smaller pieces. Many system operators and regulators are worried about losing control if the system decentralises too much and more participants are actively involved in energy, but this is inevitable, and, frankly, benefits us all. So I would say microgrids and any other solutions that facilitate the decentralisation and digitisation of power systems and end-user participation are key.

I would now like to review the overall methodology taken for this research and for creating the Excel tool. Do you believe that the Excel tool is easy to operate, has sound logic, and produces useful outputs?

I think that the methodology is very thorough. I think that having a list of 32 issues at first appears like a lot, but when you read it, it opens the reader up to thinking about the broad range of issues we face. Having case studies for these issues helps add colour and proof to these issues. On the Excel tool, if the reader first reads the list of issues and case studies, then populates the scorecards before moving to solution development, it really makes for a very objective end-to- end methodology. This is better than going to solutions first and looking for justification second. I think that the historical references plus the IEA framework are a solid approach to developing and objectively displaying what is the best solution or way forward.

I think the scorecard functions well, and I like the fact that the user gets rewarded by the multiplier when their solution for Category 1 involves benefits for Categories 2, 3, and 4. This is actually quite important. Too many engineers only resolve the problem right in front of them and are not incentivised to look at what they are doing as a platform or enabler for resolving other issues. Rewarding this bigger picture thinking is a very useful component of the tool.

Do you believe that the combination of the research and Excel tool is a clear and coherent approach? Can it help you and your company develop solutions? How can it be improved?

I would consider two things. One, digitise it, make it open source and available for others to add case studies and experiences to. Two, involve it in project-bidding processes so that regulators and power companies can more transparently promote and implement solutions.

Can you comment on the methodology used, including the research, Excel tool and site visits, to developing solutions for the EEC area?

It is essentially a funnel approach, starting with historical research and narrowing down to scored solutions. It is very organised and, in a sense, defendable when you are showing government bodies why you have come to your conclusions. I think the fact that you did site visits to understand the local area was very useful.

Again, I would consider making this an open source app so that people can add case studies and experiences to the data set, and promote the use of it in bidding processes and decision making.

Can you comment on solutions 1–4? How applicable are they? How can they be improved?

The first solution faces the fact that the industry is decentralising. I think this solution embraces that and sets a clear path for opening the market. It will require coordinating DER with the existing infrastructure, but this can be done electronically. Overall, this solution represents a critical first step to embracing nimbler, decentralised facilities that are efficient and have end-user participation. Also, storage coupled with DER is a critical reality we have to face if we are really committed to increasing renewable energy in the power mix.

For the second solution, I am a major proponent of microgrids. This is the highest potential means of building out grid infrastructure efficiently, especially in rapidly growing urban and industrial centres. This could potentially serve as the backbone to the EEC power infrastructure.

Your third solution then enables individual microgrids to function as one grid or as a coordinated series of dispersed grids. This solution also then brings in a platform for digitising a number of energy functions and for communicating with devices and end users. Digitising the system and various loads is really critical. Also, these digital solutions are becoming more affordable and more widely available, not just from speciality manufacturers and speciality system integrators. I think authorities, including EGAT, are increasingly comfortable with remote management systems.

The fourth solution is interesting but requires careful planning. CCHP is highly efficient, and in a climate like Thailand with high air conditioning load it is significantly better than smaller cooing units. Sizing this capacity for current needs and future growth is important. Having CCHP as a sort of energy and HVAC backbone in a town or a section of a town is a very effective planning method.

Overall, if these could be rolled out in a coordinated fashion, this would be highly appealing for the EEC region.

Ideally, who should use this research and accompanying tool? Regulators, companies, NGOs? How can it best be applied?
I would make it available to all of those parties via a digital application. It would be great if others could participate in adding to the case studies and share their experiences.

I think power companies can use the tool to promote their solution in an objective fashion and show real methodology.

NGOs and entities like Asian Development Bank can use it to size and scope opportunities for funding and helping regulators in planning.

Regulators can use it in their bidding processes and scoring what individual entities propose for project planning and execution.

I think it could potentially make the process of bidding for projects and determining technical and commercial adequacy of bids more transparent and universal.

Do you think that this research and accompanying tool can make a positive impact on energy efficiency in urbanising areas in developing countries? How?
Yes, and I think making it open source and a standard planning tool would benefit many people involved in power planning.

Ultimately, system operators and regulators have to allow the system to decentralise and to allow more participants. How they go about doing this, what projects or solutions provide anchors or cornerstones to this shift, is very difficult to decide. This, and other similar methodologies can help provide some step-wise process for regulators to take a view, or initial steps at opening the power sector to new supply, demand, balancing, and other solutions.

Thank you for your time. Are you able to participate in additional research?
Yes.