Chapter

Microgrids: Applications, Solutions, Case Studies, and Demonstrations

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Abstract

Rapid urbanization of the world's population is creating great sociological, environmental, and structural strains on the cities where people are moving to. Housing is becoming scarce and expensive, while the need to build new housing is placing great burdens on existing infrastructure—especially local power grids. It will be shown that integrating urban development around a microgrid concept would greatly alleviate the problems associated with urbanization. Incorporation of a microgrid, based on a cogenerating power station where waste heat is used to provide climate control and hot water and where power production is supplemented with renewable energy sources, would effectively remove the development from the local grid and greatly reduce greenhouse gas emissions. Additionally, this model can accommodate any combination of large-scale residential, commercial, or industrial developments to revitalize the local neighborhood and can do so at a level of profit that would allow for lower rents, creating housing and job opportunities for those who are most in need.

Keywords: microgrid, urban development, cogeneration, trigeneration, renewable energy

1. Introduction

Urbanization has occurred throughout history as agricultural societies evolve [1, 2]. The concentration of population (Pop.) leads to a specialization of labor, allowing individuals to concentrate their efforts into fields where they have a particular aptitude. This inevitably leads to the rise of some type of market economy in which one trades upon the skills possessed to fulfill needs in areas outside of one's chosen field of endeavor. Urbanization historically has led to greater overall prosperity in the long term [3–6]. However, immediate consequences are more varied and lead to the "known evils" of city life: poverty, slums, an uneven distribution of resources, and a marked decline in public health [7].

The historical trend toward urbanization is continuing and accelerating into the present. The world population has grown dramatically in the past 75 years and has become increasingly urbanized. The total population of the planet grew by 148% between 1960 and 2017 and by 42% in the roughly quarter century between 1990 and 2017 [8]. During that same quarter century period, the urban population of the planet grew at almost double the rate of the overall population, increasing by 83%

between 1990 and 2017 [9]. In 1990, 43% of the world's population lived in urban centers compared to 54% of a larger population in 2017, an increase of 1.9 billion people occupying the world's cities [8, 9].

The link between urbanization and the decline of public health has been weakened by advances in basic sanitation and the developments in modern medicine. There is now no discernable difference in life expectancy and infant mortality between urban and rural areas in developed countries, and metrics now favor the urban population in many developing nations [4, 6, 10]. However, the unequal distribution of resources still persists in urban centers, especially with regard to inequalities in the cost and quality of housing. The modern age has added energy to the list of resources whose availability is uneven and prosperity related [11–13]. This chapter will present a model for alleviating these systemic inequalities through the incorporation of electric microgrids directly into the planning and construction of new urban developments.

The United States Department of Energy defines a microgrid as "A group of interconnected loads and distributed energy resources that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both a grid-connected or island mode" [14]. A model is developed wherein a trigenerating, combined cycle electrical generating system is integrated into the design and construction of a combined residential (Res.) and commercial (Com.) development project. The term combined cycle indicates that steam produced as exhaust from a fossil fuel-powered turbine operates an additional steam turbine in order to increase efficiency. It is referred to as "trigenerating" because the waste heat from the combined cycle is then used to provide heat, hot water, and air conditioning (AC) to buildings on the microgrid, further increasing efficiency. The model also incorporates renewable energy sources, solar panels and wind turbines, in the building structures.

It will be shown that an integrated development is economically and environmentally sustainable and is also profitable. The integrated development will be modeled in several cities around the world which were selected in order to present a representative cross section of both environmental conditions and levels of national economic development. In developed countries, the implementation of the methodology presented will alleviate the strain on the now-aging electrical grids that accelerated urban development is causing. In less developed countries, its adoption will add to often inadequate supply. Local conditions of cost, revenue, and environment are incorporated into each model.

2. Cities selected

The following cities were selected for inclusion in this study: Cairo, Egypt; Lagos, Nigeria; Shanghai, China; Mumbai, India; London, England; New York City (NYC), United States; and Mexico City, Mexico. These cities were chosen for the following reasons. They all are considered "megacities" as defined by the United Nations, with populations greater than 10 million [15]. As seen in **Table 1**, they have all had major population increase over the past 20 years [16]. **Table 1** also shows their ranking by population globally (WPR) and with respect to their respective continents (CPR; North America, NA; South America, SA) [17, 18]. Additionally, **Table 1** shows that they are located in varied Köppen-Geiger (K-G) climate zones, a fact that affects heating and air-conditioning loads and cycles [19]. The definition of the K-G climate zones is given in **Table 2** [20].

The cities vary greatly in their wealth and development. This impacts the reliability of the electrical supply and the availability of affordable housing. **Table 3**

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City	Continent	Pop.	Pop.	Change	WPR	CPR	K-G class
Cairo	Africa	9,900,000	18,800,000	89.9%	8	1	Bwh
Lagos	Africa	4,800,000	12,200,000	154.2%	21	2	Aw
Shanghai	Asia	8,600,000	23,500,000	173.3%	3	1	Cfa
Mumbai	Asia	12,400,000	19,300,000	55.7%	6	3	Aw
London	Europe	6,800,000	8,700,000	28.0%	38	3	Cfb
Mexico City	NA	15,600,000	21,300,000	36.5%	4	1	Cwb
NYC	NA	16,100,000	18,600,000	15.5%	9	2	Cfa
Sao Paolo	SA	14,800,000	20,900,000	41.2%	5	2	Cfa

Table 1.
Population and climate of cities of interest.

Main climates		Precipitation		Temperature			
A	Equatorial	W	Desert	h	Hot arid	c	Cool summer
B	Arid	S	Steppe	k	Cold arid	d	Extremely continental
C	Warm	f	Fully humid	a	Hot summer	F	Polar frost
D	Snow	s	Summer dry	b	Warm summer	T	Polar tundra
E	Polar	w	Winter dry				

Table 2.
Köppen-Geiger climate classification.

City	Country	HDI Index	NP (%)	LCS (%)
Cairo	Egypt	0.696	25%	10.6%
Lagos	Nigeria	0.532	46%	66%
Shanghai	China	0.752	4.6%	N/A
Mumbai	India	0.640	22%	41.3%
London	United Kingdom	0.922	N/A	27%
Mexico City	Mexico	0.774	52.3%	40%
New York City	United States	0.924	N/A	20%
Sao Paolo	Brazil	0.759	8.9%	19%

Table 3.
State of economic development for cities of interest.

presents the state of economic development in the nations in which these cities are located, as measured by the United Nations Human Development Index (HDI) [21] as well as the percentage of the national population living in poverty (NP%) [22]. The percentage of any given city's population living in slums is not presented in a self-consistent manner. The United Nations defines a slum household as "a group of individuals living under the same roof in an urban area who lack one or more of the following: Durable housing of a permanent nature that protects against extreme climate conditions; sufficient living space which means not more than three people sharing the same room; easy access to safe water in sufficient amounts at an affordable price; access to adequate sanitation in the form of a private or public toilet shared by a reasonable number of people and security of tenure that prevents forced evictions" [23]. The world organizations do not keep data on such a granular level, and national data might not report poverty in terms of locality. As the purpose of this study is to use sustainable development to improve living conditions, the state of local housing quality is of prime interest. Therefore, it was deemed appropriate to use non-internally consistent data for local slum conditions in **Table 3** with data on the percentage of the population living in slum conditions for each city (LSC%) which was obtained from the following sources: Cairo [24], Lagos [25], Mumbai [26], London [27], Mexico City [28], New York City [29], and Sao Paolo [30]. There is no measure or recognition of slum conditions in Shanghai.

The data on electrical distribution and reliability shown in **Table 4** correlates strongly with the economic prosperity of the country wherein that city is located, as well as the age of the supporting infrastructure. The National Access to Electricity for 2016 (NAE) [31] and the National Average Blackout Days per Month (BD/M) [32] are strong indicators of development. Both the National Quality of Electricity Supply [33] and the National Average Interruption Frequency Index [34] are reported using the Reliability of Supply and Transparency of Tariff Index, a scale which "encompasses quantitative data on the duration and frequency of power outages as well as qualitative information on how utilities and regulators handle power outages and how tariffs and tariff changes are communicated to customers" [35]. A score of 8 is the highest possible on this scale. The measurement of power transmission and distribution losses (PD/T) is presented as an indicator of the existing strain on the local distribution networks [36].

A comparison of **Tables 3** and **4** shows a strong correlation between the National HDI Index and the quality of electricity distribution as measured by both the Quality of Electric Supply Index and the Average Interruption Frequency Index. The state of the electricity distribution grids servicing the cities cited in this work fit into three categories: insufficiently maintained and planned (Cairo [37] and Lagos [38]), extensive but aging (London [39], Mexico City [40], New York City [41], and Sao Paolo [42]), and relatively new and robust (Mumbai [43] and Shanghai [44]). The categorization broadly mirrors HDI in the nations in which the selected cities are located. China and India are rapidly modernizing from an underdeveloped base and can build or expand a modern, robust grid from scratch. The United States and United Kingdom, and, to a lesser extent, Mexico and Brazil, have long established industrial economies, meaning that increasing rate of urbanization is a straining and extensive, but aging, infrastructure. Egypt and Nigeria are underdeveloped countries relying on insufficient base infrastructure.

City	Country	NAE	BD/M	QES	AIF	PD/T
Cairo	Egypt	100%	1.8	5	3	14%
Lagos	Nigeria	59.3%	32.8	1.8	0	16%
Shanghai	China	100%	0.1	3.9	6	5%
Mumbai	India	84.5%	13.8	3.1	7	19%
London	United Kingdom	100%	0	6.7	6	12%
Mexico City	Mexico	100%	1.6	4.1	7	14%
NYC	United States	100%	0	6.3	7.2	6%
Sao Paolo	Brazil	100%	1.6	5	5.4	16%

Table 4.
Quality of electrical supply at the national level.

3. Microgrids

Growing metropolitan areas require greater local power generation capacity in order to meet growing local needs and to maintain balance in the national distribution grids. However, the fact that this energy is needed in already congested cities presents an economic problem. Reliable energy is necessary for sustained growth, but the real estate needed for additional power production facilities is also needed for further housing and commercial uses. The use of land for power production addresses a potentially catastrophic future problem, while development for residential and commercial use produces profits for developers and increased tax bases for the municipality. Barring direct government intervention, the latter is the predominantly preferred course of action.

Both needs can be simultaneously addressed through integrated development. The following sections will outline how such a development might be structured as well as the economic and ecological return produced. Although the definition of a microgrid [14] seems straightforward, this definition relies largely on self-classification and makes actual quantification difficult. The data available at microgridprojects.com, a trade-related site that is partially based upon self-reporting, illustrates the elasticity of the definition [45]. A majority of microgrids are located in remote, undeveloped areas or on distant islands, places where connecting to the distribution grid is economically unviable or even physically impossible, making local generation the only possible choice. A prime example of this is the fact that 816 MW of the total 844 MW generated in remote areas of Asia is generated by the Russia Far-East Microgrid Portfolio, a conglomeration of 82 generating station serving remote and isolated communities in Siberia which could, in fact, be considered a proper power distribution grid in its own right. Also, the municipal adoptions of microgrids in North America are illustrative of the inherent idiosyncrasies. Of 114.3 total MW generated in this sector, 104 are generated by the New Jersey Transit microgrid. The fact that the energy used to run this large commuter rail system is generated independent of the grid is energy and efficiency neutral, since the State of New Jersey could have just as easily compelled public utilities to add equal capacity for this necessary service. Additionally, with respect to the reported data, the United States military has committed, for strategic and ecological reasons, to make all domestic military bases energy self-sufficient [46]. Although the adoption of microgrid power consumption by military bases does alleviate the strain on the distribution grid at present, the relief is singular and finite and does not address the future strains which will occur due to increased population densification. In fact, only two reported microgrids in the data set addressed residential users in congested areas. Both are located in Kings County, New York, Brevoort Cogeneration Microgrid, and New York Affordable Housing Microgrid. Both are retrofits, with the structures not optimized to take advantage of the benefits of a microgrid.

It is posited that an integrated, holistic approach to real estate development using multiple technologies in buildings designed to maximize their use is not only socially responsible but also economically viable. Inclusion of the microgrid from the outset would allow buildings within the development to utilize the maximum amount of energy. Therefore, it is proposed that a future development be designed around a grid-connected microgrid capable of island-mode operation as follows:

1. **Main power generation-combined cycle gas and steam plant:** Gas and steam turbines would produce electricity at high efficiency for the development. The waste heat would be used to produce building heat, hot water, and air conditioning.

2. **Flexible sizing of the microgrid:** Depending on local regulations, neighboring entities could also be enlisted into the microgrid. Although not modeled herein, if such entities include vital facilities such as hospitals or fire stations, the microgrid facility may be eligible for non-interruptible status with respect to natural gas supply.

3. **Maximization of renewable energy assets:** Buildings would be designed from the outset to maximize both solar and wind generations, thereby decreasing the carbon footprint of the development overall and the cost of fuel.

4. The development model

A model is presented which incorporates a microgrid utilizing renewable energy assets into a development consisting of three 32-story residential towers and one 57-story commercial tower. The scale of the development is in keeping with current large-scale developments. The model is run in each of the eight cities of interest using local data on environmental conditions, construction costs (exclusive of real estate purchase), and income levels based upon local rents and power rates. Analyses of the benefits of including the microgrid, as opposed to the same scale conventional development, are performed on three levels:

1. **Infrastructure impact:** Electric load is presented with and without the microgrid.

2. **Economic:** Construction cost, anticipated revenue, and time to repay are presented with and without the microgrid.

3. **Ecological:** Greenhouse emissions are compared with and without the microgrid.

4.1 The buildings

Actual hourly electrical usage data and building specifications of one 32-story residential tower and one 57-story commercial tower located in New York City were generously provided by GridMarket LLC, New York City, NY. The dimensions of each tower, given in square feet (sq. ft.) and number of apartments (apts.), are given in **Table 5**. Rentable area for the entire four-tower development is calculated, per industry standard, at 50% of total square footage, with the remaining 50% designated for hallways, stairwell, elevator shafts, and other such types of general-use areas.

	Built	ES	Lot area	Internal area (sq. ft)	Floors	Retail (sq. ft)	Office (sq. ft)	Res. (sq. ft)	Apts.
Res.	1916	94	80,333	938,324	32	26,805	0	879,019	608
Comm.	1972	165	127,966	2,689,635	57	216,912	2,319,046	0	0

Table 5.
Specifications for buildings to be used in the model (provided by GridMarket LLC).

4.2 Power generation

A 2 × 1 (two gas turbines 7.9 MW powering 1 MW steam turbine) was the optimal configuration for the cogeneration plant. This would be supplemented by power provided by 10,500 solar panels and 295 1 kW vertical drum-type wind turbines. The number of solar panels was estimated by covering the entire roof area of the four proposed buildings with standard 77 inch by 39 inch panels, while the number of wind turbines was estimated by placing a turbine every 10 feet around the periphery of each roof. It is recognized that whole-roof coverage with solar panels is impracticable; however, the estimate is valid because some amount of appropriately facing surface area would be available for additional panels. Also, it is assumed for these calculations that the buildings will be boring rectangles. As this is neither likely nor desirable, setbacks will create additional space for more wind turbines. Energy storage devices will be included in the design from the outset in order to balance generated power between times of low load and high load.

4.3 Calculations

4.3.1 Power generation potential

Publically available commercial data was used to estimate all generating capabilities for gas turbines, steam turbines, and wind turbines as follows: two 7.9 kW gas turbines operating at 30.6% efficiency [47] driving a single 750 kW gas turbine [48] raising the total efficiency to 50.2% and 1 kW wind turbines [49]. All power generation was calculated on an hourly basis and balanced with the hourly load as much as possible. Renewable energy sources were given precedence. Annual average daily data for wind speed at 50 meters aboveground [50], sunrise and sunset [51], and average solar irradiance in kWh/m^2 [50] were obtained for each city of interest. As the wind speed and irradiance data were daily averages, they were applied for all 24 hr in each given day. Sunrise and sunset data were used to "turn on" and "turn off" the solar component of the system.

There are multiple methods for determining the efficiency of trigeneration systems [52–55]. For this study, general estimates based upon these methods will be used. The fast-start capability of modern turbines was utilized to estimate cogeneration outputs with one gas turbine operating at all times. If hourly load minus available renewables exceeded the capacity of one gas turbine, the second turbine was started. If the hourly load still exceeded the capacity of both gas turbines, the steam turbine was included. Solar generation was calculated on an hourly basis by multiplying the irradiance by the total panel area (total roof area) at a 15% conversion efficiency and a 75% transmission efficiency. For wind energy, the manufacturer's power generation curve was used [49]. The power curve, with a cut-in at 6 miles per hour of wind speed, was applied to the hourly average wind speed to determine the kW delivered by the posited 295 turbines. Usable waste heat from cogeneration (as well as input fuel needs) was calculated on an hourly basis. Input energy in kW was calculated as hourly output divided by hourly efficiency of the cogeneration set, 30.6% for gas-only generation and 50.2% for combined generation. Gross waste heat was obtained by subtracting this number from generated power (Eq. 1):

$$\left((\text{kWh/hr})/\text{Efficiency} - (\text{kWh/hr})\right)/0.0002931\ \text{BTU/kWh} = \text{Gross BTU} \quad (1)$$

Usable waste heat was calculated by obtaining the ideal thermodynamic efficiency of the system (Eq. 2) [56] and multiplying this by the results of Eq. 1 (Eq. 3):

$$(T_{high} - T_{low})/T_{high} = 0.61 \quad (2)$$

$$BTU/hour\ (gross) \times 0.61 \quad (3)$$

The annual volume of natural gas (NG) required to run the cogeneration system, measured in industry standard cubic feet (ft^3), was calculated by summing the hourly energy input, (kWh/hr) divided by hourly efficiency of cogeneration and converted to cubic feet of gas (Eq. 4):

$$\Sigma\left(\left((kWh/hr)/Efficiency\right) \times (3412\ Btu/kWh) \times \left(1\ ft^3/103.7\ BTU\right)\right) \quad (4)$$

4.3.2 Estimated usage

Building performance in terms of ENERGY STAR rating (EGR) was not modified. Usage was normalized to environmental conditions in each of the given cities as follows. Daily average high and low temperatures for obtained for each city [57]. Hourly temperatures were calculated using a linear regression each day of the year in each city, starting from the daily low for the day at 1:00 a.m. up to the daily high for the day at 12:00 noon and going back to the daily low again at 12:00 midnight. It was assumed that, on any given day, air conditioning (AC) would be required at or above a daily high of 80°F, and heat would be needed at a daily low of 50°F (**Table 6**).

Days	Cairo	Lagos	Shanghai	Mumbai	London	Mexico City	NYC	Sao Paolo
AC	206	365	103	365	0	110	98	245
Heat	63	0	107	0	199	107	178	0
None	96	0	155	0	166	148	89	120

Table 6.
Annual climate control needs for cities of interest.

In order to estimate the base electric usage for the proposed development, the hourly base building usage data provided by GridMarket was increased by 30% for each day for each city that air conditioning was assumed to be needed. (Given that the New York City data is actual usage, days that the data indicated that air conditioning would be needed in both New York and any other given city were not modified.) This provided a reference point for the estimated electrical load for the proposed development being connected to the regional/national power grid. Since inclusion of the microgrid would essentially eliminate electricity usage for air conditioning, daily usage data for the development with an included microgrid was reduced by 30% assuming that air conditioning increases daily load by 30% (**Table 6**).

Hourly heat usage for both hot water and building heat was assumed to remain constant across all cites and climates since the heat capacity of water is constant and the amount of hot water required on a daily basis would be independent of location or climate. Also, as the configuration (and hence the volume) of the buildings was identical in all cities, and the need for heating is temperature dependent, the amount of heat required to provide building heat on an hourly basis would also be constant. Hourly heat requirements for both needs were therefore calculated based upon the New York City data and applied to all cities. The total annual energy use breakdown for New York is available from the United States Energy Information Agency as follows: electricity, 27.2%; heating, 55.8%; and hot water, 17.0% [58].

Total actual electrical usage for the four-tower development was converted to BTUs and divided by 0.272 (27.2%) to give total energy usage (Eq. 5):

$$(1.81 \times 10^8 \text{ kWh Annual Electrical}/.272) \times 3412 \text{ BTU/kWh} = 2.27 \times 10^{12} \text{ BTU/year} \tag{5}$$

This number was then multiplied by 0.17 (17%) to provide annual hot water usage and divided by 8760 hr/year to arrive at an hourly hot water usage of 4.4×10^7 BTU/hr. for hot water (Eq. 6). This was applied to every hour of the year in all cities:

$$(2.27 \times 10^{12} \text{ (BTU/year)} \times 0.17)/8760 \text{ hr./year} = 4.4 \times 10^7 \text{ BTU/hr.hot water} \tag{6}$$

Hourly structural heating power was calculated at 0.558 (55.8%) of total energy divided by actual hours of heat usage in New York. This number of 2.96×10^8 BTU/hour was then applied to each city for each hour (Eqs. 7–8):

$$(2.27 \times 10^{12} \text{ (BTU/year)} \times 0.558) = 1.27 \times 10^{12} \text{ BTU/year building heat} \tag{7}$$

$$1.27 \times 10^{12} \text{ BTU/year}/(178 \text{ days heat/year} \times 24 \text{ hr/day}) = 2.96 \times 10^8 \text{ BTU/hour} \tag{8}$$

Usable hourly waste heat (Eq. 3) was initially applied as needed for climate control. Hourly heat transfer needs were calculated at 80% of available waste heat for building heating, with 80% efficiency being the average efficiency of a standard heat exchanger [59]. Hourly heat transfer needs were calculated at 120% of available waste heat for air-conditioning needs, with 120% being the average efficiency of a two-stage absorption chiller [60]. Remaining heat, on an hourly basis, was then applied to provide hot water, again at 80% efficiency.

5. Results

5.1 Infrastructure impact

Infrastructure impact is defined by the degree that the implementation of an integrated development model would relieve strain on the local power distribution grid. As can be seen in **Table 7**, this is highly correlated to air-conditioning needs as shown in **Table 6**. This is the expected result as heat provided from the trigeneration plant to the absorption chillers replaces electrical load for air conditioning. Mumbai and Lagos, cities which essentially require air conditioning year-round, had the highest reduction in load, while London, which essentially requires no air conditioning, saw no reduction in load.

The microgrid must be grid-connected for both safety and regulatory reasons in an urban environment. To be effective, the system must not add additional load to the grid but must also be balanced in order to protect the local grid infrastructure; it should not push power onto the distribution grid at any point. In case of emergency, such as a blackout condition, the microgrid should also be able to disconnect from the local power grid and provide all needed services in island mode. **Table 7** indicates that the proposed model succeeds in this respect. The incorporated power generating systems produce surplus electricity on an hourly basis between 40% and 60% of the time, depending upon the city ("% hours off-grid"). Excess energy produced in hours of low load can be stored in incorporated batteries to meet demand in hours of high load, producing a system that is completely grid-neutral throughout the year. The annual difference between electricity usage and

City	No microgrid (kWh/year)	Microgrid (kWh/year)	Saved	Microgrid production (kWh/year)	Hours off-grid	Surplus/ deficit (kWh/year)	Surplus/ deficit
Cairo	1.96E+08	1.75E+08	10.6%	1.73E+08	48.0%	(2,274,872)	−1%
Lagos	2.05E+08	1.60E+08	21.8%	1.75E+08	61.8%	14,415,926	9%
Shanghai	1.83E+08	1.80E+08	1.2%	1.76E+08	44.0%	(4,663,087)	−3%
Mumbai	2.16E+08	1.69E+08	21.6%	1.77E+08	57.7%	8,210,049	5%
London	1.81E+08	1.81E+08	0.0%	1.72E+08	41.2%	(9,295,666)	−5%
Mexico City	1.90E+08	1.77E+08	7.0%	1.73E+08	48.3%	(3,766,257)	−2%
NYC	1.81E+08	1.63E+08	10.0%	1.71E+08	55.8%	8,533,701	5%
Sao Paolo	2.12E+08	1.71E+08	19.6%	1.76E+08	51.8%	5,855,500	3%

Table 7.
Load and production comparison (selected cities).

production in each city as shown in **Table 7**, be it positive or negative, is small and can be corrected in the local design phase.

5.2 Socioeconomic impact

The cost of constructing the proposed development buildings was calculated using local average construction cost data and applying it to the total square footage found in **Table 5** (**Table 9**-"Cost-Less Microgrid") [61]. The cost of integrating the microgrid is calculated on average prices in the United States (**Table 8**) [62]. An internally consistent data set containing all cities of interest for this metric was not found. It is assumed that the cost would be fixed since the capital components required are not locally produced. The cost of batteries, absorption chillers, and heat exchangers was not included, as it is assumed that these costs would be balanced by the deletion of HVAC equipment, cooling towers, boilers, and hot water heaters. Cost differential is presented in **Table 9**.

Revenue is calculated on local monthly rental rates per square foot of rental. As previously mentioned, rentable space is calculated at 50% of available floor space. Internally consistent residential rental rates were found [63]. However, internally consistent rates for residential, commercial, and retail were only found for New York City [64, 65]. Therefore, commercial rates for other cities are calculated at the ratio of those rates to residential rates for New York. As the microgrid will also be a revenue source, local electricity rates are included and applied to the revenue for each city [66]. Total annual revenue from rents and electrical for each city, as well as the rates used, is given in **Table 10**. **Table 11** then estimates the gross time to repay the initial investment, with "Cost-Less Microgrid" in **Table 9** divided by the

Cogeneration	$895	Per kW	15,660	MW	$14,015,700
Solar panels	$2434	Per kW	2100	Watts	$5,111,400
Wind turbines	$1630	Per kW	292	Turbines	$475,960
				Total	$19,603,060

Table 8.
Microgrid cost.

City	Res. twrs	Com. tws	Total sq. ft.	Per sq. ft. res.	Per sq. ft. com.	Cost-less microgrid	Cost-with microgrid
Cairo	3	1	5,504,607	$31.13	$35.94	$184,295,560	$203,898,620
Lagos	3	1	5,504,607	$30.00	$32.00	$170,517,480	$190,120,540
Shanghai	3	1	5,504,607	$21.23	$33.82	$150,725,311	$170,328,371
Mumbai	3	1	5,504,607	$18.96	$20.09	$107,406,636	$127,009,696
London	3	1	5,504,607	$112.63	$120.56	$641,312,692	$660,915,752
Mexico City	3	1	5,504,607	$52.41	$22.36	$207,672,921	$227,275,981
NYC	3	1	5,504,607	$285.32	$534.00	$2,239,432,901	$2,259,035,961
Sao Paolo	3	1	5,504,607	$18.11	$42.17	$164,401,051	$184,004,111

Table 9.
Construction cost comparison of proposed development: incorporating vs. not incorporating a microgrid.

sums of all rentals in **Table 10** to determine the number of years to repay the development if built conventionally and the "Cost-With Microgrid" divided by the sum of all rentals plus electricity revenue in **Table 10** used. Operating and real estate costs were not considered in the gross time to repay, but it can be assumed that these costs will be identical in both scenarios in any given city.

From **Table 11**, it can be seen that the gross time to repay initial investment is lower when the microgrid is present. This has positive sociological implications. Since repayment time is shorter, long-term revenue will be higher, making the proposed development model economically profitable and therefore feasible. This has an additional advantage; the charging of premium rents is not economically required due to the lower repayment time of a microgrid inclusive development. The enhanced revenue stream and lowered operating costs associated with building a development around this model would also make affordable housing economically viable, serving to include those who are often left behind and displaced when a neighborhood is redeveloped.

5.3 Environmental impact

Buildings generate greenhouse gases indirectly by consuming electricity produced from various fuels and directly generate such gases through the production of heat and hot water. **Table 12** presents the breakdown of fuels used to generate electricity for the local power grid in each of the cities of interest [67]. **Table 13** shows the greenhouse gas emissions for each of those sources per kWh [68]. **Table 14** presents the percentage of energy derived from renewable sources incorporated into the microgrid in each city of interest. **Table 15** contains data on natural gas usage for the development both with and without inclusion of the microgrid. In both cases, annual hot water needs are calculated according to Eq. 7 multiplied by 8760 hr/year, and heating needs are calculated by Eq. 8 multiplied by the number of heating hours estimated in each city from **Table 6**. For the traditional version of the development, it is assumed that these needs will be supplied by burning natural gas, although less environmentally friendly fuel oil could also be used. When the microgrid is present, heat and hot water needs are met first by trigeneration waste heat, and any unmet needs are met by the same natural gas feed that would fuel the gas turbines. Finally, **Table 16** compares the calculated greenhouse gas emissions between the two scenarios with data from **Tables 8, 13, 14** and **15**.

City	Res./sq. ft./month	Office/sq. ft./month	Retail/sq. ft./month	Electricity/kWh	Res. ent/year	Office rent/year	Retail rent/year	Electricity/year
Cairo	$1.11	$2.35	$17.51	$0.02	$17,562,800	$32,725,167	$31,235,468	$3,501,974
Lagos	$1.12	$2.37	$17.67	$0.08	$17,721,023	$33,019,989	$31,516,869	$3,207,401
Shanghai	$1.07	$2.27	$16.88	$0.09	$16,929,906	$31,545,882	$30,109,866	$3,607,725
Mumbai	$0.60	$1.27	$9.46	$0.07	$9,493,405	$17,689,280	$16,884,037	$3,382,754
London	$2.40	$5.09	$37.86	$0.22	$37,973,621	$70,757,118	$67,536,148	$3,617,546
Mexico City	$0.49	$1.04	$7.73	$0.08	$7,752,948	$14,446,245	$13,788,630	$3,536,433
NYC	$3.45	$7.31	$54.42	$0.18	$54,587,080	$101,713,358	$97,083,212	$3,425,333
Sao Paolo	$0.53	$1.12	$8.36	$0.19	$8,385,841	$15,625,530	$14,914,233	$3,412,530

Table 10.
Estimated rental and electrical rates and annual revenues per source.

City	Oil	NG	Coal	Nuclear	Hydroelectric	Non-hydroelectric renewables
Cairo	44.67%	50.72%	0.47%	0.00%	3.49%	0.65%
Lagos	42.12%	28.25%	21.80%	0.82%	5.87%	1.14%
Shanghai	18.95%	6.20%	61.83%	1.58%	8.62%	2.82%
Mumbai	29.38%	6.23%	56.91%	1.18%	4.03%	2.27%
London	38.89%	36.70%	5.83%	8.63%	0.65%	9.31%
Mexico City	44.41%	43.20%	5.26%	1.28%	3.63%	2.21%
NYC	0.00%	44.00%	1.00%	31.00%	19.00%	5.00%
Sao Paolo	46.61%	11.06%	5.55%	1.21%	29.19%	6.38%

Table 11.
Electric power generation source fuels.

City	Oil	NG	Coal	Nuclear	Hydroelectric	Nonhydroelectric renewables
Cairo	44.67%	50.72%	0.47%	0.00%	3.49%	0.65%
Lagos	42.12%	28.25%	21.80%	0.82%	5.87%	1.14%
Shanghai	18.95%	6.20%	61.83%	1.58%	8.62%	2.82%
Mumbai	29.38%	6.23%	56.91%	1.18%	4.03%	2.27%
London	38.89%	36.70%	5.83%	8.63%	0.65%	9.31%
Mexico City	44.41%	43.20%	5.26%	1.28%	3.63%	2.21%
NYC	0.00%	44.00%	1.00%	31.00%	19.00%	5.00%
Sao Paolo	46.61%	11.06%	5.55%	1.21%	29.19%	6.38%

Table 12.
Electric power generation source fuels.

Lbs/BTU	Coal	Oil	NG	Solar	Hydroelectric	Nuclear	Wind
CO_2	2.15E-04	1.61E-04	1.17E-04	2.89E-05	1.54E-05	7.70E-06	7.10E-06
SO_2	2.59E-06	1.12E-06	7.00E-09	*Negligible*	*Negligible*	*Negligible*	*Negligible*

Table 13.
Greenhouse gas emissions per source fuel.

KwH/year	Cairo	Lagos	Shanghai	Mumbai	London	Mexico City	NYC	Sao Paolo
Total	1.73E+08	1.75E+08	1.76E+08	1.77E+08	1.72E+08	1.73E+08	1.71E+08	1.76E+08
Wind	2.47E+06	7.62E+05	2.17E+06	1.74E+06	2.06E+06	1.70E+06	2.26E+06	2.01E+06
Solar	2.89E+07	3.35E+07	3.18E+07	3.48E +07	2.76E+07	2.99E+07	2.81E+07	3.32E+07
Renewable	**18.1%**	**19.6%**	**19.3%**	**20.6%**	**17.3%**	**18.3%**	**17.7%**	**20.0%**

Table 14.
Percent renewable power generation on microgrid.

	On national power grid				Trigenerating microgrid					
	Cubic feet NG annually				Cubic feet NG annually					Difference
City	Hot water	Heat	AC	SUM	Hot water	Heat	AC	Turbine	SUM	
Cairo	1.0E+07	4.3E+09	0	4.4E+09	0.0E+00	2.7E+09	0.0	1.5E+10	1.8E+10	**1.4E+10**
Lagos	1.0E+07	0.0E+00	0	1.0E+07	0.0E+00	0.0E+00	0.0	1.5E+10	1.5E+10	**1.5E+10**
Shanghai	1.0E+07	7.4E+09	0	7.4E+09	0.0E+00	4.5E+09	0.0	1.5E+10	2.0E+10	**1.2E+10**
Mumbai	1.0E+07	0.0E+00	0	1.0E+07	0.0E+00	0.0E+00	0.0	1.5E+10	1.5E+10	**1.5E+10**
London	1.0E+07	1.4E+10	0	1.4E+10	1.0E+07	9.5E+09	0.0	1.3E+10	2.2E+10	**8.8E+09**
Mexico City	1.0E+07	7.3E+09	0	7.3E+09	0.0E+00	4.6E+09	0.0	1.5E+10	2.0E+10	**1.2E+10**
NYC	1.0E+07	1.2E+10	0	1.2E+10	1.0E+07	7.8E+09	0.0	1.5E+10	2.3E+10	**1.0E+10**
Sao Paolo	1.0E+07	0.0E+00	0	1.0E+07	0.0E+00	0.0E+00	0.0	1.5E+10	1.5E+10	**1.5E+10**

Table 15.
NG consumption: with microgrid compared to without microgrid.

These results are significant. As seen in **Table 15**, a development incorporating a microgrid uses over 10 times the natural gas in all cases than the identical development drawing power from the local distribution grid. However, **Table 16** definitively shows that the use of a microgrid would greatly reduce the greenhouse gas emissions from the development, with approximately half of the CO_2 and virtually all SO_2 emissions eliminated. By incorporating trigeneration from the outset, all upstream emissions from electricity generation are eliminated. Additionally, the use of waste heat in the building systems eliminates emissions from the production of hot water, halves the emissions from building heat, and also eliminates any emissions from air conditioning (bearing in mind that, in a conventional arrangement, air-conditioning emissions would be included in electricity generation emissions). Finally, **Table 14** shows that incorporating maximal renewable assets by design accounts for roughly 20% of the electricity production which, at 50% generator efficiency,

Tons/year	On power grid		Microgrid		Reduction (%)	
City	CO_2	SO_2	CO_2	SO_2	CO_2	SO_2
Cairo	9.84E+04	4.80E+02	4.46E+04	2.67E+00	54.64%	99.44%
Lagos	7.54E+04	5.25E+02	2.81E+04	1.68E+00	62.80%	99.68%
Shanghai	1.12E+05	6.56E+02	5.58E+04	3.34E+00	50.08%	99.49%
Mumbai	7.93E+04	6.73E+02	2.81E+04	1.68E+00	64.55%	99.75%
London	1.49E+05	4.93E+02	8.58E+04	5.14E+00	42.53%	98.96%
Mexico City	1.14E+05	4.70E+02	5.62E+04	3.36E+00	50.88%	99.28%
NYC	1.41E+05	8.04E+02	7.56E+04	4.52E+00	46.21%	99.44%
Sao Paolo	7.81E+04	5.01E+02	2.82E+04	1.69E+00	63.87%	99.66%

Table 16.
Comparison of greenhouse emissions for development: without vs. with microgrid.

amounts to a 40% drop in potential greenhouse gas production through electricity generation.

6. Conclusions

Urbanization of populations is occurring at an accelerating pace worldwide, and, in all countries, the increasing densification of population is putting a strain on the pre-existing infrastructure. Depending on the state of national economic development, that infrastructure could be robust, aging, or nonexistent, but was not designed to support the increasing strain. Additionally, this seismic population shift requires housing and employment opportunities in relatively small geographic areas. While growth has always bought opportunity, that opportunity was never immediate or evenly distributed. Hence, slum populations are increasing, and both housing and economic opportunity are increasingly scarce.

History has shown that economies cannot be managed, but it is the job of the government to "promote the general welfare" [69]. At present, various local, national, and international entities are promoting the general welfare through establishing programs to create sociological and environmentally sustainable opportunity. These incentives recognize the existence of a need which can be addressed by a new model of urban growth, one that is economically advantageous and sociologically and environmentally sound, such as the design model proposed herein. The work presented develops a new model for urban development, a model which incorporates a myriad of mature technologies into a real estate development at the design stage. The model bases the development around a self-contained microgrid using trigeneration of power where, at the first stage, fossil fuel-powered turbines produce electricity and heat which, at the second stage, powers a steam turbine to produce more electricity. The third stage of trigeneration is to use the remaining exhaust heat to provide building heat, hot water, and air conditioning. The system is supplemented by renewable solar and wind power, with the buildings designed from the outset to maximize such assets. Modern power storage assets are included in the design to balance the load between times of high usage and low usage.

The study demonstrates that the proposed model succeeds in meeting all sustainability requirements. It is more profitable than constructing the same development on the national power grid. This is vital since economic sustainability is a sine qua non for any urban development. It balances load and generation capability on a large scale, allowing the construction of large numbers of buildings to accommodate increasing populations with essentially no impact on the existing power distribution infrastructure. It is also environmentally sustainable, producing fewer emissions than traditional developments on the same scale.

These conclusions point to the viability and the economic and environmental desirability of proceeding with urban development under the model herein presented and also lead to a sociological conclusion. Cities are historically built by the poor striving to make a better life for themselves and their families. In developed countries, the consequence of real estate development is too often to push such people out of their homes and further to the fringes. In developing countries, such people are often not even considered, relegated to living in shanty towns. The economic and environmental advantages of this development model present an opportunity to promote the general welfare of all. Environmental financial incentives, coupled with increased profitability, will allow for the maintenance of exceptional living conditions at comparatively low rents. Since renewability and regeneration are incorporated into the building design, heat and hot water, so necessary for everyday life, will be readily available. Lower rents are economically possible since all these usual living expenses are being provided for by the same source. Most importantly, the model is scalable and variable and power is fungible. A commercial tower was included in this study to both provide an economic focus point to start the development and to provide jobs to the people living in the residential towers because real-world data was made available. The model could be applied to any combination of residential, commercial, retail, or industrial spaces providing centers for human advancement, with both jobs and housing provided at an economically and environmentally favorable rate.

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Dedication

This work is dedicated to the memory of Mr. Peter Tymus, formerly of Turner Constructions, Inc. and Long Island University, Brooklyn, NY. Mr. Tymus was a gentleman in the truest sense of the word, and his vision and sharing of knowledge were the inspiration for this work.

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