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# Economic and Environmental Changes in Shenzhen—A Technology Hub in Southern China

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**Abstract:** Shenzhen has been established as the technology and innovation center in China. The study reviews its economic development and environmental change over the past four decades. Specifically, it tests whether environmental Kuznets curve relationship between haze as a proxy indicator of environmental condition and gross domestic product (GDP) per capita holds in Shenzhen. The study also examines the contribution of Shenzhen's secondary sector to its GDP and highlights some changes in the computer, communication and electronic product manufacturing industries over the years. We collected the official data from the Shenzhen Municipal Government. Economic, social and environmental changes in Shenzhen were identified using tables and stacked graphs. Environmental Kuznets curve revealed that the worst environmental condition appeared in Shenzhen during the period 2003–2004. Environmental analysis showed that Shenzhen's computer, communication and electronic product manufacturing industries consumed 52,595 TJ of energy and produced 10.1 million tons $CO_2$-eq in 2019. As gross output value of the industries was USD 336 billion in 2019, the industries had an energy efficiency of 156,716 MJ/million USD and an emission efficiency of 30.6 tons $CO_2$-eq/million USD, improving by 74% and 65%, respectively, since 2008. Nevertheless, the industries should focus more on high value-added and low energy-intensive technologies and innovations. Additionally, the Shenzhen Government shall increase the use of clean energy sources such as nuclear, wind and solar power in order to sustain the continual improvement of energy and emission efficiencies for all industries.

**Keywords:** economic change; environmental change; gross domestic product; haze; hi-tech industry; Shenzhen

**Citation:** To, W.-M.; Lee, P.K.C.; Lau, A.K.W. Economic and Environmental Changes in Shenzhen—A Technology Hub in Southern China. *Sustainability* **2021**, *13*, 5545. https://doi.org/10.3390/su13105545

Academic Editor: Antonio Boggia

Received: 14 April 2021
Accepted: 14 May 2021
Published: 16 May 2021



## 1. Introduction

After years of a closed-door policy, China reformed and opened up its economy to global trade in 1978 [1]. Specifically, Shenzhen was designated as one of the first four China's special economic zones in May 1980; the other three were Zhuhai, Shantou and Xiamen [2]. At that time, Shenzhen was a small village with a population of 332,900 [2,3]. Yet, it was strategically located on the north of Hong Kong that had transformed from a fishing village to a global logistics hub, tourism center and international financial center over the past hundred years [4–6]. In 1981, Shenzhen alone attracted over 50 percent of total foreign direct investment (FDI) in China [2]. In 1984, Shenzhen and the other three special economic zones accounted for 26 percent of total FDI in China. Shenzhen hosted a large number of joint venture projects with investment from Hong Kong and Macao [2]. As a special economic zone, Shenzhen has a separate customs area so that manufacturers and business firms in Shenzhen can enjoy duty-free benefits and streamlined import and export, financial and employment procedures. With a laissez-faire environment and a huge international and domestic market at its core, Shenzhen has experienced a phenomenal growth over the past forty years. In 2018, Shenzhen's gross domestic product (GDP) reached

USD 366 billion, surpassing Hong Kong's GDP at USD 362 billion in the same year. Unlike Hong Kong that has primarily relied on the tertiary (i.e., service) sector in the past three decades [4], the secondary sector of Shenzhen including different manufacturing industries plays a significant role in propelling its economic growth over the past forty years. Recently, China's President Xi Jinping visited Shenzhen in October 2020 and called on Shenzhen to be a world-class technological and industrial innovation powerhouse [7]. Furthermore, the institutional environment of China is highly influential that the manufactures of Shenzhen are likely in line with the national policies with respect to innovation and environmental practices [8]. Thus, it is expected that one of Shenzhen's manufacturing industries, namely the computer, communication and electronic product manufacturing industry will look for all sorts of ways to sustain its growth while achieving its environmental and social objectives [9].

Researchers [10–13] studied environmental issues including carbon emissions and haze in Shenzhen. Haze is particularly problematic because it adversely affects physiological and psychological health of humans. It is more pronounced during the dry season in China [14–16]. Research evidence indicated that haze is significantly associated with the consumption of fossil fuels such as aviation kerosene and liquefied petroleum gas (LPG) [15,16]. Haze was found to associate with mortality [17–19]. In Shenzhen, haze was a serious problem during the period 1995–2015 because there were close to or over 100 haze days per year [11,12]. It was not unusual that Shenzhen was covered by a blanket of haze continuously from October to January [12,20,21]. Fortunately, with the concerted efforts from the Government and private sectors such as using cleaner fuels for vehicles and power generation [22–25] and adopting low energy-intensive production methods [10,26,27], the number of haze days in Shenzhen fell dramatically in recent years [28,29].

Shenzhen is also known as the world's computer, smartphone and electronics factory [30] and it is home to a number of high-tech firms including Huawei, ZTE (formerly known as Zhongxiang Semiconductor Co., Ltd.), drone-maker DJI and Foxconn (Apple's main iPhone maker). It is vital to identify this specific (i.e., computer, communication and electronic product manufacturing) industry's energy use and its environmental consequences. In sum, there is scant literature on the evolution of Shenzhen's using a long-term time series that spans four decades and Shenzhen's economic growth and environmental change. Thus, this study aims to answer the following four research questions: (1) how has Shenzhen grown economically in the past forty years? (2) How do its social and environmental conditions (i.e., using haze as a proxy indicator) change? (3) Does its environmental condition follow an environmental Kuznets curve—an inverting curve suggesting that as a country's economic condition continually improves, its environmental condition first deteriorates and then improves when the economic condition passes a critical point? (4) How does it perform economically and environmentally as a technology hub in southern China? The findings of the study can contribute to a deeper understanding of the phenomenal growth of Shenzhen including its economic, environmental and social changes. Additionally, the study's findings can demonstrate with appropriate efforts from the Government and private enterprises, environmental deterioration such as haze can be reversed. Finally, the study's findings can also be used to gauge the economic and environmental performance of Shenzhen's computer, communication and electronic product manufacturing industry and contribute to the existing literature by examining the environmental consequences and management practices of Chinese firms and emerging new research on the future of technology and environmental management.

The rest of the paper is structured as follows. First, Section 2 presents a literature review on the association between economic growth and environmental change, and Shenzhen as a member of the world's cities and its haze conditions. Section 3 presents the data source and methods of analysis, followed by Section 4 Results and Section 5 Discussion. Section 6 concludes the study with implications and limitations.

## 2. Literature Review

### 2.1. Economic Growth and Environmental Change

Researchers have studied the associations between economic growth, energy consumption and environmental change for decades [4,31–45]. Some researchers focused on exploring the relationships between economic growth, energy use such as electricity consumption and greenhouse gases (GHG) emissions in a single country or city [31,32,35,36,40,42–44] while others preferred the study of the relationships using panel data i.e., multiple countries simultaneously [34,37–39,41,45–48]. Specifically, Bilan et al. [46] reported that there is a long-run causal relationship running from the use of renewable energy in the form of capital and human resources to economic growth in the form of GDP per capita in EU member countries. The truth is that green investment including the use of renewable energy was found to positively influence economic growth in the form of GDP per capita and reduce GHG emissions [47]. Additionally, Sterpu et al. [45] reported that the environmental Kuznets curve based on GHG per capita versus GDP per capita existed in 17 out of the 28 EU member countries. Interestingly, there was very few articles [15,16,29] linking economic growth and haze as a proxy indicator of environmental change in the extant literature, even though haze was mentioned frequently in public and social media as the most prominent air pollution problem in many countries such as China [49–51].

### 2.2. Shenzhen as a Member of the World's Cities and Its Haze Conditions

All countries and cities are interlocked with each other in a certain sense [52]. Derudder et al. [52] studied how Chinese cities including Shenzhen were connected with all other world's cities using the 2016 data. They reported that Shenzhen ranked the sixth in the Greater China Region with about 32% global network connectivity. Its ranking was only lower than Hong Kong, Beijing, Shanghai, Taipei and Guangzhou but higher than the rest of 41 Chinese cities covered in the study. Nevertheless, Shenzhen was a 'new' city which was only established by the central government in 1980. Specifically, Shenzhen is a technological and innovation hub in China and the growth of China has been phenomenal over the past few decades [53]. It is very likely that Shenzhen will not only surpass its neighboring cities in the Greater China Region including Taipei, Guangzhou, Hong Kong in terms of global network connectivity, it will join other world's most well-connected cities and innovative centers such as New York, London and Tokyo soon [54].

In Shenzhen, Jing et al. [10] studied its carbon emissions during the period 2005-2012. They reported that Shenzhen's carbon emissions from the manufacturing industry decreased from 2005 to 2010 due to its light manufacturing industry utilizing advanced manufacturing systems to replace traditional energy-intensive manufacturing approaches. Wang et al. [11,12] and Zhao et al. [13] studied haze in Shenzhen. A haze day is recorded as a meteorological condition in which the mean visibility is less than 10 km in the day and the mean relative humidity is lower than 90% [14]. Wang et al. [11] reported that the number of haze days per year had an increasing trend between 1981 and 2010 in Shenzhen. Haze days were frequently recorded in the winter months, followed by the autumn months [11,12]. Haze was associated with higher concentrations of particulate matter (PM), sulfur dioxide ($SO_2$) and nitrogen dioxide ($NO_2$) [11]. Wang et al. [12] suggested that $PM_{2.5}$ was the primary cause of haze condition, followed by ozone ($O_3$). Zhao et al. [13] investigated the frequency of haze episodes and emission fractions from different sources including vehicles. Empirical evidence showed that vehicle exhaust was an overstated cause for haze conditions in China [13]. To and his associate [15,16] studied poor visibility and haze in Hong Kong and Macao. To [15] reported that the number of hours of reduced visibility increased rapidly from 1990 to 2011 in Hong Kong and burning of aviation fuels significantly adversely affected visibility, followed by the use of liquefied petroleum gas (LPG) and liquefied natural gas (LNG). To and Lee [16] reported that the number of haze hours per year increased from 3 in 1986 to 766 in 2007 in Macao. Nevertheless, the number of haze hours per year dropped to 57 in 2016. To and Lee [16] indicated that haze was positively and significantly associated with primary energy use and haze condition improved because Macao imported a significant portion of electricity from its neighboring city—Zhuhai (i.e., burning much less fuel oil and diesel in its power plants) after 2007. Haze in Macao was found to be a local phenomenon due to emissions from the consumption of fossil fuels locally rather than cross-border air pollutants. Gu et al. [17], Liu et al. [18] and Zeng et al. [19] studied the effects of haze on human health. Liu et al. [18] used meteorological, air pollution and mortality data in Guangzhou during the period 2006–2011. A distributed lag linear model showed that light, medium and heavy levels of haze episodes were associated with increased mortality of 3.4%, 6.8% and 10.4% at a lag of 0 to 6 days. The association was more pronounced during the winter months and for males and people aged over 60 [18]. Gu et al. [17] reported the similar association between haze and mortality in Ningbo using the daily meteorological, air pollution and mortality data during the period 2011–2013. They suggested that haze could be used as surrogates of air quality where air pollution data are scarce, unavailable or incomplete. Zeng et al. [19] studied the mortality risk from haze using meteorological and mortality data in the Pearl River Delta region during the period 2013–2016. They reported that haze significantly increased mortality, particularly for the elderly. Additionally, haze-induced mortality risk increased when the duration and intensity of haze increased [19].

## 3. Materials and Methods

### 3.1. Data and Data Sources

Data were extracted from various issues of the Shenzhen Statistical Yearbook—1990 to 2020 [55], various issues of the Shenzhen Municipal Statistical Communiqué on Economic and Social Development—2000 to 2020 [56], and the Meteorological Bureau of Shenzhen Municipality's website. Specifically, Shenzhen's GDP data, population data, the number of haze days per year, total gross output values of industry and its percentage from the computer, communication and electronic product manufacturers, the number of units produced by these manufacturers and the corresponding energy use of these manufacturers were input to a Microsoft Excel file. Shenzhen's GDP, population, GDP per capita, haze days per year and the composition of GDP from 1980 to 2019 were presented as tables, and line and stacked graphs. Shenzhen gross output values of industry were presented as a line graph. The numbers of units produced such as computers, printers, hard drives, mobile phones, electronic components and semiconductor integrated circuits were summarized in a table.

### 3.2. Environmental Kuznets Curve

An environmental Kuznets curve is a hypothetical and an inverted U-shaped relationship between an environmental change and a country's or city's economic development. It argues that environmental condition first deteriorates, reaches a certain peak level and then improves as the country's or city's economy continually evolves. As this idea follows what Simon Kuznets—a Nobel laureate in economics who suggested that income inequality would first rise but then would fall when a country's economic condition kept improving [57] proposed closely, the inverted U-shaped curve is named after him (i.e., Kuznets) [58]. Researchers have investigated the relationship between environmental degradation and economic growth in different countries [59–62]. The World Bank [59] and Munasinghe [60] reported that environmental degradations including all kinds of air pollutants per capita and economic development based on income per capita resembled an environmental Kuznets curve. Neagu [61] analyzed $CO_2$ emission and economic complexity index data in 25 European Union countries during the period 1995–2017. She reported that $CO_2$ emission had an inverted U-shaped relationship with economic complexity index in France, Finland, the United Kingdom and the European Union as a whole. Xu et al. [62] studied the relationship between $CO_2$ emission and urbanization in the Pearl River Delta and identified the relationship displaying an inverted-U shape. However, the inverted U-shaped curves identified by Xu et al. [62] were not obvious because the Pearl River Delta has ongoing rapid economic development in the past decade. In the present study, haze days per year was used as a proxy indicator of environmental change/degradation while GDP per capita was used as a proxy indicator of economic development in Shenzhen. A log-log plot was used to determine whether environmental condition first deteriorated, reached a peak level and then improved due to continued economic growth. The environmental Kuznets curve is mathematically expressed as:

$$\ln(HD) = \left(-a\left(\ln\left(GDP_{per\ capita}\right) - b\right)^2 + C\right) \quad (1)$$

where $\ln(HD)$ is natural logarithm of the number of haze days, $\ln(GDP_{per\ capita})$ is natural logarithm of GDP per capita, $a$ and $b$ are coefficients and $C$ is a constant. The quadratic form represents that environmental degradation (in this case to be 'haze') will peak and then decrease when economic condition in terms of GDP per capita continuously improves.

### 3.3. Determination of Energy Use and the Associated GHG Emission in the Computer, Communication and Electronic Product Manufacturing Industry

Shenzhen Statistical Yearbooks published energy use data of the computer, communication and electronic product manufacturing industry after 2008. Additionally, the Yearbooks categorized the consumption of energy in terms of crude oil, gasoline, kerosene, diesel oil, fuel oil, LPG, natural gas (NG) and electricity. The combustion of fossil fuels such as oil products and natural gas would produce GHG such as carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) [4,63]. Table 1 presents the conversion and emission factors of different fuels used in Shenzhen.

**Table 1.** Conversion and emission factors of fossil fuels.

| Fuel | Calorific Values | GHG Emissions kg/TJ | | |
|---|---|---|---|---|
| | | $CO_2$ | $CH_4$ | $N_2O$ |
| Crude oil | 42,300 MJ/ton | 73,300 | 3 | 0.6 |
| Gasoline | 44,300 MJ/ton | 69,300 | 3 | 0.6 |
| Kerosene | 43,800 MJ/ton | 71,900 | 3 | 0.6 |
| Diesel oil | 43,000 MJ/ton | 74,100 | 3 | 0.6 |
| Fuel oil | 40,400 MJ/ton | 77,400 | 3 | 0.6 |
| LPG | 47,300 MJ/ton | 63,100 | 1 | 0.1 |
| NG | 369,230 MJ/10,000 $m^3$ | 56,100 | 1 | 0.1 |

Note: Calorific values and emission factors of fossil fuels were obtained from Chapters 1 and 2 of Volume 2 (Energy) of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [63].

In order to determine the total energy use of Shenzhen's computer, telecommunication and electronic product manufacturing industry, the consumption of fossil fuels and electricity was obtained from the Statistical Yearbooks published by the Shenzhen Municipal [55] and the following equation was applied:

$$ENERGY_{Total,k} = 10^{-6} \times \sum_{i=1}^{m} C_i W_{i,k} + 3600 \times ELEC_k \quad (2)$$

where $ENERGY_{Total,k}$ was in TJ, $C_i$ was the conversion factor for the $i$th fuel given in Table 1, $W_{i,k}$ was the amount of the $i$th fossil fuel consumed from the Yearbook in the year $k$ and $ELEC_k$ was the consumption of electricity in the year $k$.

The Intergovernmental Panel on Climate Change (IPCC) reported that $CH_4$ and $N_2O$ have relatively large influences on global warming compared to $CO_2$ [64]. IPCC suggested that the global warming potentials of $CH_4$ and $N_2O$ relative to $CO_2$ should be set to 28 and 265, respectively, based on cumulative forcing over 100 years [64]. Emission factor of electricity was set to 726 g $CO_2$-eq/kWh because researchers reported that the production of 1kWh electricity generated 715 to 736.8 g $CO_2$-eq in China [65,66]. This value was about the same as emission factor of electricity in Hong Kong at 722 g $CO_2$-eq/kWh in which a portion of electricity was generated by nuclear power in Daya Bay Nuclear Power

Plant [4,67]. Thus, Equation (3) was used to determine the total GHG emission due to energy use in a particular sector/industry:

$$GHG_{Total,k} = EF_i \times \sum_{i=1}^{m} ENERGY_{i,k} + EF_{Electricity} \times ELEC_k \quad (3)$$

where $GHG_{Total,k}$ was in tonnes/kg $CO_2$-eq, $EF_i$ was emission factor for the $i$th fuel given in Table 1, $ENERGY_{i,k}$ was the energy of the $i$th fossil fuel consumed in the year $k$, $EF_{Electricity}$ was emission factor due to the electricity use and $ELEC_k$ was the consumption of electricity in the year $k$.

Additionally, energy efficiency and emission efficiency were given in Equations (4) and (5):

$$Energy\ efficiency_k = \frac{ENERGY_{Total,k}}{Gross\ output\ value_k} \quad (4)$$

$$Emission\ efficiency_k = \frac{GHG_{Total,k}}{Gross\ output\ value_k} \quad (5)$$

where *Energy efficiency*$_k$ was energy efficiency for a particular year $k$, *Emission efficiency*$_k$ was emission efficiency for a particular year $k$, $ENERGY_{Total,k}$ and *GHGTotal,k* were the total energy use and GHG emission and *Gross output value*$_k$ was gross output value for a particular year $k$.

## 4. Results

### 4.1. Shenzhen's Economic Development

Before being demarcated as a special economic zone, Shenzhen was a city of Bao'an County with farmlands, many small villages and small trading areas. The Shenzhen Special Economic Zone was officially established in May 1980 with a land area of 327.5 $km^2$. Its governing area increased dramatically to 1997.5 $km^2$ in July 2010.

Table 2 presents Shenzhen's economic change during the period 1980–2019. It shows that Shenzhen's GDP grew rapidly from USD 0.04 billion in 1980 to USD 403.91 billion in 2019, an increase of nearly 10,000-fold. Based on the GDP data shown in Table 2, the annual compound growth rate in Shenzhen was found to be 51% from 1980 to 1990, 29% from 1990 to 2000, 16% from 2000 to 2010 and 12% from 2010 to 2019. Figure 1 shows a stacked area graph of the composition of Shenzhen's GDP on a yearly basis during the period 1980–2019. It illustrates that Shenzhen's economic structure changed slightly in the past fifteen years. Specifically, the contribution of the tertiary sector to GDP increased steadily from 46% in 2005 to 60.9% in 2019 while the contribution of the secondary sector to GDP decreased steadily from 53.8% in 2005 to 39% in 2019.

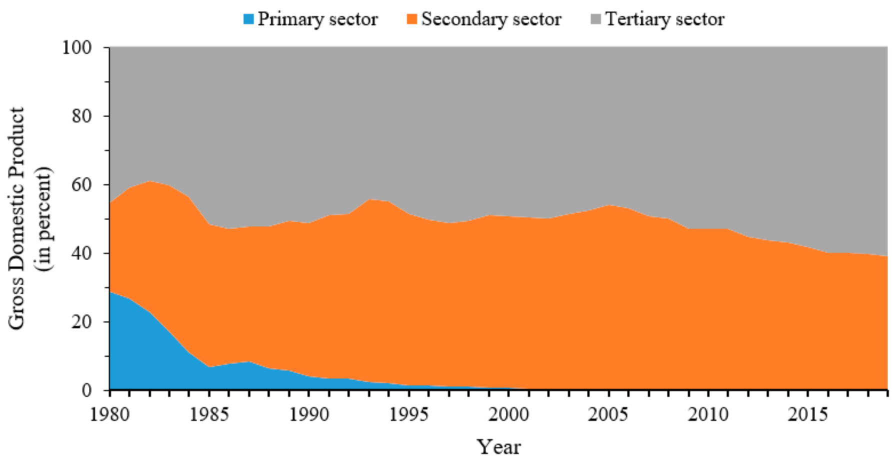


**Figure 1.** Composition of Shenzhen's GDP during the period 1980–2019.

**Table 2.** Gross domestic product (GDP) by economic activity.

| Year | Total GDP in Billion USD | GDP by Sector in Billion USD (Percent) | | |
|---|---|---|---|---|
| | | Primary [1] | Secondary [2] | Tertiary [3] |
| 1980 | 0.04 | 0.01 (28.9) | 0.01 (26.0) | 0.02 (45.1) |
| 1985 | 0.59 | 0.04 (6.7) | 0.25 (41.9) | 0.30 (51.4) |
| 1990 | 2.58 | 0.11 (4.1) | 1.15 (44.8) | 1.32 (51.1) |
| 1995 | 12.64 | 0.18 (1.5) | 6.34 (50.1) | 6.12 (48.4) |
| 2000 | 33.28 | 0.23 (0.7) | 16.63 (50.0) | 16.42 (49.3) |
| 2005 | 75.54 | 0.15 (0.2) | 40.65 (53.8) | 34.74 (46.0) |
| 2010 | 151.04 | 0.09 (0.1) | 70.92 (47.0) | 80.03 (52.9) |
| 2015 | 276.55 | 0.11 (0.1) | 115.31 (41.6) | 161.13 (58.3) |
| 2019 | 403.91 | 0.38 (0.1) | 157.44 (39.0) | 246.09 (60.9) |

Notes: [1] The primary sector is the one making direct use of natural resources. It includes agriculture, fishing, logging, mining, etc. [2] The secondary sector is the one creating finished goods based on the output of the primary sector. It includes manufacturing, construction and the production of electricity and water supply. [3] The tertiary sector is about 'services.' It consists of the production of services instead of end products; thus, may involve the transport, distribution and sale of goods from producers to consumers. Other examples include tourism, finance, professional services and education.

Table 3 shows Shenzhen's population increased from 0.33 million in 1980 to 13.43 million in 2019. Annual data shows that Shenzhen's population increased at about 0.12 million per year between 1980 and 1989. After that, its population increased at about 0.51 million per year until 2000. Since then, its population has increased at about 0.34 million per year. Shenzhen's GDP per capita increased from USD 122 in 1980 to USD 30,078 in 2019, an increase of over 240-fold. Shenzhen's GDP per capita ranked first among China's cities excluding two special administrative regions—Hong Kong and Macao. The number of haze days per year in Shenzhen was also given in Table 3. The number of haze days per year first increased, reached a peak level and then decreased while GDP per capita continually increased in Shenzhen.

**Table 3.** Population, GDP per capita and the number of haze days.

| Year | Population in Million | GDP per Capita in USD | Number of Haze Days per Year [1] |
|---|---|---|---|
| 1980 | 0.333 | 122 | 7 |
| 1985 | 0.882 | 664 | 16 |
| 1990 | 1.678 | 1535 | 15 |
| 1995 | 4.492 | 2815 | 90 |
| 2000 | 7.012 | 4747 | 73 |
| 2005 | 8.278 | 9126 | 161 |
| 2010 | 10.372 | 14,562 | 115 |
| 2015 | 11.379 | 24,304 | 35 |
| 2019 | 13.429 | 30,078 | 9 |

Note: [1] The number of haze days per day peaked in the year of 2004 with 187 haze days.

### *4.2. Environmental Kuznets Curve*

Tables 2 and 3 show that Shenzhen's GDP, population and GDP per capita have increased quite dramatically over the past forty years. On the other hand, Shenzhen's air quality (an environmental condition using the number of haze days per year as a proxy indicator) first deteriorated, reached a rather bad state at 44% of days of a year covered by haze (i.e., 161 haze days in 2005), then improved quite significantly after 2010. Figure 2 shows the graph of the number of haze days per year in Shenzhen versus GDP per capita in log-log form. It demonstrates that Shenzhen's air quality (using haze as a proxy indicator) had an inverted U-shaped relationship with its economic growth (using GDP per capita as a proxy indicator). Thus, the environmental Kuznets curve was applicable to the situation in Shenzhen. A quadratic nonlinear fit was applied to the data from 1988 to 2019 in which GDP per capita and the number of haze days were USD 1086 and 6 in 1988 and USD 30,078 and 9 in 2019, respectively. The coefficients and constant of Equation (1), namely a, b and C, were found to be 0.8529, 8.8416 and 5, respectively.

The number of haze days was predicted using Equation (1) with the coefficients and constant presented in the last paragraph for different values of GDP per capita and the curve was also plotted in Figure 2 in blue. It was observed that the reproduced values of the number of haze days per year closely resembled the measured data. Equation (1) shows that the turning point of GDP per capita was USD 6916 (=exp(8.8416)) with the highest number of haze days per year at 149 (=exp(5)). These values were very close to the observed values in the year of 2003. In fact, the highest number of haze days per year happened in 2004 with a value of 187 and GDP per capita in that year was USD 8149. When the reproduced values of the number of haze days were correlated with the corresponding measured values, it was found that the coefficient of determination (i.e., $R^2$) was 0.731, meaning that 73.1% of variance of the number of haze days per year can be explained by GDP per capita in that year using Equation (1).

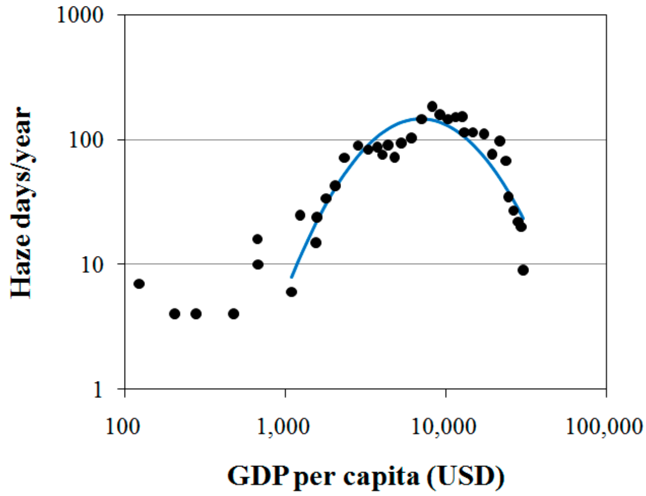


**Figure 2.** The number of haze days per year versus GDP per capita.

### 4.3. *Gross Output Value of Industry and Outputs of the Computer, Communcaition and Electronic Product Manufacturers*

Gross output value of the industry sector (i.e., all industries) in Shenzhen was USD 12.7 million in 1980. It increased to USD 3.2 billion in 1990, USD 44.3 billion in 2000 and USD 560 billion in 2019. Figure 3 shows Shenzhen's gross output value of the industry sector during the period 1990–2019. It illustrates that Shenzhen's gross output value of industry increased continuously, except in 2009 due to the global financial crisis.

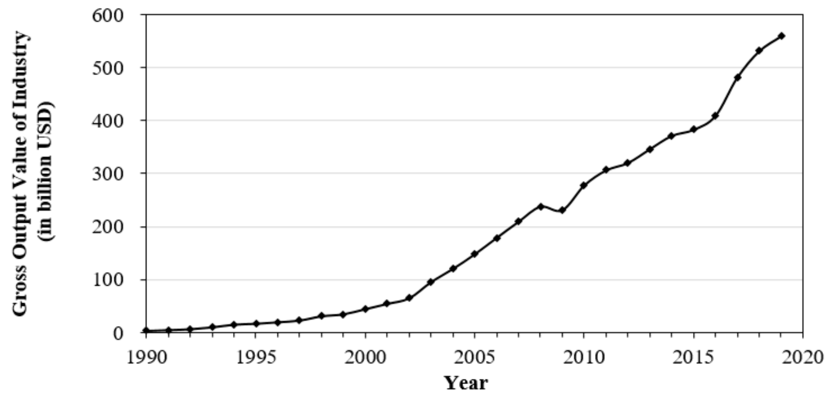


**Figure 3.** Gross output value of industry in Shenzhen during the period 1990–2019.

The computer, communication and electronic product manufacturing industry is one of the key industries in Shenzhen. It alone contributed to 43.8% of gross output value of all industries in 1990. Its contribution to gross output value of industry peaked at 67.1% at 2002. Since then, the contribution of the computer, communication and electronic product manufacturing industry to gross output value of industry ranged from 55.1% to 59.8%.

Table 4 presents outputs of the computer-related manufacturers in Shenzhen during the period 1990–2019. It indicates that the output of the computer-related manufacturers peaked in 2012, producing 52.29 million computers, 22.67 million printers and 82.19 million hard drives. These manufacturers produced 29.47 million computers, 5.39 million printers and 2.61 million hard drives in 2019. Table 4 also shows outputs of the communication-related manufacturers. It indicates that these manufacturers produced the largest number of phones at 436.96 million in 2014. They produced 224.80 million phones in 2019. Table 4 also presents outputs of the electronic product manufacturers. It shows that the number of electronic components increased quick significantly in the past five years, from 111.91 million units in 2015 to 283.04 million units in 2019. Additionally, the number of semiconductor integrated circuits increased from 13.11 million units to 31.04 million units, probably due to the emergence of Internet of Things (IoTs).

**Table 4.** Outputs of computer, communication and electronic product manufacturers in Shenzhen.

| Year | Computer | | | Mobile Phone [2] in Million | Electronic Product | |
|---|---|---|---|---|---|---|
| | Computers [1] in Million | Printers [1] in Million | Hard Drives [1] in Million | | El. Comp. [3] in Million | Semicond. IC [3] in Million |
| 1985 | >0.01 | | | | | |
| 1990 | 0.02 | | | | 3.10 | 0.01 |
| 1995 | 0.19 | 1.95 | 2.00 | | 96.82 | 0.15 |
| 2000 | 1.08 | 5.08 | 8.67 | | 5.27 | 0.88 |
| 2005 | 11.44 | 9.85 | 22.67 | 35.78 | 26.01 | 2.68 |
| 2010 | 34.03 | 19.74 | 68.66 | 320.19 | 218.63 | 12.41 |
| 2015 | 27.79 | 13.05 | 44.40 | 370.31 | 111.91 | 13.11 |
| 2019 | 29.47 | 5.39 | 2.61 | 224.80 | 283.04 | 31.04 |

Notes: [1] Computer-related manufacturers produced the largest number of computers, printers and hard drives in 2012. In that year alone, these manufacturers produced 52.29 million computers, 22.67 million printers and 82.19 million hard drives. [2] Mobile phone manufacturers produced the largest number of phones in 2014. In that year alone, these manufacturers produced 436.96 million mobile phones. [3] Outputs of electronic components and semiconductors/integrated circuits manufacturers continually increased during the period 2015–2019.

Energy Consumption and GHG Emission in the Computer, Communication and Electronic Product Industry

Table 5 presented the consumption of primary energy sources including oil products and natural gas by the computer, communication and electronic product manufacturers in Shenzhen from 2008 to 2019. Table 5 also showed the electricity consumption of these manufacturers in the same period.

**Table 5.** Primary and secondary energy consumed by the computer, communication and electronic product manufacturers in Shenzhen during the period 2008–2019.

| | Primary Energy from Fossil Fuels | | | | | | | Electricity in Billion kWhr |
|---|---|---|---|---|---|---|---|---|
| | Oil Products (in Kilotonne) | | | | | | NG in | |
| Year | Crude Oil | Gasoline | Kerosene | Diesel Oil | Fuel Oil | LPG | Million $m^3$ | |
| 2008 | | 42.48 | 0.35 | 333.10 | 473.84 | 3.25 | 28.64 | 12.46 |
| 2009 | 0.10 | 34.36 | 0.64 | 351.61 | 220.34 | 2.76 | 18.43 | 10.94 |
| 2010 | | 40.10 | 1.00 | 413.80 | 2.18 | 3.37 | 22.98 | 12.59 |

**Table 5.** *Cont.*

| | Primary Energy from Fossil Fuels | | | | | | | Electricity in Billion kWhr |
|---|---|---|---|---|---|---|---|---|
| | Oil Products (in Kilotonne) | | | | | | NG in | |
| Year | Crude Oil | Gasoline | Kerosene | Diesel Oil | Fuel Oil | LPG | Million $m^3$ | |
| 2011 | | 25.90 | 0.14 | 37.75 | 1.94 | 2.99 | 12.21 | 13.00 |
| 2012 | | 23.26 | 0.09 | 28.38 | 1.34 | 2.52 | 20.02 | 10.14 |
| 2013 | | 22.59 | 0.13 | 18.36 | 0.87 | 2.08 | 23.70 | 10.32 |
| 2014 | | 23.67 | 0.06 | 16.11 | 0.34 | 1.72 | 21.27 | 10.65 |
| 2015 | | 27.52 | 0.03 | 13.65 | 0.29 | 2.53 | 19.74 | 10.97 |
| 2016 | | 21.14 | 0.05 | 10.99 | 0.23 | 9.90 | 24.01 | 12.08 |
| 2017 | | 19.47 | 0.06 | 9.74 | 0.54 | 1.08 | 28.15 | 12.33 |
| 2018 | | 18.94 | | 10.96 | 0.15 | 0.64 | 28.25 | 12.85 |
| 2019 | | 18.40 | | 6.91 | 0.11 | 0.40 | 32.62 | 13.96 |

The total energy use of the computer, communication and electronic product manufacturers in a particular year *k* were determined by Equation (2). Figure 4 shows the total energy use of the computer, communication and electronic product manufacturers from 2008 to 2019. In this period, the consumption of energy decreased from 81,433 TJ in 2008 to 39,665 TJ in 2012 and then increased to 52,595 TJ in 2019.

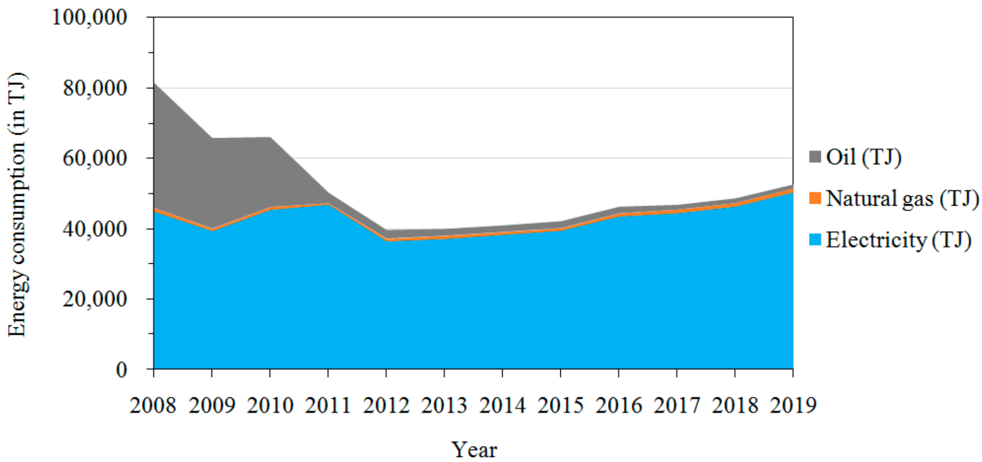


**Figure 4.** Energy consumption by the computer, communication and electronic product manufacturers from 2008 to 2019.

GHG emissions from the consumption of fossil fuels were obtained by multiplying the emission factors shown in Table 2 and the associated energies in TJ. Additionally, emission factor of electricity was about 726g $CO_2$-eq/kWh (ranging from 715 to 736.8 g $CO_2$-eq/kWh) in China [65,66] as illustrated in Equation (2). Figure 5 presents the corresponding GHG emission from the computer, communication and electronic product manufacturers. It shows that GHG emission decreased from 11.8 million tons $CO_2$-eq in 2008 to 7.7 million tons $CO_2$-eq in 2012. After that, GHG emission increased to 10.3 million tons $CO_2$-eq in 2019.

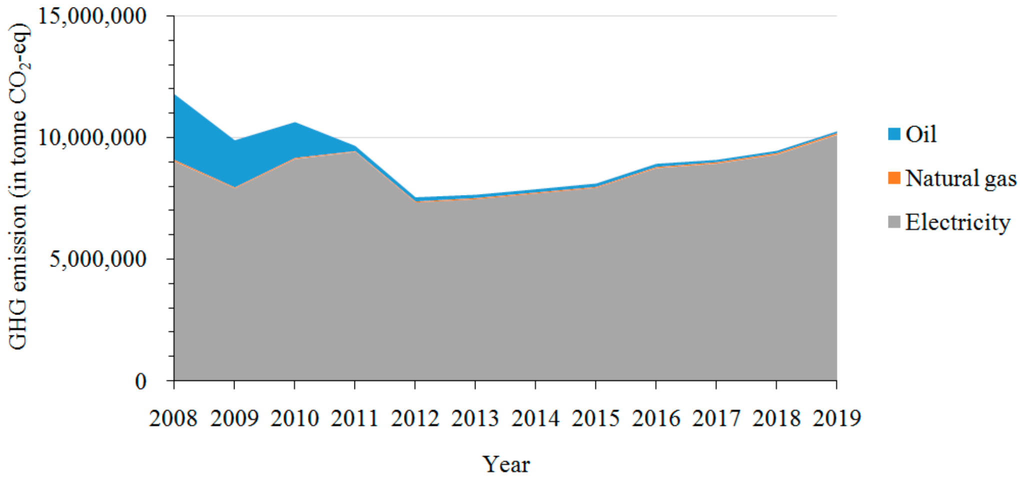


**Figure 5.** GHG emission from the compute, communication and electronic product manufacturers during the period 2008–2019.

Energy efficiency was obtained by dividing the total energy use by gross output value based on Equation (4). Similarly, emission efficiency was calculated by dividing GHG emission by gross output value using Equation (5). Figure 6 presents energy efficiency and emission efficiency of the computer, communication and electronic product manufacturers during the period 2008–2019. It shows that energy efficiency improved from 603,888 MJ/million USD in 2008 to 156,716 MJ/million USD in 2019 while emission efficiency improved from 87.5 tons $CO_2$-eq/million USD in 2008 to 30.6 tons $CO_2$-eq/million USD in 2019.

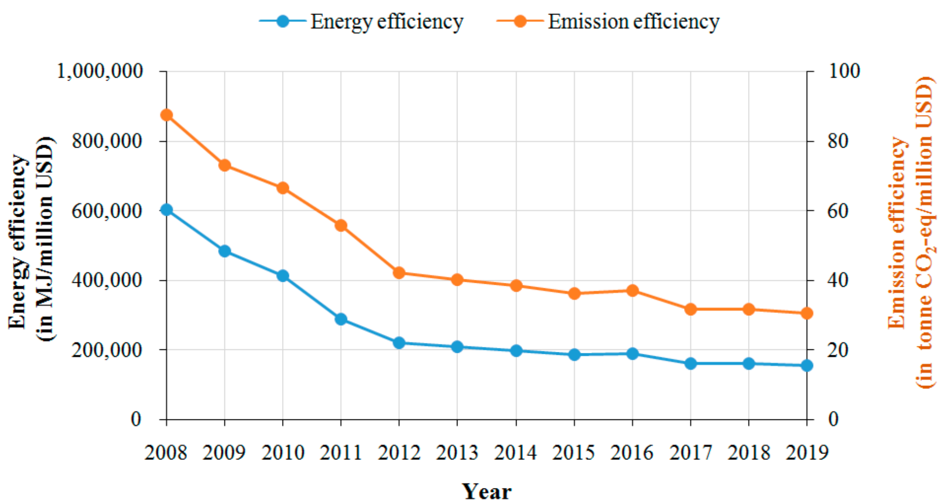


**Figure 6.** Energy efficiency and emission efficiency of Shenzhen's compute, communication and electronic product manufacturing industry during the period 2008–2019.

## 5. Discussion

The study was set to answer four important research questions. The first one was about Shenzhen's economic growth in the past forty years. We reviewed the information from the Shenzhen Statistical Yearbooks and other sources published by the Shenzhen Municipal Government. The truth is that Shenzhen has experienced a phenomenal growth since it was designated as the first special economic zone in China. Shenzhen's GDP reached USD 403.9 billion in 2019, with nearly 10,000-fold increase from USD 40.5 million in 1980. As Shenzhen serves as China's experimentation field and window to the world, many talents from different parts of China move to Shenzhen seeking for opportunities [68]. It is the great passion, diligence, initiative and creativity of entrepreneurs [69] that help

Shenzhen edge Hong Kong and many coastal cities in China as the technological and innovation hub. Additionally, the Government implements favorable entrepreneurial policies such as the construction of science parks and support of co-working spaces [69,70].

The second research question was about how Shenzhen's social and environmental conditions change. It was found that Shenzhen's population increased from 0.33 million in 1980 to 1.68 million in 1990 (i.e., the first 10 years after it was turned into China's first special economic zone. Within the next 10 years, another 5.33 million people called Shenzhen their homes. Between 2000 and 2019, Shenzhen's population increased continually at around 0.34 million per year. At the time of writing this article, Shenzhen has transformed itself from a small village to a megacity [71]. Yet, Shenzhen, like many other cities in the world, has experienced severe environmental pollution during its transformation [16,45,59]. As shown in Table 3, the number of haze days per year was mostly single-digit or no more than 20 in the first 10 years (i.e., between 1980 and 1990). The number of haze days per year increased rapidly in the next twenty years, with a peak of 187 haze days in 2004. Fortunately, Shenzhen's environmental condition (in the form of haze days per year) improved continually and quite dramatically after 2013. The number of haze days was back to single digit in 2019. Thus, the study's findings extended the work of Wang et al. [11,12] who investigated Shenzhen's haze problems up to 2010. Additionally, we confirmed that environmental degradation such as haze problems in Shenzhen was reversed due to continual technological improvement and favorable government policies such as the promotion of electric vehicles and adopting clean and renewable sources for power generation.

The third research question was whether Shenzhen's environmental condition followed an environmental Kuznets curve. The answer to this specific question is "Yes" because we identified that Shenzhen's environmental condition in the form of haze days per year first increased, peaked at certain level when its economic condition improved and then fell when its economic condition further developed. More importantly, we confirmed that the number of haze days per day continuously decreases when economic condition keeps improving after 2010 as expected by the environmental Kuznets curve. This finding complemented Xu et al.'s [62] study who used carbon emissions as a proxy indicator of environmental condition in the Pearl River Delta region but failed to produce a distinct inverted-U shaped curve.

The fourth (and final) research question was about how Shenzhen performed economically and environmentally as a technology hub in southern China. We focused on gross output value and the number of products of the computer, communication and electronic product manufacturers—the key industry in Shenzhen. Data from the Shenzhen Municipal Government showed that gross out value of the entire industry sector was USD 0.56 trillion in 2019 in which approximately 60% was contributed by the computer, communication and electronic product manufacturers. However, it was observed that the production volume of individual industries varied significantly over the years. For instance, the production of computers, printers and hard drives was peaked in 2012 and then displayed negative trends in the units produced. The markets of computers, printers and hard drivers are relatively saturated that their manufacturers suffered low levels of profit margins. Yet the economy of Shenzhen had become fairly highly developed over the same period of time that the cost of production of the city was high in comparison with many other less developed regions in China or Asia, thereby causing manufactures of computers, printers and hard drives to move their operations out of the city. On the other hand, some other products may maintain a high or increasing level of profit margin for different reasons. For instance, mobile phones are still in the growth stage of their product life cycle, and semiconductor integrated circuits have significant advancement in the design and production processes. Thus, such products displayed steady increases in the production volume during the review period of this study. Huawei has massively produced smartphones since 2010. It also has been a leader in the design and manufacture of telecommunications products and networks since 2012. Huawei employed 180,000 people in 2016 with about

80,000 of them focusing on research and development (R&D) [72]. Most of them worked in its Shenzhen's headquarters. Huawei has spent over USD 45 billion in R&D and has achieved significant breakthroughs in a number of 5G technologies in the past decade [72]. With respect to environmental performance of the computer, communication and electronic product manufacturers in Shenzhen, due to the shift from labor-intensive operations such as assembly of computers and printers to the recent highly automated systems for products such as semiconductor integrated circuits, the consumption of fossil fuels such as oil products had reduced significantly from 2008 to 2013. Additionally, high value-added products such as semiconductor integrated circuits sustained the growth of gross value output, making that energy efficiency and emission efficiency were significantly improved by more than 74% and 64%, respectively, during the period 2008 and 2013. These results complemented the work of Quying et al. [73] who studied industrial energy efficiency in the Greater Bay Area including Shenzhen.

## 6. Conclusions

The study reviewed the economic and environmental changes in Shenzhen during the period 1980–2019. It was found that Shenzhen's GDP and population grew by about 10,000 times and 40 times, respectively, in the past four decades. Yet, Shenzhen also encountered environmental degradation due to its transformation. Between 2001 and 2011, over one-fourth of the days each year (i.e., >91 days) were categorized as haze days and the worst year was 2004 in which over half of the year were covered by haze. Fortunately, with the government and business initiatives such as closing fuel-oil power plants, stopping the use of fuel oil in industrial companies and switching from traditional energy-intensive manufacturing approaches to advanced manufacturing processes, air pollutants from industrial settings reduced substantially and the number of haze days decreased back to single-digit in 2019. An environmental Kuznets curve was obtained by plotting the number of haze days per year versus GDP per capita in log-log form. As a technology and innovation hub, the computer, communication and electronic product manufacturing industry still plays a significant role in Shenzhen's economic development. Gross output value of this industry was more than doubled while the emission efficiency of the industry improved by more than 64 percent during the period 2008–2019. Nevertheless, it is suggested that the industry should focus more on high value-added and low energy-intensive technologies and innovations. With the Shenzhen government puts more effort to adopt the use of clean energy sources such as nuclear, wind and solar power, the continual improvement of energy and emission efficiencies in all industries can be achieved. In what follows, the implications and limitations of the study are presented.

Shenzhen is now one of China's most important cities. Due to its rapid and yet consistent economic growth in the past several decades, it is widely considered a role model by many developing cities or regions within or outside China. By integrating and analyzing the official data from multiple sources concerning Shenzhen, this study offered important contributions in four aspects.

First, through our review on the economic growth of Shenzhen in the past forty years, we offered evidence to demonstrate that the benefits (i.e., nearly 10,000-fold of increases in GDP) resulted from successfully developing the economy of a city could be enormous. Other developing regions' governments may learn from the experience of Shenzhen in detail in order to identify insights to formulate their policies for achieving sustained growth in their economies.

Second, this study showed Shenzhen's environmental condition (in the form of haze days per year) first deteriorated, peaked at a certain level when its economy grew and then improved when its economy grew further. The plot of haze days per year versus GDP per capita in Shenzhen in log-log form displayed an inverted U-shaped curve, supporting that environmental Kuznets curve existed in Shenzhen. However, it should be noted that the Shenzhen Municipal Government had done lot of things to curb air pollution. On one hand, the Government encouraged manufacturers to switch from low-cost energy intensive manufacturing to high-end less energy demanding manufacturing. Additionally, the Government increased the use of nuclear power to generate electricity. The first nuclear power plant—Daya Bay Nuclear Power Plant started commercial operation in 1993 while the second nuclear power plant—Ling Ao Nuclear Power Plant started commercial operation in 2002 for its Phase I development and in 2010 for its Phase II development.

Third, the study focused on examining the computer, communication and electronic product manufacturers with respect to their gross value output and the numbers of functional units produced. The findings showed that different manufacturing industries displayed varying levels of economic performance over time. With such insights, governments should tailor make polices to support the development of different industries and such policies should be flexibly modified over time to fit with the development stages of the industry concerned. Additionally, by analyzing the environmental performance of the computer, communication and electronic product manufacturers, this study offered insights that economic growth helped enhancing environmental performance. This is an important finding demonstrating that economic growth benefits not only the wealth of businesses and individuals, but also the natural environment when industrial companies start to embrace environmental goals as strategic imperatives. Governments should formulate policies to strategically leverage on their economic growth to help protect the environment which has been stated clearly in China's 13th and 14th Five-Year Plans to actualize an overall improvement in the country's ecosystems with green practices in production and daily life during the period 2016–2025.

Forth, while many countries and cities across the world suffered huge economic losses due to the Covid-19 pandemic in 2020, Shenzhen still enjoyed a steady economic growth of around 6% increase in its GDP, reaching USD 429 billion in 2020 because it has a rather broad range of secondary and tertiary industries. Hong Kong, as emphasizing too much on tourism and its associated hospitality industries, suffered a contraction of 6.1% in its GDP to USD 349 billion while Macao, as a gambling-dependent economy, suffered a plunge of 56% in its GDP to USD 24.4 billion in 2020 [74].

The study has some limitations. First, although we collected data from the Shenzhen Municipal Government's website and publications, some data such as energy use in various industries were not available before 2008. Second, all data we used were city dependent. Thus, the generalization of this study's findings should be made with great caution. Third, we used haze as a proxy indicator of environmental degradation in Shenzhen. It is very likely that other pollutants might exhibit the inverted U-shaped curve when time passed or GDP per capita increased. We suggest that researchers can test the environmental Kuznets curve hypothesis using other pollutants. We also recommend that researchers can perform similar studies in other technology and innovation hubs in China such as Shanghai, Hangzhou and Hengqin of Zhuhai and overseas such as London and Tel Aviv.

**Author Contributions:** Conceptualization, W.-M.T., P.K.C.L. and A.K.W.L.; methodology, W.-M.T.; formal analysis, W.-M.T.; resources, P.K.C.L.; data curation, W.-M.T.; writing—original draft preparation, W.-M.T.; writing—review and editing, W.-M.T., P.K.C.L. and A.K.W.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by a grant from Kyung Hee University in 2020 KHU-20201224].

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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