Development of Integrated Performance Indicators and Integrated Energy Systems for Smart Cities

by

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An oral defense of this thesis took place on November 6, 2020, in front of the following examining committee:

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

The urge to develop and innovate net zero energy systems for smart city applications has never been more pressing. As the world population is rapidly growing, the global energy demand expands exponentially. The setback with higher energy consumption is the substantial greenhouse gas emissions associated with using fossil-based fuels, which make up the primary energy sources in the world today. This thesis has two main aspects: it introduces a novel and comprehensive smart city concept composed of 8 domains and 32 indicators, which are computed to make the Smart City Index. On the other hand, it introduces four innovative and integrated net zero energy systems for smart city applications. While simple integration of information communication technology (ICT) applications is integral in the development of smart cities, the concept is much more comprehensive to include smart environment, economy, society, governance, infrastructure, transportation, energy, and pandemic resiliency. In this thesis, 20 cities have been analyzed using four distinct weighing scenarios. Based on the sustainability triad scheme, the city with the highest SCI is Toronto at 0.77, whereas the city with the lowest SCI is Abuja at 0.31. Toronto, Vancouver, and Montreal remain part of the top 5 cities in the equal weighting, sustainability triad and energy focused schemes. In fact, the energy focused scheme places four Canadian cities at the highest SCI, with Montreal at the top, scoring 0.7 and Oshawa at 0.66. Life cycle assessment results show that systems 2 and 3 have higher environmental impacts due to their electricity generation through the Organic Rankine Cycle. Human toxicity is the impact category most affected, followed by global warming and acidification. Furthermore, system optimization is completed in order to reach to the optimal design parameters and model selection. System 4 has the highest energy and exergy efficiencies of 74.6% and 62.9% respectively. This system also accounts for the lowest exergy destruction of only 12% of the total systems destruction. Genetic algorithm optimization results reached a plateau after the 20th generation, with the environment, transportation and pandemic categories having the highest scores.

Keywords: Smart Cities; Energy Sustainability; Energy Systems; Clean Fuels; Energy Storage

AUTHOR'S DECLARATION

STATEMENT OF CONTRIBUTIONS

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

ACKNOWLEDGEMENTS

“Say, "In the bounty of God and in His mercy - in that let them rejoice; it is better than what they accumulate.” (Quran, 10:58).

It has been a long and adventurous journey and now it has come to an end. My deepest appreciation to my mentor and supervisor Prof. Ibrahim Dincer for his wise guidance, insightful scholarship, and inspiring leadership. Not only that I have specialized in science and engineering, but it was also a journey of self-exploration and life-coaching with Prof. Dincer. I feel privileged to have absorbed his life paradigm and extraordinary work ethics.

Shifting from work to home, I salute my loving parents, Mohammad Abu-Rayash and Hanan Al-Awadi for providing me with a loving and motivating home. They are my true inspiration, and I would not have reached this auspicious milestone in my life without their guidance and support, for they have instilled in me every noble character that I possess. I am indebted to their sleepless nights and years of care and sound mentorship through my childhood, youth, and adulthood. In fact, it was the title that my father gave me as a child “Dr. Azzam” that instigated this journey.

This success would not have been possible without the comradery of Dr. Yusuf Bicer, Dr. Abdullah Al Zahrani, Ali Ismael and my colleagues in Prof. Dincer’s research group. I sincerely cherish our friendship and colleagueship as I hope to cross paths again in the future.

I embarked on this journey to find answers that will yield in vital benefit to humanity and the existence of the human race on earth. My genuine care and passion for this earth is the stem of pursuing this research. As inheritors and caretakers of earth, its ecosystems, various species and the betterment of the human race, I am convinced that it is our duty to preserve this precious gift. To do that, we as humans must stop being arrogant by treating everything else as commodities. Animals, plants, mountains, and every other species are nations just like us, and they have social communities, languages, and even feelings, that we must be considerate of. In fact, particle swarm optimization is a computational science method that was inspired by other species such as bird flocks and fish schools.

Our anthropogenic activities and egoistical approaches have caused corruption, resulting in detrimental impacts globally, including adverse human health impacts. I wanted to find viable and practical solutions to these trending phenomena of capitalistic and consumeristic lifestyles. I hope this humble work can be of benefit and can result in a greener and brighter future.

Lastly, I rejoice today and hope to be rewarded for my efforts in the afterlife. Alhamdulillah (Thank God) for giving me the strength, steadfastness and perseverance to complete this work and I am hopeful that He accepts this as a small token of love and appreciation for the precious gifts and bounties He has bestowed upon us all.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Area (m^2)
$\dot{C}$	Cost rate ($/kWh)
c	Cost ($)
Cp	Specific heat at constant pressure (kJ/kg K)
E	Energy rate (kW)
ex	Specific exergy (kJ/kg)
$\dot{E}x$	Exergy rate (kW)
h	Specific enthalpy (kJ/kg)
I	Current (A)
I	Irradiance (W/m^2)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
N	Number
$\dot{Q}$	Heat transfer rate (kW)
P	Power (kW)
R	Reflectance
s	Specific entropy (kJ/kg K)
S	Entropy (kJ/K)
T	Temperature (°C or K)
V	Cell potential (V)
W	Work (kJ)
$\dot{W}$	Work transfer rate (kW)
$\dot{Z}$	Capital maintenance and operation cost

Greek letters

η_{en}	Energy efficiency
η_{ex}	Exergy efficiency

Subscripts

batt	Battery
chg	Charge
des	Destruction
dischg	Discharge
en	Energy
eva	Evaporator
ex	Exergy
gen	Generation
geo	Geothermal
HPT	High pressure turbine

i	State number
in	Inlet
out	Outlet
s	Source or sink
0	Ambient condition

Superscripts

.	Rate
°	Degrees

Acronyms

BAU	Business as usual
CAES	Compressed air energy storage
CPV	Concentrated photovoltaic
CSP	Concentrated solar power
DHW	Domestic hot water
EBE	Energy balance equation
EES	Engineering equation solver
ExBE	Exergy balance equation
GA	Genetic algorithm
GHG	Greenhouse gas
GWP	Global warming potential
ICT	Information and communication technology
IEA	International energy agency
IESO	Independent electricity service operator
IPCC	International panel on climate change
ISO	International organization for standardization
LCA	Life cycle assessment
MBE	Mass balance equation
NOx	Nitrogen oxides
NZEB	Net zero energy building
NZEC	Net zero energy community
NZEF	Net zero energy farm
NZEH	Net zero energy house
ORC	Organic Rankine cycle
PSO	Particle swarm optimization
PV	Photovoltaic
PV/T	Photovoltaic/thermal
SOx	Sulfur oxides
TES	Thermal energy storage
TRACI	Tool for the reduction and assessment of chemical & environmental impacts

Chapter 1: Introduction

Cities are important and critical metropolitan hubs that drive the economic, social, and environmental aspects of societies. Understanding the various aspects that could transform and assess our cities for their smartness therefore becomes critical.

1.1 Importance of Cities and Global Population

Metropolitan areas act as a hub for significant segments of society to come close together and initiate civilizations. Despite the fact that these metropolitan areas or cities only occupy less than 5% of the earth's land area, they consume more than 75% of its natural resources and emit 60-80% of the global greenhouse gases (GHG) (Musango et al., 2017). Figure 1 shows the total world population between 1950 and 2019 along with projected population growth from 2020 and 2100. It is evident that the world population is experiencing significant increase, which demands special attention to cities development in order to be able to handle these dynamic changes.

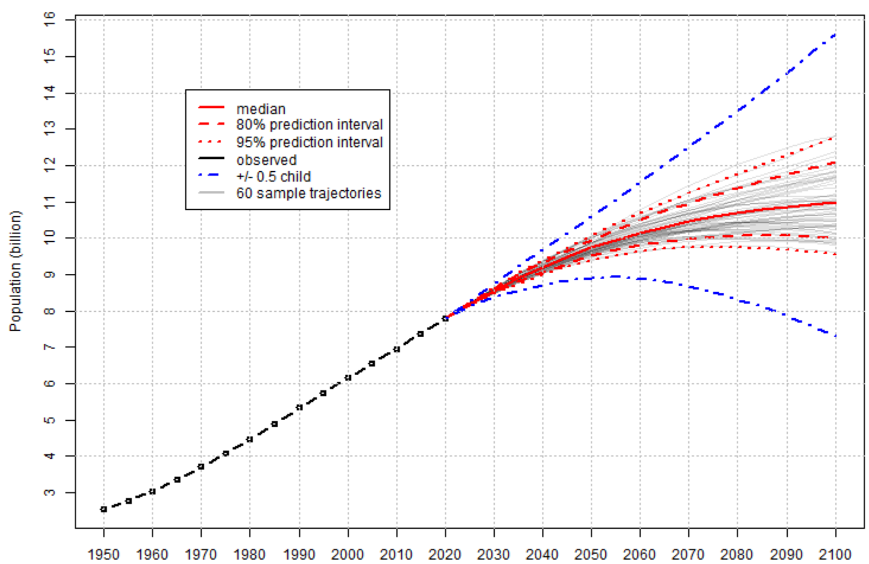


Figure 1.1 Probabilistic projections of the total world population between 1950 and 2100 (Data from: UN WPP, 2019)

Pooling the talents and skills of society members, cities have been the stem for the technological innovation, economic growth, and modernization. The rate at which cities evolve in the 21st century is unprecedented. The digital revolution and continuous technological advancements influence all areas of life including social, economic, and environmental trends. In fact, these continuous novelties lead to a very fast-paced, efficient, and intuitive culture. The critical issue at hand is that amidst this considerable wave of change and reform, cities remain unchanged in terms of infrastructure, municipal organization, and services as well as general processes. This gap introduced the field of smart cities, which intends to revitalize cities in line with available technologies or processes in order to incur financial and environmental savings in addition to scoring socially. Furthermore, the large expansions of cities along with the massive wave of reform coming from the digital revolution, have negative impacts on cities and the entire world. For instance, global climate change is a result of irresponsible activities inspired by the rate of change of cities. Moreover, energy security, demographic dynamics, and negative social tendencies are all examples of the side effects to the rate of urbanization. Figure 2 shows the forecast for the global CO_2 emissions based on recorded data between 1960 and 2014.

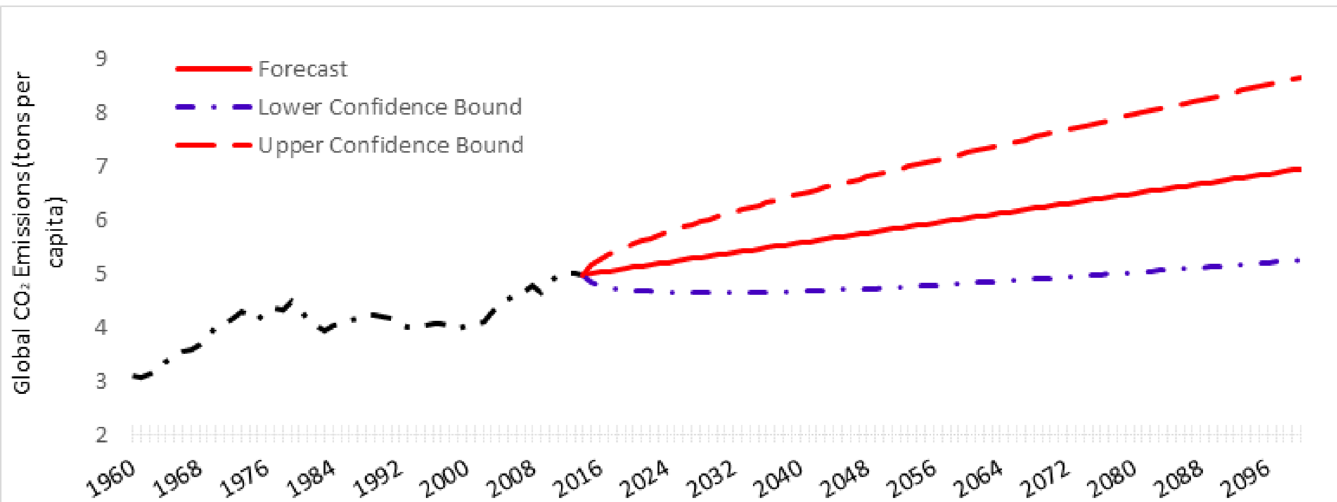


Figure 1.2 Probabilistic projections of the total world CO2 emissions between 1960 and 2100 (Data from: WDI, 2019)

The trends are clearly increasing and as the world population is expected to be growing drastically, the global pollution per capita is projected to increase considerably as illustrated. Therefore, the urge to evolve our cities to smart cities that address the environmental challenges, provide access to infrastructures, deal with mobility, safety, health, and other challenges, never became more pressing. A smart city is a hyper-connected city, where data is shared widely between citizens and governance systems.

As the world continues to use more energy and emit greenhouse gases (GHGs), the environmental impact becomes concerning. The environment refers to the physical and natural environments that encompass all living and nonliving organisms.

Environmental pollution and contamination are phenomena that emerged after the utilization of fossil-based fuels for energy purposes. The total global emissions for 2012 was 51,840 Mt CO_2-eq with the industrial sector accounting for almost one third of the total emissions. Figure 1.3 illustrates the global CO_2 emissions by source and sector for 2013.

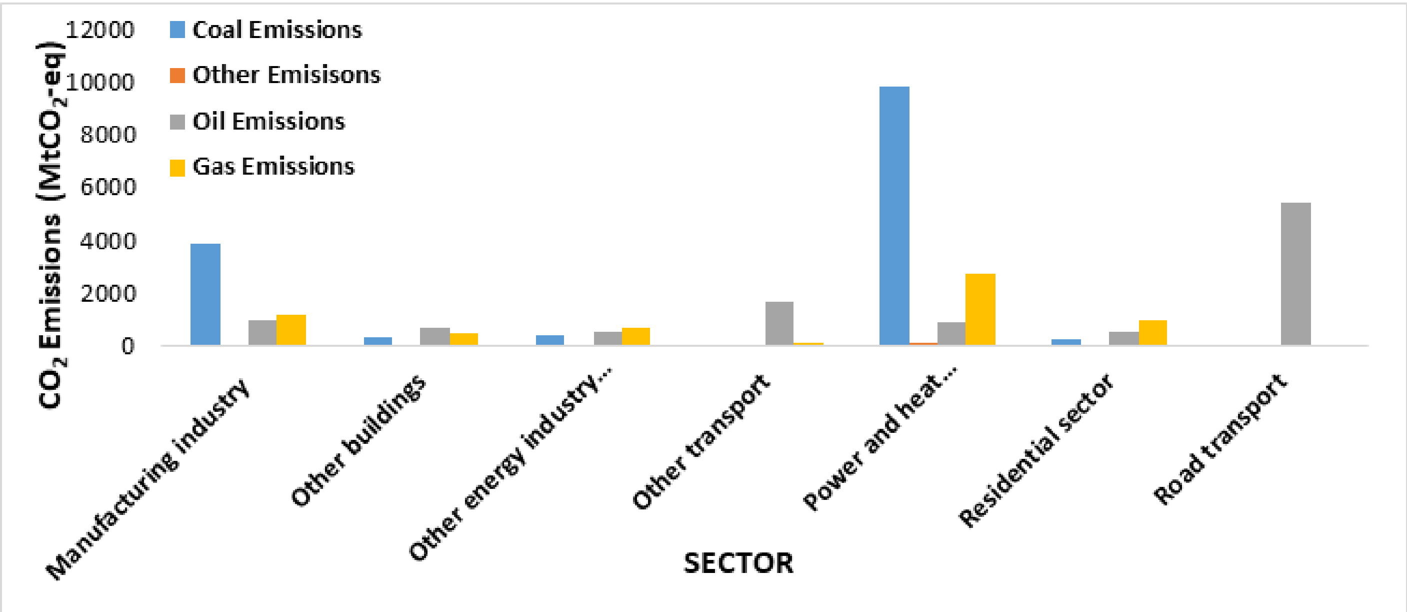


Figure 1.3 Global CO2 emissions by source and sector for the year 2013

1.2 Energy Sustainability

As described in the previous sections, the world is moving into a digital era with rapid increase in population, energy demand, urbanization, and environmental impact. Therefore, adopting sustainable energy solutions and establishing sustainable energy infrastructure becomes a critical priority worldwide.

Energy sustainability is a multi-disciplinary field that aims to optimizing energy systems, conserving energy, reducing cost and emissions associated with energy utilization. Furthermore, sustainability is a complex and interdisciplinary concept, which relates to various domains including resources, environment, economy, education, ethics, public policy, culture, and energy. Moreover, energy sustainability is illustrated using the 3S approach, outlining the cycle of energy from sources to services and with the utilization of storage solutions in between each phase as illustrated in Figure 1.4.

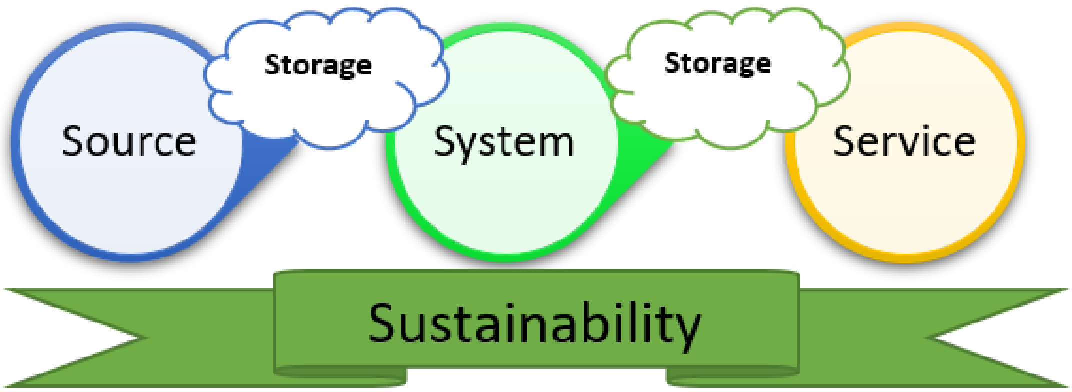


Figure 1.4 The 3S approach to sustainability (Modified from: Dincer and Acar, 2017)

1.3 Energy Demand and Commodity Breakdown

For this thesis, the design parameters revolve around a city with 50,000 dwellings. The approximate energy consumption per dwelling based on (Natural Resources Canada, 2019) is 150 GJ, distributed as illustrated in Figure 1.5.

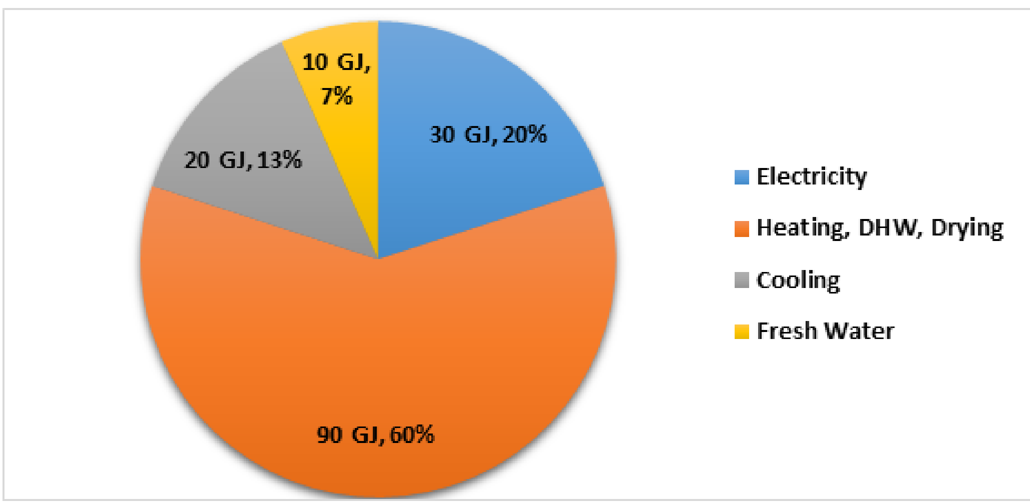


Figure 1.5 Energy demand per dwelling for each useful commodity (Natural Resources Canada, 2019)

Based on this thesis, the four systems are designed to meet the need of 50K households and thus, the demand for each commodity that needs to be met by each system is described in Table 1.1.

Table 1.1 Predicted energy capacity adopted as the demand in this thesis (NRCan, 2019)

Commodity	Capacity
Electricity	50 MW
Heating, DHW and Drying	145 MW
Cooling	35 MW

1.4 Energy Economics

Without a surprise, renewable energy solutions are now the cheapest options available according to IRENA (2018). In fact, the report emphasizes that unsubsidized renewable energy is the most frequent and cheapest source for energy generation. The cost of installation and maintenance of renewables continues towards a downward trajectory, leading to mass adoption. Report findings show a decrease in the global weighted average cost of electricity by 26% for concentrated solar power (CSP), followed by 14% for bioenergy, 13% for photovoltaic (PV) and onshore wind, 12% for hydropower, and finally 1% for geothermal and offshore wind. Other significant findings include the following:

- Without any subsidy or financial support, onshore wind and solar PV options are now less expensive than any fossil-fuel option.
- New wind and solar installations will increasingly undercut even the operating-only costs of existing coal-fired plants.
- Renewable energy has become very competitive and a leading source towards energy decarbonization.
- Utility-scale solar PV total installed cost trends in selected countries between 2010 and 2018 (IRENA, 2018)

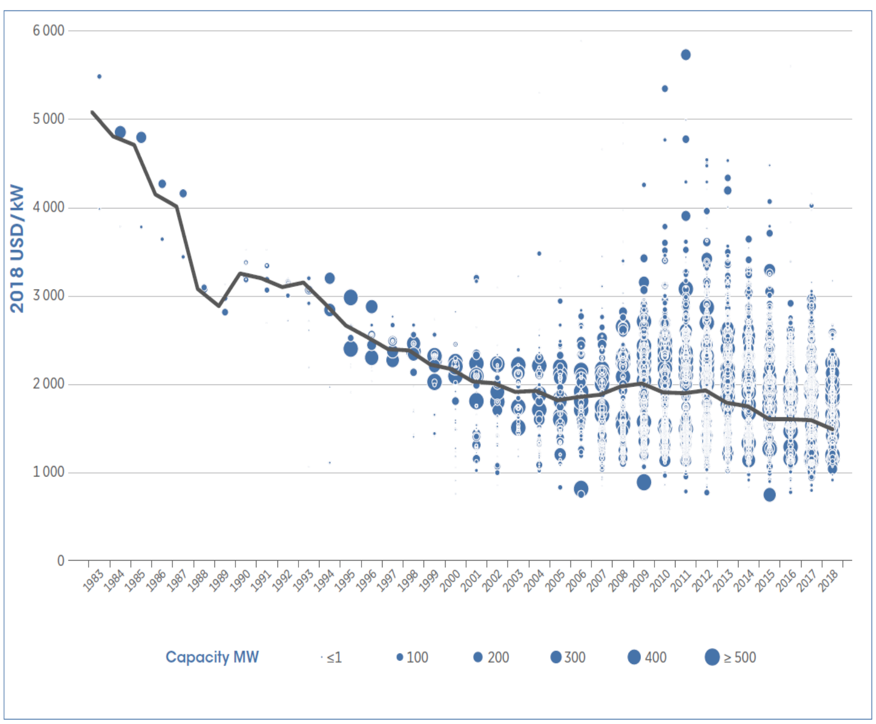


Figure 1.6 Total installed costs of onshore wind projects and global weighted average between 1983 and 2018 (IRENA, 2018)

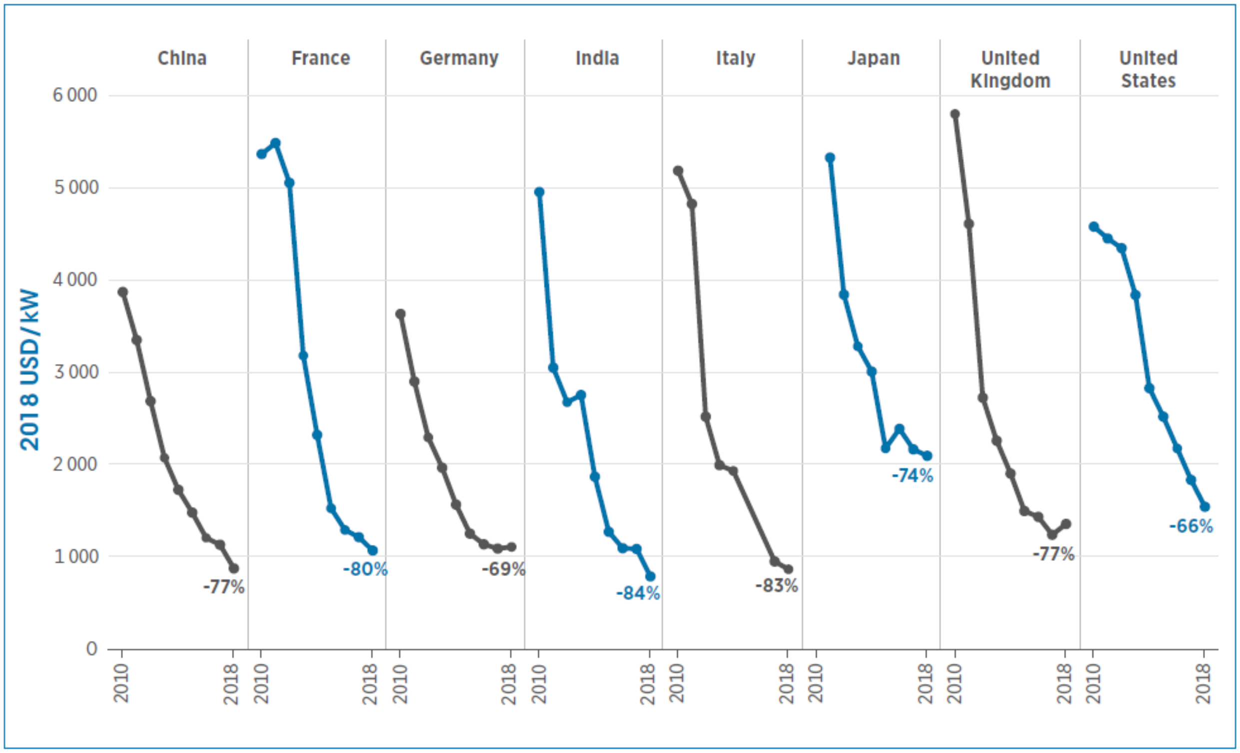


Figure 1.7 Utility-scale solar PV total installed cost trends in selected countries between 2010 and 2018 (IRENA, 2018)

Figures 1.6 and 1.7 show the installed infrastructure for wind and solar PV systems in various countries as of 2018. Connolly et al. (2016) modeled a scenario of 100% renewable energy systems for Europe for 2050. The transition from business as usual (BAU) scenario is analyzed through a series of phases. Environmental and economic impacts along with the energy aspect are assessed for each phase. Results indicate that transitioning to 100% renewable energy in 2050 is technically feasible and cost 10%-15% higher than BAU scenario. However, the additional flexibility due to interconnection between sectors including electricity, heating, cooling, and transport sectors together enables an intermittent renewable penetration of over 80% in the electricity sector. Furthermore, this scenario is expected to create approximately 10 million additional direct jobs within Europe. Maier (2016) conducted a study on smart energy systems for smart districts with a case study on the Reininghaus District. The case study combines on-site energy sources coupled with nearby industrial waste heat along with grid-based resources such as existing district heating, natural gas, and electricity. The study also explores the competition between centralized energy systems such as district heating and heat pumps with decentralized technologies such as small-scale combined heat and power units. Results show that decentralized systems with low-temperature waste heat and decentralized heat pumps in the building groups show the most feasible financial return compared to other options. Kraemer (2017) stresses out that the shift away from fossil fuel energy resources in inevitable and unstoppable. He further analyzes the implications by such a shift and suggests that significant and potentially disruptive impacts in areas of capital formation, international trade, finance, investment, growth and tax revenue will eventually take place. He also suggests that the fossil fuels industry will leave behind “stranded assets”, which refers to worthless commodities. These stranded assets also include stranded industries, infrastructure, and legacies. Ghorab (2019) studied the economic and environmental impact of smart energy systems for community application. He concluded that load sharing between 20 buildings reduces system capacity sizes and capital costs. Furthermore, he claimed that PV technology reduces costs and CO_2 emissions by 80% and 43% respectively. Optimization study took place to minimize the energy economics and environmental impacts of the system.

1.5 Energy System Infrastructure

Lund et al. (2017) conducted a review study on smart energy systems found in the literature and found that the smart energy systems concept represents a paradigm shift in energy management. They also conclude that smart energy systems are those that follow an integrated and holistic approach by integrating the energy need of multiple sectors and treating them. For example, the energy needs for the industrial, residential, commercial and transportation sectors would be addressed altogether and not in silos. Therefore, a notable feature of smart energy systems is the holistic and integrated approach from a sectorial perspective.

Dincer and Acar (2017) investigated the smart energy systems and identify the expectations of such systems to be exergetically sound, energetically secure, environmentally benign, economically feasible, commercially viable, socially acceptable, integrated, and reliable. They also highlight the important of ensuring the smartness of the system throughout all stages of energy from the generation, to conversion and then distribution and use. Dominković et al. (2018) developed an integrated model for smart urban energy systems that included air pollution and CO_2 emissions. The model also explored the interaction between power, cooling, gas, mobility, water and desalination sectors. The study also modeled five different large-scale storage systems. The optimal share of district energy, energy efficiency and renewable supply was found using linear optimization. Lund et al. (2016) studied the optimal solutions for integrating renewable energy. They used an integrated cross-sector approach to argue the most efficient and least-cost storage options for the entire renewable energy system. Their integrated energy system features multiple energy sources including bioenergy fuels, wind and solar that meet the basic demands of mobility, power, cooling and heating. Electrifying the transportation sector is highlighted as necessary to achieve the smart energy system objective. This can be done by using electro fuels or intermediator storage options such as hydrogen. The authors also argue that electricity storage leads to the most expensive form of energy storage, which is 100 times more expensive than thermal storage.

1.6 Energy and Transportation

Bachmann et al. (2013) addressed the urban traffic management challenge by deploying real-time traffic speed estimation using seven multi-sensor data fusion-based estimation techniques. Their results show that most data fusion techniques improve accuracy over single sensor approaches and the improvement by data fusion depends on the technique, the number of probe vehicles, and the traffic conditions. Tu et al. (2018) introduced the development of policies that aim to reduce the transportation GHG emissions by catering policies to specific trips based on their emission intensity. Using microscopic simulation, GHGs (in CO_{2eq}) and nitrogen oxides (NO_x) emissions were estimated by generating second-by-second speed data for entire trajectories. Results indicate that trips originating and ending in the Toronto downtown area are responsible for a small share of total emissions, although they have high emission intensity. On the other hand, trips with high total emissions and high emission intensity have substantial GHG emission contribution. El-Tantawy et al. (2013) addressed the traffic congestion in dense urban areas and introduced a novel system of multiagent reinforcement learning for integrated network of adaptive traffic signal controllers (MARLIN-ATSC) that offers two modes; one that allows traffic signals to operate autonomously whereas the second mode allows for traffic signals to coordinate signal control action. This system was tested in downtown Toronto and results show reduction in the average intersection delay ranging from 27% in mode 1 to 39% in mode 2 at the network level and travel-time savings of 15% in mode 1 and 26% in mode 2, along the busiest routes in downtown Toronto. Sun et al. (2017) explored the information and communication technologies (ICT) needed to enable real-time responses in order to actualize the concept of smart city. Their work also contains the most recent research results in the field of communications, signal processing and computing sciences for facilitating smart homes, buildings, and cities. Zanella et al. (2014) investigated the application of the Internet of Things for smart cities with focus on municipal infrastructure such as street lighting and facility automation systems as well as the environment by focusing on parameters such as air quality and climate change. Their research featured practices of the Padova smart city project as proof of concept. Monzon (2015) examined the smart city concept in a very comprehensive manner, taking into consideration challenges that cities face in areas of governance, economy, mobility, environment, living standards and people. His research proposes Projects Guide as a tool for the implementation of Smart City projects that efficiently respond to complex and diverse urban challenges without compromising their sustainable development and while improving the quality of life of their citizens. Kamel et al. (2016) explored the role of big data simulation in addressing the transportation domain. Thye presented a model for the GTA transportation network using artificial intelligent techniques. Ouoba et al. (2016) investigated the deployment of ICT-based technologies in the public transportation sector for Sub-Saharan Africa. Results show the advantage of integrating ICT solutions to provide more efficient and satisfying public transportation services. Poxrucker et al. (2016) introduced a large-scale multi-agent simulation tool for simulating adaptive, personalized, multi-modal mobility. Real-world data is used to calibrate the model for more accurate results.

Chapter 2: Literature Review and Background

The concept of smart cities is novel and multidisciplinary. While it could be complex, some have tried to simplify it in order for it to be practical and applicable. There are various definitions for smart cities, all revolving about similar concepts. Research around net zero energy buildings, farms and communities have matured. However, net zero energy cities remain a hub for evolving methodologies and ideas. In fact, Hoornweg (2016) proposes that cities are less transient than countries and they are the hub of market and wealth generation. He also proposes that cities should be the most responsive level of governance with least distortion and uncertainty.

2.1 Smart City Concept

The definition of smart city or smart energy city needs clarification. In fact, there is no universally adopted definition for smart cities. Besides, many terminologies are used interchangeably in this discipline including intelligent cities, sustainable cities, eco-cities, and digital cities (De Jong, 2015). On the other hand, (Calvillo et al., 2018) provides a more concise definition for a smart city and states" "A smart city is a sustainable and efficient urban center that provides a high quality of life to its inhabitants through optimal management of its resources." In their research, they classify specific energy-related activities as energy interventions including energy generation, energy storage, infrastructure, facilities and transport. While this classification addresses the energy source and storage aspects, energy service is limited to the transportation sector and the facilities. In fact, energy services cover a wider range than simple transportation and facilities consumption. Caragliu et al. (2011) defined some criteria for a city to be smart as such: "city to be smart when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance."

The concept of smart cities has been the center of research in the past decade with focus on digital integration and utilization of advanced technologies, the Internet of Things and artificial intelligence in automating processes and optimizing decision-making. Therefore, this topic is heavily studied and explored from a software engineering perspective and seldom were smart energy systems discussed or researched. Maheswari (2011) introduced the concept of energization instead of electrification and used genetic algorithm along with neural network and fuzzy logic to find the optimal size while minimizing cost and maximizing reliability of energy systems for rural applications. He developed energy systems for a small rural town of 700 people, 120 homes and 450 cattle and introduced a model named Smart Integrated Renewable Energy System. On the other hand, Xie (2014) explored system modeling of renewable energy systems from a supply chain perspective. He investigated the biofuel supply chain system design and considered environmental and transportation domains. He used mixed integer programs to better understand how to achieve cost efficient and environmentally friendly biofuel supply. He also conducted superb optimization work with the objective function of minimizing cost and maximizing environmental friendliness. Furthermore, Sharif (2015) investigated the municipal utilities and the corporate social responsibility (CSR) adoption. He took into consideration the style of municipal management, the intensity of green practices adoption. The CSR was explored in detail including the legal, governance structure, operational, spatial, and temporal aspects. Moreover, See Tao (2017) developed a methodology to primarily visualize the energy sustainability problem using a holistic system thinking approach. He evaluated key phenomena associated with sustainable energy systems and his thesis aimed to raise awareness about energy and its assessment. Finally, Alawdah (2017) addressed the gap between the theory of smart city and the actual practice. By using pragmatic qualitative research design methods, she analyzed 34 US smart-designed cities. She also developed a taxonomy that includes 144 initiatives.

The smart city concept can be very subjective and ambiguous. In fact, (Desdemoustier, Crutzen, & Giffinger, 2019) have explored the perceived understanding of 113 Belgian municipalities on their understanding of smart cities. Their results show that municipalities view the smart city concept from four viewpoints: technological, societal, comprehensive, and nonexistent. In fact, a comprehensive methodology for planning and assessing the development of smart energy systems leading to complex energy provision technology networks using both on-site and off-site resources is proposed by (Maier, 2016). In this case study, various energy sources including a solar system, coupled with an industrial waste heat recovery system along with grid-based resources such as district heating, natural gas and electricity are all combined. In addition, this case study features centralized technologies such as large-scale combined heat and power and district heating and decentralized technologies such as boilers and solar collectors. Their results show that decentralized systems with low-temperature waste heat and decentralized heat pumps in buildings are most feasible financially and ecologically. These results can be questionable as centralized systems such as district heating and cooling are proven to be more environmentally benign with larger financial investments needed. Methods used in this study include the Process Network Synthesis (PNS), the Energy Long-term Assessment of Settlement Structures (ELAS), and the Sustainable Process Index (SPI). On the other hand, smart cities in future energy system architecture is explored by (Mekhdiev, Prokhorova, Makar, Salikhov, & Bondarenko, 2018), where they investigate the impact of future electric power systems on production, storage, transmission, distribution and consumption of electricity.

In addition, Mosannenzadeh et al. (2017) provides a multidisciplinary and a comprehensive definition of smart energy city by integrating the application of information communication technology (ICT) with various domains and the collaboration of key stakeholders. The principles in development smart energy cities according to them revolve around energy conservation, efficiency, and renewable energy. While energy management is extremely important for smart cities, principles are missing economic, social and environmental aspects. A Superconducting Magnetic Energy Storage (SMES) system is simulated for the use of the Spanish electricity network with various advantages and disadvantages including the high cost of construction and operation (Colmenar-Santos, Molina-Ibáñez, Rosales-Asensio, & López-Rey, 2018). Moreover, a comprehensive framework for smart cities including a holistic energy model is presented by (Fokaides, Apanaviciene, & Klumbyte, 2018), where the main parameters of an intelligent city are outlined along with discussion on different standards and initiatives for smart cities. In addition, technical standards and standardization initiatives are discussed along with recent advancement in the field of energy management in smart cities including metrics, handling of big data, and the role of zero energy buildings and lifecycle assessment in the smart city vision. Smart cities from an information systems (IS) perspective is presented by (Ismagilova, Hughes, Dwivedi, & Raman, 2019) by focusing on smart mobility, smart living, smart environment, smart citizens, smart government, and smart architecture as well as related technologies and concepts. This work also alludes to the relationship between smart cities and the UN sustainable development goals. They also claim that the technological aspects of smart cities have been extensively researched within literature, but more recent studies have taken a holistic IS perspective focusing on aspects such as citizens, quality of living and sustainability.

Moreover, implementing smart city policies and their impact on energy and greenhouse gas reductions in urban transport, and building construction and operation is investigated (Wang & Moriarty, 2019). Some challenges highlighted by smart cities include privacy and security as well as reliability. The integration of energy management between residential and transportation sectors is investigated by (Calvillo, Sánchez-Miralles, & Villar, 2018), where a linear programming model to find the optimal operation and planning of distributed energy resources (DER) in a residential district, while considering electric private and public transport systems, in particular electric vehicles and metro is presented. These two sectors are specified as they account for a significant amount of energy consumption in metropolitan areas.

Results show important cost savings in the overall system, especially a significant power cost reduction for the metro system. The objective function proposed in this study minimizes the costs of all the considered systems including the metro, the EVs and the prosumers (producer-consumers) of the district modeled in an aggregated manner. Variables pertaining to energy consumption are used by (Caponio, Massaro, Mossa, & Mummolo, 2015) when planning the energy management for residential buildings in a smart city model using a System Dynamics approach. Variables include population, costs and benefits, energy savings, emissions, energy consumption rates and emission factors in addition to other factors.

Municipalities of rural areas had little understanding of smart cities, which was interpreted as a sign of rejection to the smart city concept in these areas. On the other hand, medium and large-sized municipalities adopt a more comprehensive and societal understanding of smart cities. Therefore, this work shows a dichotomy in the understanding of smart cities between peripheral and central municipalities. In order to answer the question of what makes a city smarter, (Camboim, Zawislak, & Pufal, 2019) investigated this topic in light of current literature, interviews with experts as well as insights from various smart cities projects across the world. Their results shows that a smart city is “an urban innovation ecosystem where knowledge easily flows from a deliberated interaction and collaboration among different stakeholders to create wealth, supported by a flexible institutional structure, an integrated-participative governance model, a digital-green infrastructure and a functional urban design with diversified amenities and facilities.” (Camboim et al., 2019).

Review of existing concepts and implementation cases for smart cities along with the main challenges is conducted by (Strasser, Siano, & Ding, 2019). They highlight that suitable methods are still needed to handle complex networks of actors, especially with competing objectives, while determining design and operational decisions for systems across a wide spectrum of features and timescales.

These intelligent solutions for control and operational excellence are often driven by the goal of reducing energy consumption, emission or reducing costs, while maintaining energy sustainability and robustness (O'Dwyer, Pan, Acha, & Shah, 2019). Furthermore, energy management in future cities is investigated in detail by analyzing energy management and optimization problems, demand response approaches, energy market concepts, microgrid control, energy storage system applications, metering and sensor technology (Mohammadi et al., 2018).

2.2 Energy Systems for Smart Cities

Amft et al. (2011) explored various methods for building automation towards establishing smart infrastructure systems. Behavioural methods were also investigated including information sharing between the utilities and consumers for more efficient and cognizant energy consumption. Furthermore, automating energy systems based on metadata such as forecasted solar radiation, wind speed, temperature and humidity is discussed.

Lund et al. (2016) emphasize that smart energy systems approach is cross-sectorial and inclusive to the entire energy system in its identification of suitable energy infrastructure designs and operation strategies. Most effective and cost-efficient energy solutions are actualized when combining sectors such as electricity, heating, cooling and transportation together.

Furthermore, the combination of electricity and gas infrastructures could also result in a practical design of future renewable energy systems. The authors also highlight the urge for a 4^{th} generation district heating design to be adopted. Such designs revolve around the combination of low-temperature district heating resources and heat savings. Table 2.1 summarizes the main research already conducted in this field and their research focus.

Table 2. 1 Summary of literature review including the area of research and main findings

Researcher	Area of Research	Description
Giffinger et al. (2007)	Smart City Assessment	Developed a model to assess smart cities by considering six characteristics, 31 factors and 74 indicators; providing an integrated assessment that attempted to include the opinions of decision makers
Maheswari (2011)	Software	Introduced the concept of energization instead of electrification and used genetic algorithm along with neural network and fuzzy logic to find the optimal size while minimizing cost and maximizing reliability of energy systems for rural applications
Manville et al. (2014)	Smart City Assessment	Examined European cities for smart initiatives and projects following the six dimensions of smart cities, integrated with three core factors impacting these dimensions: technology, human and institutional factors
Monzon (2015)	Smart City Development	Developed a tool for the implementation of Smart City projects that efficiently respond to complex and diverse urban challenges
Lund et al. (2016)	Energy Systems	Investigated optimal solutions for integrating renewable energy. They used an integrated cross-sector approach to argue the most efficient and least-cost storage options for the entire renewable energy system
Hamzah et al. (2016)	Smart City Assessment	Modified Giffinger et al.'s model to assess a city's smartness. They have done this by incorporating the six smart city dimensions with the city's main function; the city's planned smart initiatives, city stakeholders' actual requirements and on-the-ground smart initiatives.
Adnan et al. (2016)	Smart City Performance	Proposed a simpler approach (a modification of Giffinger's) based on qualitative assessment of initiatives data.
Dincer and Acar (2017)	Energy Systems, Economy, Environment, Social	Investigated the smart energy systems and identify the expectations of such systems to be exergetically sound, energetically secure, environmentally benign, economically feasible, commercially viable, socially acceptable, integrated, and reliable
Alawdah (2017)	Social, Economy	Addressed the gap between the theory of smart city and the actual practice. By using pragmatic qualitative research design methods, she analyzed 34 US smart-designed cities. She also developed a taxonomy that includes 144 initiatives
Dominković et al. (2018)	Energy Systems	Developed an integrated model for smart urban energy systems that included air pollution and CO_2 emissions. The model also explored the interaction between power, cooling, gas, mobility, water and desalination sectors
Hunter et al. (2018)	Energy Systems, Economy, Environment, Infrastructure	Assessed the sustainability of smart energy cities for various projects throughout Europe and concluded that integration of various sectors in the city at the planning stage including buildings, transportation, ICT and energy technologies will result in social, environmental, economic and governmental-related benefits.
Victoria et al. (2018)	Smart City Development	Developed a holistic framework for assessing and interrelating smart city projects and urban challenges in a specific region and for evaluating the projects' potential to generate effects. A generalized Smart City Projects Assessment Matrix (SC[PAM]) is proposed as a tool and applied to the South and East Mediterranean Region at both the regional and project levels.

2.3 Motivation and Objectives

This section discusses the motivation and the objectives behind this thesis in further detail. The motivation is highlighted along with the specific research objectives. The research novelties and the contribution of this thesis to knowledge is also summarized in this section.

2.3.1 Motivation

Smart energy cities lead to the optimization of processes by integrating renewable energy solutions, increasing economic performance as well as yielding in environmentally friendly cities. Therefore, this thesis aims to develop a smart city concept by considering various domains and to design and assess integrated smart energy systems for smart city applications. Moreover, while NZEB, NZEH, NZEF, and NZEC have been investigated previously in the literature. The topic of net zero energy city remains open with minimum research conducted on the topic, making it a hotspot for research and development.

2.3.2 Objectives

This thesis aims to develop a conceptual model of a net zero energy smart city that can realistically be implemented. The specific objectives of this thesis are as follows:

- *Establish a comprehensive concept development methodology for the smart city model.*
    - To develop a novel methodology to characterize smart cities and assess their smart performance based on eight main domains.
- *Developing integrated and energy-efficient systems for city applications.*
    - To develop integrated net zero energy systems for smart city applications.
    - To integrate the energy systems to provide essential energy services.
    - To evaluate the performance of these energy systems from energetic and exergetic aspects.
    - To conduct thermodynamic, economic, and environmental impact assessment studies of these energy systems.
    - To analyze the economic, technical, and environmental aspects concerning smart cities.
- *Conducting a complete lifecycle assessment to compare the different environmental impacts of the various systems.*
    - To carry out a lifecycle assessment (LCA) for the developed systems.

- *Performing an optimization study to determine the combination of parameters for optimal results, given the objective function and constraints.*
    - To conduct optimization studies in order to find the optimum design parameters given the objective function and the set constraints.

2.4 Novelties

This thesis is also unique because it addresses a gap in the literature concerning smart cities development. This topic has been researched in detail from various aspects, especially the software engineering aspect, the supply chain aspect, the social and governance aspects. The research gap lies in addressing critical aspects to the development of smart cities including the economic and the environmental aspects from an energy systems perspective. Therefore, this thesis is contributing to science through the following key elements:

- Developing a comprehensive smart city concept by integrating various domains
- Designing net zero energy systems for smart city applications
- Assessing the environmental perspective in a smart city model
- Investigating the economic implications of a smart city model

Chapter 3: Model Development and Methodology

Past research was limited to introducing aspects to smart cities and evaluating local and regional projects based on smart cities objectives. Such research relies heavily on the development and utilization of effective composite indicators. These composite indicators are used to simplify the comparison between cities as well as to illustrate complex and elusive issues when it comes to smart cities. The downside of using composite indicators include the possibility for these composite indicators to send misleading policy messages if they are poorly constructed. Advantage and disadvantages of the use of composite indicators are illustrated in Figure 3.1.

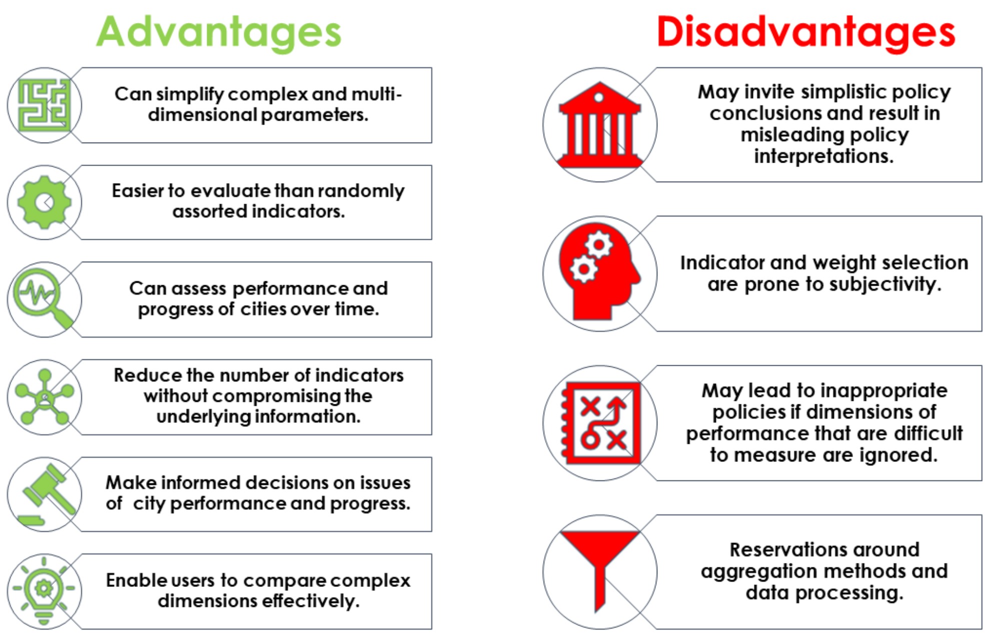


Figure 3.1 Advantages and disadvantages of composite indicators [Modified from (OECD, 2008)]

The literature on composite indicators is extensive as new methodologies and proposals are published monthly on this subject. For the purpose of this thesis, reference is restricted to well-established methodologies and procedures. Specific reference is made to the handbook on constructing composite indicators by the OECD (the Statistics Directorate and the Directorate for Science, Technology and Industry) and the Applied Statistics and Econometrics Unit of the Joint Research Centre (JRC) of the European Commission (OECD, 2008). In spirit of this methodology, ten steps are followed to establishing a composite indicator, starting with the development of a theoretical framework to the presentation and dissemination of a composite indicator. Each step is vital and coherent with specific objectives in order to ensure comprehensiveness and coherence.

3.1 Guiding Principles to Construction a Composite Indicator

As discussed earlier, the methodology used to establish the smart city index is a detailed and comprehensive methodology that is adopted by the OECD and JRC. These ten steps ensure that the final composite indicator, which is the smart city index for this thesis is very fine-tuned, robust, and practical, mirroring accurate conclusions. Figure 3.2 illustrates these different steps, starting from developing a theoretical framework to data selection and imputation all the way through various analyses until reaching the presentation and visualization step.

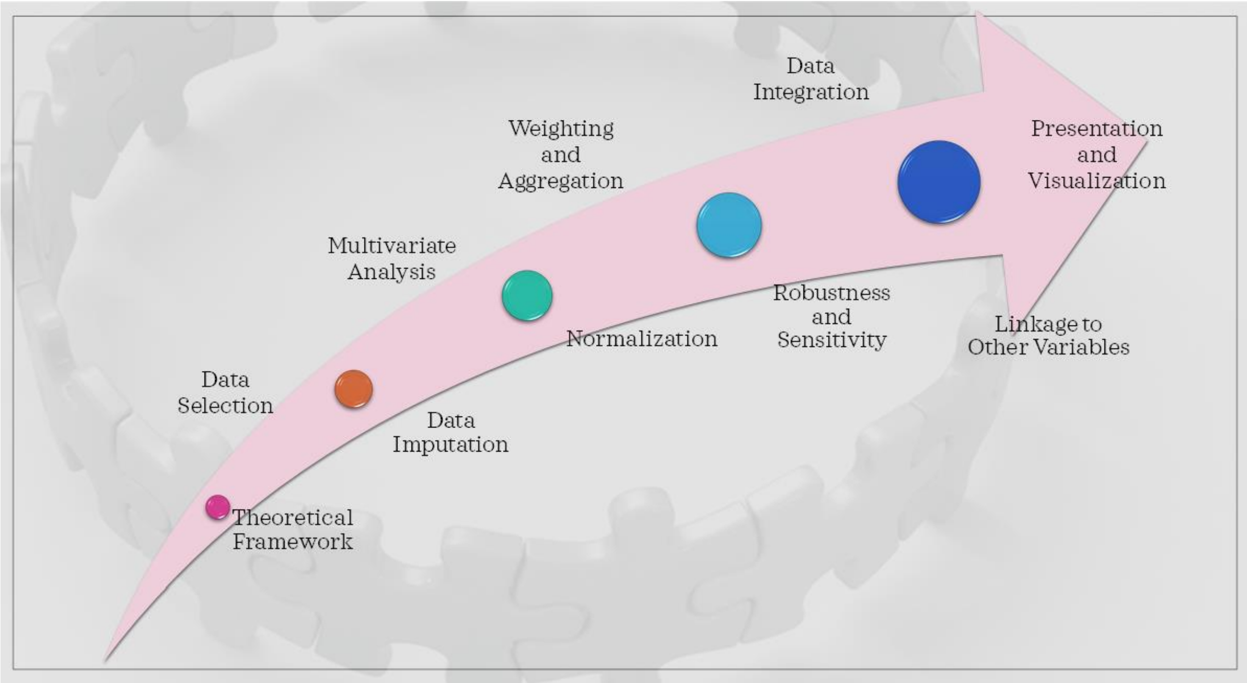


Figure 3.2 Ten guiding principles to constructing a composite indicator

3.1.1 Step 1: Theoretical Framework

This is the first step of the guiding principles to constructing a composite indicator. This step is the stem that provides foundation to the selection and combination of variables, following a fitness-for-purpose principle. Usually experts, stakeholders are engaged at this point along with conducting an extensive literature review. Furthermore, the purpose of this step is to shape a clear understanding of the multidimensional phenomenon to be evaluated. In addition, structuring the various sub-groups of the phenomenon as well as compiling a list of selection criteria for these variables are completed at this stage. The primary output of this step is a clear understanding and definition of the multidimensional phenomenon to be evaluated. In addition, a nested structure of the various sub-groups of the phenomenon is established if needed. Furthermore, a list of selection criteria for the underlying variables, such as input, output, and process. Finally, this step is concluded with a clear documentation of data acquisition.

3.1.2 Step 2: Data Selection

In this step, data is selected based on the analytical soundness, specificity, measurability, attainable, realistic, and time-bound aspects. Data availability, city coverage and relevance of the indicators to the phenomenon being measured and their relationship to each other. Proxy variables can be used in the absence of desired data sources. The purpose of this step is to check the quality of the available indicators as well as analyze the strengths and weaknesses of the selected indicators. Like the indicators, variables should be selected based on their relevance, analytical soundness, timeliness, availability, and accessibility. The primary output of this step is to check the quality of the available indicators and discuss the strengths and weaknesses of each selected indicator. A summary table on data characteristics, which includes data availability, source, and type of data is also suggested.

3.1.3 Step 3: Data Imputation

Imputation of missing data ensures data completeness by means of single or multiple imputation. The purpose of this step is to estimate missing values, provide a measure of the reliability of each imputed value. Highlighting the presence of outliers in the dataset is also an objective of this step. Missing data can either result in a case deletion, single imputation, or multiple imputation. Data imputation can be seductive as it may lure the researcher to believe that data is complete. The primary output of this step is a data set without any missing values. Each imputed value is measured for reliability and its impact on the composite indicator. Single imputation for missing data is used by incorporating the sample mean and explicit modeling. Finally, the presence of outliers throughout the dataset is also discussed.

3.1.4 Step 4: Multivariate Analysis

Individual indicators cannot be selected in an arbitrary manner. Attention should be paid to the interrelationships between them. The trend of overwhelmed indices is viewed as indicator rich, but information poor. The suitability of the data set is assessed in this step along with a deeper understanding of the implications of the methodological choices such as weighting or aggregation. Principal components analysis (PCA) is used to assess whether the dimensions of the phenomenon are statistically well-balanced in the composite indicator. The goal of this analysis is to explore how different variables change in relation to each other and how they are associated. Using a covariance matrix, correlated variable is transformed into a new set of uncorrelated variables. Factor analysis (FA), which is like PCA, but with foundation on a particular statistical model. Cronbach coefficient alpha (c-alpha) is the most common estimate of internal consistency of items in a model, used to investigate the degree of correlation among a set of variables. The primary outcome of this step is to check the underlying structure of the data along various dimensions as well as to apply the suitable multivariate methodology such as PCA, FA, and cluster analysis. In addition, cities that are statistically similar are identified as sub-groups of indicators or groups. Furthermore, the structure of the data set is analyzed and compared to the theoretical framework. Multivariate analysis is used as a preliminary step to assess the suitability of the data set and provide an understanding of the implications of the methodological choices such as weighting and aggregation in the next steps. For this thesis, principal component analysis (PCA) is used to conduct this multivariate analysis. PCA is a method for compressing substantial amount of multi-disciplined data into a product that captures the essence of the original data. Data from various indicators, variables and dimensions for multiple cities is analyzed using the PCA. Some dimensions are more important than others. In other words, PCA takes a dataset with many cities and flattens it to 2 or 3 dimensions, so we can visually observe the trends. The ultimate goal behind PCA is to reveal how different variables change in relation to each other and how they are associated.

3.1.5 Step 5: Normalization

Data normalization is a critical prerequisite step prior to data aggregation. This is because indicator data often have different units. Normalization includes treating or processing the data point to have a scalable value between 0 and 1. In fact, it is a widely common step throughout all models in order for policymakers and researcher to be able to analyze and assess the interconnectedness of indicators and the interrelationship between variables within the model. Several normalization methods exist, each with advantages and disadvantages, all summarized in Table 3.1

Table 3.1 Summary of various methods for data normalization

Method	Equation
Ranking	$I_{qc}^{t} = Rank\ (x_{qc}^{t})$
Standardization (z-scores)	$I_{qc}^{t} = \frac{x_{qc}^{t} - x_{qc=\bar{c}}^{t}}{\sigma_{qc=\bar{c}}^{t}}$
Min-Max	$I_{qc}^{t} = \frac{x_{qc}^{t} - min_c\ (x_q^{t_0})}{max_c\ \left(x_q^{t_0}\right) - min_c\ (x_q^{t_0})}$
Distance to a reference city	$I_{qc}^{t} = \frac{x_{qc}^{t} - x_{qc=\bar{c}}^{t}}{x_{qc=\bar{c}}^{t_0}}$
Categorical scales	$I_{qc}^{t} = \begin{cases} 0 & if\ x_{qc}^{t} < P^{15} \\ 20 & if\ P^{15} \le x_{qc}^{t} < P^{25} \\ 40 & if\ P^{25} \le x_{qc}^{t} < P^{65} \\ 60 & if\ P^{65} \le x_{qc}^{t} < P^{85} \\ 80 & if\ P^{85} \le x_{qc}^{t} < P^{95} \\ 100 & if\ P^{95} \le x_{qc}^{t} \end{cases}$
Indicators above or below the mean	$I_{qc}^{t} = \begin{cases} 1 & if\ w > (1+p) \\ 0 & if\ (1-p) \le w \le (1+p) \\ -1 & if\ w < (1-p) \end{cases}$ where $w = \frac{x_{qc}^{t}}{x_{qc=\bar{c}}^{t_0}}$
Cyclical indicators (OECD)	$I_{qc}^{t} = \frac{x_{qc}^{t} - E_t(x_{qc}^{t})}{E_t\left(\left\lvert x_{qc}^{t} - E_t\left(x_{qc}^{t}\right)\right\rvert\right)}$
Balance of opinions (EC)	$I_{qc}^{t} = \frac{100}{N_e} \sum_{e}^{N_e} sgn_e\ \ (x_{qc}^{t} - x_{qc}^{t-1}$
Percentage of annual differences over consecutive years	$I_{qc}^{t} = \frac{x_{qc}^{t} - x_{qc}^{t-1}}{\sigma_{qc=\bar{c}}^{t}}$

3.1.6 Step 6: Weighting and Aggregation

Weights are considered value judgements and have a vital influence on the composite indicator and overall results. There are numerous statistical models for weighting such as the unobserved components model (UCA), budget allocation processes (BAP), analytical hierarchy processes (AHP), and conjoint analysis (CA). Depending on expert opinion or to better reflect policy priorities, researchers may reward or punish components that are deemed more or less influential. Aggregation methods include the basic arithmetic aggregation, geometric and multi-criteria aggregation. In composite indicators, there will almost always be some positive correlation between different measures of the same aggregate (OECD, 2008). Linear aggregation is useful when all individual indicators have the same measurement unit. On the other hand, geometric aggregation considers non-compensability between individual indicators or dimensions. Aggregation methods that do not allow compensability should be used to ensure that weights remain a measure of importance. This is especially critical when highly different dimensions are aggregated in the composite. For example, an environmental index includes physical, social and economic data. "If the analyst decides that an increase in economic performance cannot compensate for a loss in social cohesion or a worsening in environmental sustainability, then neither the linear nor the geometric aggregation is suitable." (OECD, 2008). Therefore, a non-compensatory multi-criteria approach (MCA) could assure non-compensability. Table 3.2 summarizes the different weighting and aggregation methods (OECD, 2008). Due to the complexity of this thesis, selected combination of weighting and aggregation methods can be implemented. Only multi-criteria aggregation method can yield in meaningful results for such a complex composite index. EW, PCA and BAP are the weighting methods chosen for this research.

Table 3.2 Compatibility between weighting and aggregation methods

Weighting Method	**Aggregation Method**		
	Linear	Geometric	Multi-Criteria
EW	◯	◯	◯
PCA/FA	◯	◯	◯
BOD	◯	◯	◯
UCM	◯	◯	◯
BAP	◯	◯	◯
AHP	◯	◯	◯
CA	◯	◯	◯

3.1.7 Step 7: Robustness and Sensitivity

Sensitivity analysis is used to evaluate the robustness of the composite indicators. This is because many judgements must be made when constructing a composite indicator such as the selection of variables and indicators, data normalization methods, weighting and aggregation methods. The process used in this analysis is summarized in Figure 3.3. Throughout this process, the robustness of the composite indicator may be contested. Both uncertainty analysis as well as sensitivity analysis can help gauge the robustness of the composite indicator. The propagation of the uncertainty of the input values on the structure of the composite indicator is gauged through the uncertainty analysis. On the other hand, the contribution of the individual source of uncertainty to the output variance is assessed through the sensitivity analysis (OECD, 2008).

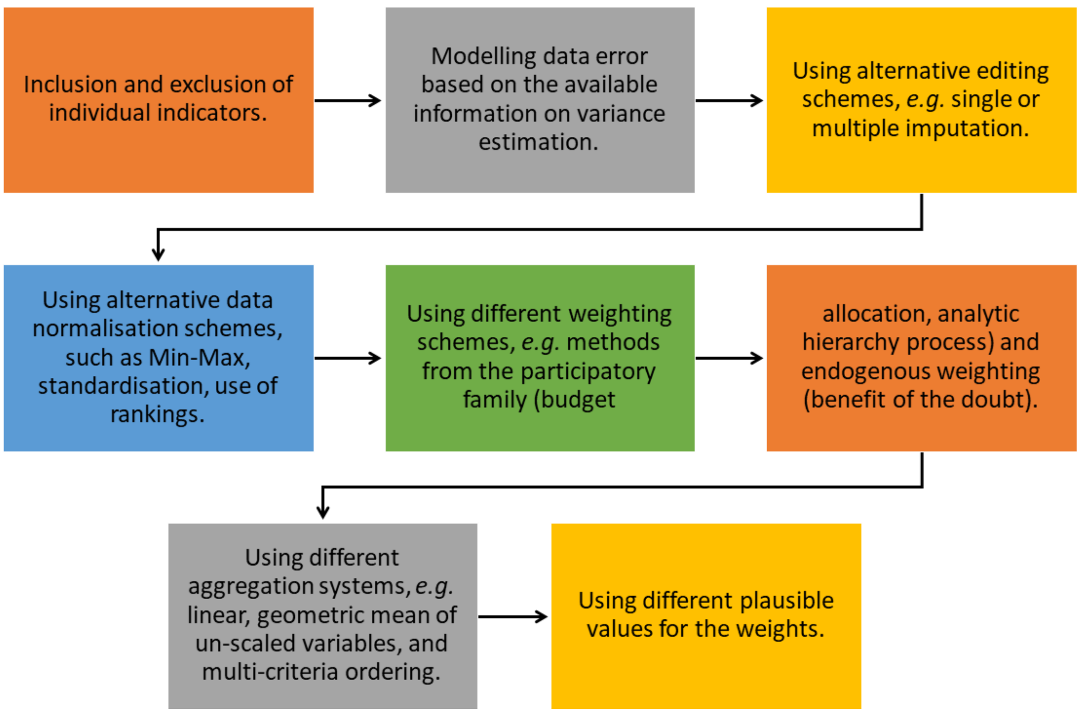


Figure 3.3 Approach to assess uncertainties in composite indicators

Robustness and sensitivity analysis alone are not sufficient to gauarantee sensible composite indicators. It is all dependant on the methodical and sound theoretical framework. The primary output of this step is to identify all srouces of uncertainty within the composite indicator, assess the impact of those uncertainties on the final result and condcut a sensitivity analysis of the inference.

3.1.8 Step 8: Data Integration

In this step, the contribution of the sub-components of the composite indicator are investigated further. Each sub-component contributes differently to the aggregated composite indicator and city rankings. The decomposition of the composite indicator subsequently provides feedback on the overall performance of a given city. The relationship between the composite and its components can be better understood by utilizing tools such as path analysis, Bayesian networks, and structural equation modeling.

3.1.9 Step 9: Linkage to Other Variables

Composite indicators usually evaluate concepts that are interlinked and parameters that are measurable. In this step, the link between the measurable parameters and the composite indicator can be assessed to test the explanatory power of the composite. For example, the smart economy sub-index can be correlated with a measurable indication, which is the GDP per capita. In this step, a correlation analysis, which must not be mistaken for a causality analysis can be conducted. In short, the correlation analysis simply indicates that the variation in the two datasets is similar. Causality analysis can be conducted using more detailed econometric analyses such as the Granger causality test. The Monte Carlo framework can also be used to assess the influence of the weights, normalization, and aggregation methods on the degree of correlation between a composite indicator and another variable of interest.

3.1.10 Step 10: Presentation and Visualization

Careful and special attention must be made on how to present research findings. Composite indicators need to be able to communicate a story to policy makers and researchers with accuracy and speed. Graphics need to be designed carefully for clarity and aesthetics. A mixture of tabular and graphical illustrations is also important. It is crucial to choose the correct type of visual illustration when presenting diverse types of datasets or results.

3.2 Smart City Index Framework

This research expands on the aspects of a smart city by including critical components such as energy and resources as part of the assessment. These aspects and their consequent indicators are assessed and categorized into five levels of increasing smartness. Figure 3.4 shows the levels of smartness for cities adopted in this thesis. Each indicator is evaluated and given a level, based on the indicator value. Together, they form the smart city matrix. As cities integrate more smart initiatives, they transition from level 1 to level 5.

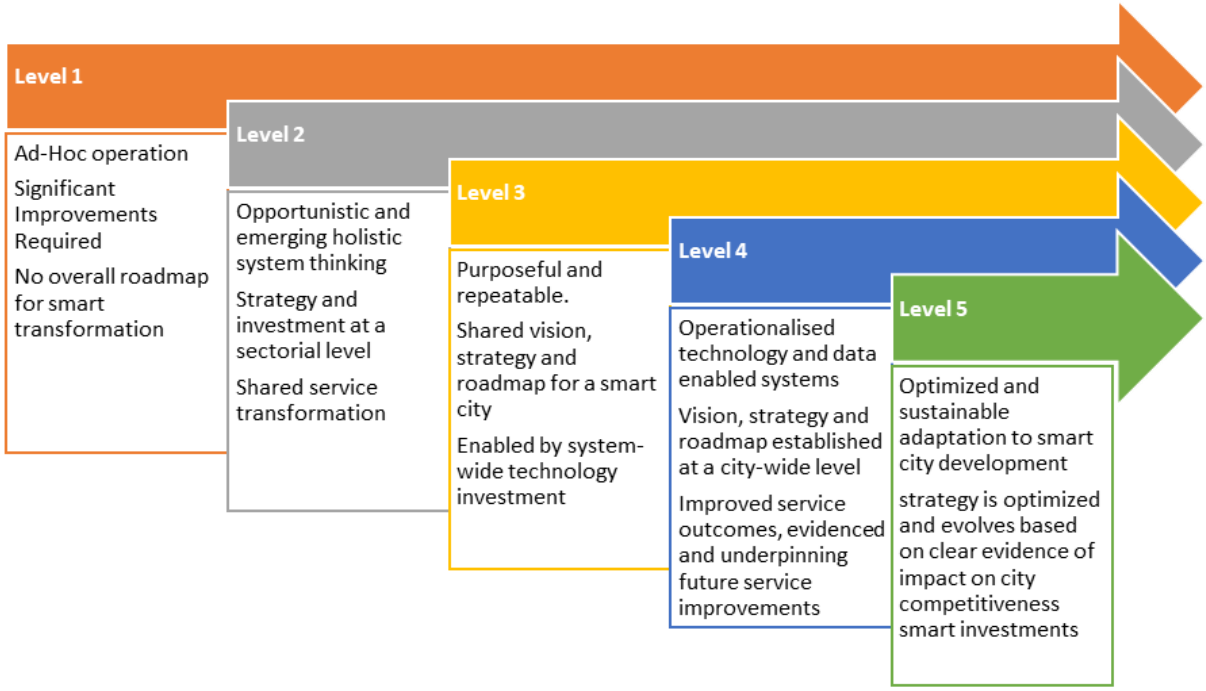


Figure 3.4 Levels of increasing smartness for cities

The aspects considered in the smart city concept for this thesis are comprised of eight main sub-indexes. Each aspect constitutes several indicators that can be quantified for further analysis using this methodology. These aspects are described in detail in Figure 3.5 and are as follows:

- Smart Environment
- Smart Economy
- Smart Society
- Smart Governance
- Smart Energy
- Smart Infrastructure
- Smart Transportation
- Pandemic Resiliency

These sub-indexes and corresponding indicators will be used to assess cities for their smartness. The Smart City Index (SCI) is the metric used to assess cities in their smartness. This index is composed of eight main domains including the smart environment index, smart economy index, smart society index, smart governance index, smart energy index, smart infrastructure index, smart transportation index and pandemic resiliency index. These indexes are further assessed with specific indicators. The domains and indicators selected are aligned with the UN's SDGs as well as the WCCD. For instance, SDG 1 is no poverty, and for this model, poverty rate is evaluated as a percentage. Furthermore, a smart economy considers the GDP per capita, R&D expenditure, unemployment rate and the Gini coefficient. Smart governance is assessed based on government effectiveness, digitalization, public participation, and the corruption rate within the government. Smart energy takes into consideration the energy efficiency of the systems, utilization of clean energy, energy storage, and the overall cost of energy.

As for the rest of the domains, further details about their characterization and assessment are elaborated later in their respective sections. Furthermore, the economic aspect must be both viable as well as inclusive, allowing for growth and economic prosperity. Smart cities without smart people and elevated level of innovation, creativity and education is virtually impossible. Moreover, smart cities have laws, bylaws, and written policies to ensure the longevity and sustainability of measure that the city takes regardless of political turnover. The energy sector for a smart city must rely on clean, abundant, and reliable energy sources coupled with efficient, integrated, and multigenerational systems to provide dependable and reliable services. Finally, a smart city is one with efficient mobility and reliable transportation.

Lastly, a smart city is one that is resilient in face of pandemics and national catastrophes which target the loss of life. Considering COVID-19, the world has witnessed cities that have managed the outbreak better than other cities. The frailty of the health system worldwide has been exposed clearly. A smart city is one that has an effective response rate to any pandemic or outbreak. In addition, a smart city is one that utilizes all available resources to minimize loss of life and support the well-being of effected citizens economically, socially, and mentally. Lastly, a smart city is one that already has a robust infrastructure and health system that will remain steadfast and effective considering any outbreak. This comprehensive concept is illustrated further in Figure 3.5.

Step by step process from framework development to the identification of the smart city index is illustrated in Figure 3.6. The framework development is completed as illustrated earlier. Four indicators are selected to evaluate each domain. Granular-level data is collected for 20 cities worldwide. Once data is available, it undergoes processing as explained earlier from imputation, normalization, weighting, and aggregation.

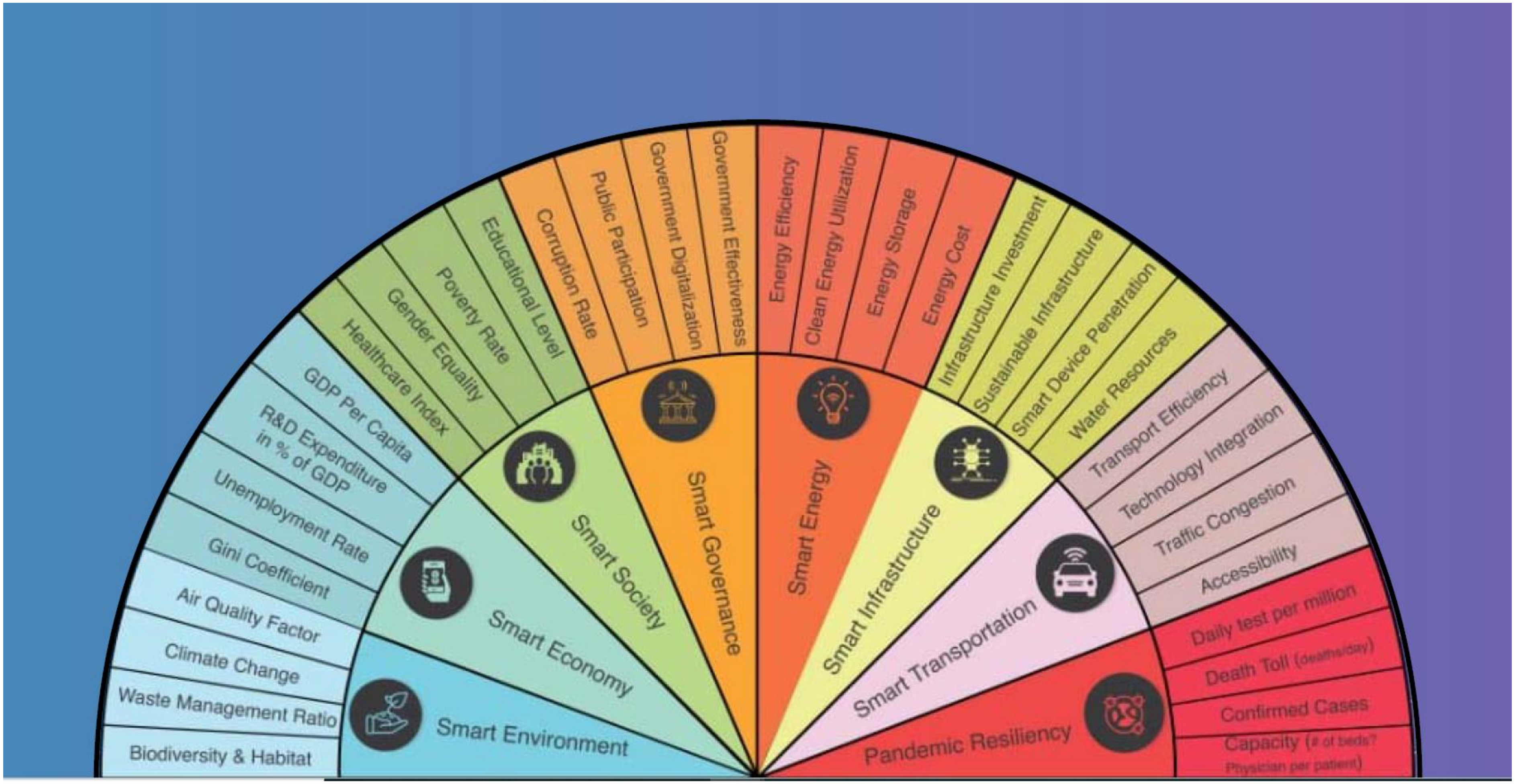


Figure 3.5 Aspects of smart cities including main indicators for each sub-index

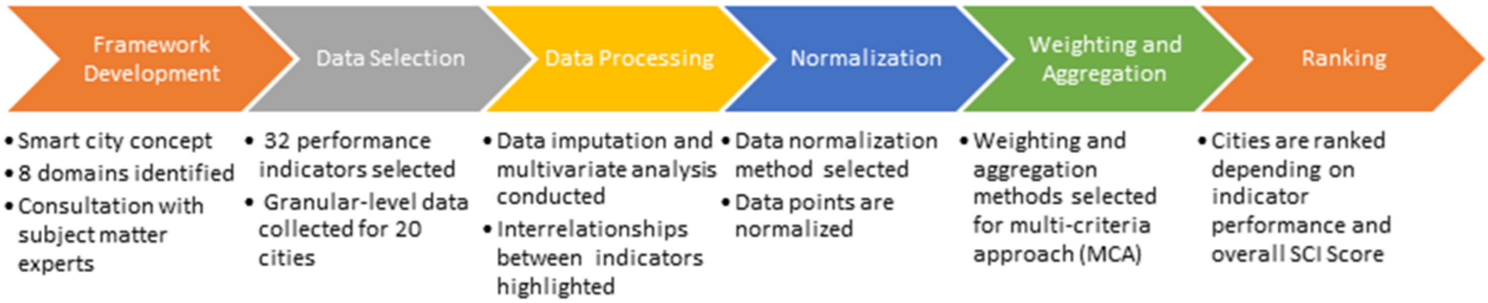


Figure 3.6 Overview of the smart cities assessment methodology

The model will follow several stages illustrated below in Figure 3.6. It is important to mention that such an assessment is complex and integrated various disciplines together.

3.3 Guiding Principles to Achieving the Smart City Concept

Integrated design considers the environmental impact and uses an integrated methodology to establish energy and environmental performance objectives in the design process. This step also considers following sustainable infrastructure urbanization, which results in smart and prosperous economies. Design choices also support health and wellness and considers all stages of the life cycle of the components of a city. Furthermore, fact-based, and data-driven governance, transportation and utilities' planning are also considered essential in this first guiding principle.

The second guiding principle revolves around energy performance and optimizing design parameters surrounding energy. For buildings, and optimized energy performance is 30% better than the current American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 standard. However, in the case of a smart city, optimizing energy performance institutes using energy efficient products and ensuring that the city's energy performance is at least 20% more efficient than the energy baseline based on the last decade. For example, if the city's energy performance in the year 2000 was assessed to be 40% efficient, then the energy performance in 2010 should be at least 48%. Furthermore, this guiding principle also inspires renewable and clean energy adoption. Evaluating and implementing, wherever appropriate life cycle cost-effective renewable energy projects as well as considering long-term off-site renewable sources. Utilizing clean and alternative energy in light of ongoing innovation and commercialization of such technologies is imperative to developing a smart city. Moreover, metering and data collection is essential to achieving optimized energy performance. In fact, the city must adopt smart metering for all of its utilities including electricity, water and natural gas. Installing advanced or standard meters as appropriate allows for accurate data analysis, which founds the basis for optimization design studies. Lastly, benchmarking city's energy performance on annual basis by following this methodology and numerically assessing each domain is critical in maintaining a sustainable smart city. Regularly monitoring energy performance and comparing it to historic performance data for each sector if possible, assists in achieving this second guiding principle.

The third guiding principle is to enhance sustainable development and environmentally friendly infrastructure. Urbanization and development of buildings in various sectors and establishing several types of energy systems must be regulated to ensure sustainable development. Energy cognizant infrastructure allow for more environmentally benign cities.

This guiding principle ensures that the infrastructure domain is fully integrated in the smart city concept by proposing energy systems that go in line with the spirit of the smart city concept. These energy systems need to be designed with care to allow for the highest system efficiencies and the lowest environmental impact as well as meeting the local demand for various commodities. Furthermore, this guiding principle attends to all the existing and new buildings within a city throughout all sectors and ensures that these buildings are sustainable and uphold a common standard for sustainability.

The fourth guiding principle is to foster economic growth and financial success. A smart city is one that attracts new opportunities and competitive markets. Furthermore, a smart city is self-sufficient and productive economically. A balance between capitalism and minimalism is necessary to achieve a smart city concept, where the city cares for its financial success through the growth of the gross domestic product (GDP) per capita, as well as adopts simple and minimalistic lifestyle simultaneously. Enhancements through the other guiding principles will yield in substantial financial savings, avoided costs and ensuring proper efficiency. This is because a smart city concept embraces process automation and system optimization throughout all domains, which alleviates municipal challenges and enhances economic prosperity.

The fifth guiding principle is to engages society and develop ownership. After all, society is a critical player in the development of a smart city. If all segments of society unitedly embrace and uphold the vision for a smart city, its implementation and realization become more conceivable. On the other hand, if social acceptance and public awareness were missing in this concept, the realization for a smart city becomes fictitious concept that is confined to all limited group of people. Therefore, massive public engagement and social adoption and pressure must be present in order to achieve the smart city concept. Social segments include the various social classes and population variabilities. Involving the social sector and the public in this holistic urban transformation is key to success. This can be achieved through local roundtables, various communication tools such as municipalities' portals and showcasing benefits and feasibility of a smart city.

The sixth guiding principle is to integration information and communication technology throughout all domains. The inception of the smart city concept was triggered by the integration of evolving technology in the infrastructure and the processes that are established in a city. Therefore, data-driven cities are naturally smarter because they have access to information in any domain. Furthermore, ensuring that all domains communicate with each other is also a component as part of this guiding principle. This means that the infrastructure domain communicates with the economy and environment domains to ensure that assets are both financially viable and environmentally benign for instance. Each sub-domain must also be able to communicate with each other by utilizing evolving and innovative communication tools that enables the realization of a smart city concept.

The seventh guiding principle towards a smart city is to endorse entrepreneurial innovation and development. A smart city must continue to thrive to maintain its smartness. This is realized by a continuous integration of innovative tools and processes into the model and achieving higher performance throughout all domains on a regular basis. Stagnation and adoption of current technologies will only allow the city to be smart for a limited period of time. Rather, the concept embraces the continuous support for innovation and development as a guiding principle. Furthermore, a smart city addresses its challenges on an ongoing basis and innovates solutions to ensure success and continued growth while mitigating obstacles and challenges.

The eight-guiding principle is continuous education for human resources and assets. The reality is that human resources are the most crucial and important asset in any organization. Making certain that these resources are well trained and continually develop and learn is recipe to achieving a smart city. Throughout all domains, plans and processes must be in place to ensure resources growth and development. It is imperative that resources are trained on innovations and technologies and are given sufficient guidance in order to adopt actualize these efficiencies. Novel innovations may be very technical and may need specific training and coaching before the optimized results are achieved. Therefore, continuous education for resources throughout the various domains is essential in a smart city concept.

The ninth principle is to develop satisfactory and efficient transportation services. In a smart city, people must be able to move around freely in a smooth and efficient manner. This principle focuses on the transportation domain and ensures that the public transportation network is one that is smart, efficient, reliable, and satisfactory to the users.

On the other hand, efficient and smart urban planning is also integrated to ensure easy transportation using other modes. As technologies evolve, the modes of transportation may change, but the common factor between all modes is easy transportation, free movement, efficient and satisfactory service.

The tenth and the last guiding principle to achieve the smart city concept is continuous assessment and evolution of governance systems. Throughout history, governance systems are similar and may become stagnant because governors are used to certain processes and culture. The smart city concept can only be achieved by continually improving this governance system as technology evolves and as the dynamics of the city change from one era to another.

Changes could be social, environmental, economic or health in nature. This guiding principle is inspired by the practices of quality management, where processes are constantly assessed for improvement and positive feedback. Therefore, this principle also dictates that the concept of the smart city is a dynamic concept and not a stagnant one. Furthermore, it is a concept that is regularly and naturally evolving given the various circumstances. Figure 3.7 illustrates how these guiding principles relate to the development of smart cities. The collaboration of all of these principles throughout all domains allow for the emergence of smart cities.

Figure 3.7 Guiding principles to achieving the smart city concept

3.4 Indicators

The process needs to be carefully methodical and quantified in order to yield in reliable information. Furthermore, the indicators are carefully selected based on a logical and methodical appraoch to truly reflect each aspect of the smart city, yet ensure simplicity and reliability of the model. Figure 3.8 summarizes the different framework used in selecting these indicators. Indicators are gauges that enable researchers to summarize, simplify and condense complex dynamic information into meaningful and useful data. Each domain is limited to four performance indicators that are used to reflect the valuation of the respective domain. Indicators are selected on the basis of their relevance, analytical soundness, timeliness and data accessibiltiy.

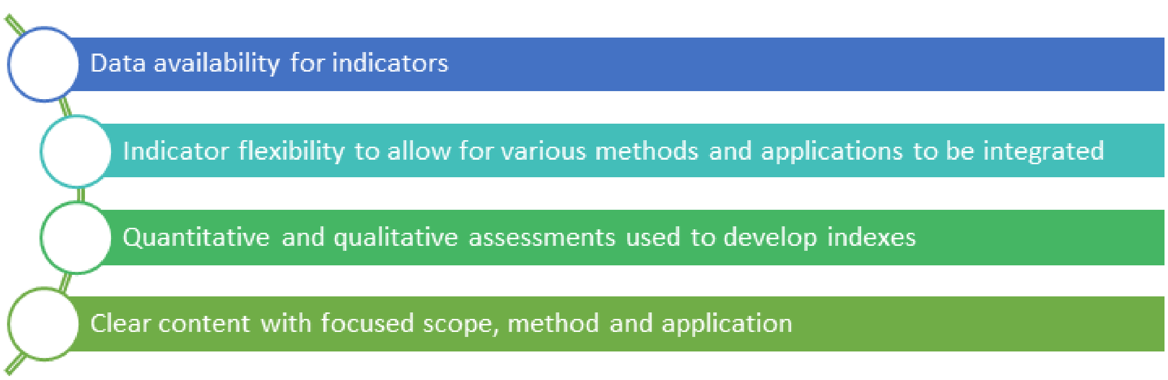


Figure 3.8 Characterization and evaluation criteria for indicators used in this study

3.4.1 Environment Index

This aspect is essential to the concept of smart city as it pertains to the wellbeing of the natural resources universally. Many local emissions and outputs have global and regional impacts. In fact, the world is vulnerable to global climate change that has been evident with numerous signs of danger across all continents. In order to assess this aspect of a smart city, the following function is used:

$$\gamma_{SEnv} = {\beta_{AQ}}^{\omega_{AQ}} \times {\beta_{CC}}^{\omega_{CC}} \times {\beta_{WM}}^{\omega_{WM}} \times {\beta_{BH}}^{\omega_{BH}} \tag{3.1}$$

where β represents the dimensionless normalzied value for the respective indicator and ω represents the weight associated with each indicator. This sub-index is composed of air quality β_{AQ} , climate change and GHG emissions β_{CC}, waste management β_{WM}, and biodiversity and habitat β_{BH}. Weighting will be discussed in detail later in the chapter. The environment is a critical domain that must be considered in a smart city concept. As illustrated earlier in the introduction, the global population increase and the projected emissions increase urge us to develop smart cities that are environmentally friendly. This domain intersects with other domains such as infrastructure to ensure that facilities and urban development are all environmentally benign. It also intersects with governance and utilities to ensure that laws and internal processes go in support of a healthier environment. Furthermore, this domain is assessed by evaluating emissions, pollution, water quality, air quality and waste management systems. Optimizing wastes by converting them into useful energy reduces operational costs and better addresses the environmental issues.

3.4.1.1 Air Quality Factor

The quality of air and ensuring that pollution does not impact it is considered essential in a smart environmenty. In fact, air pollution has become a concerning public health concern. Also, permature deaths can be attributed to poor air quality. The pollutants associated with air quality include, but are not limted to greenhouse gases (GHGs), $PM_{2.5}$, O_3, NO_2, SO_2, CO, and the total reduced sulphur compounds (TRS). The concentrations of these pollutants are measured and then compared to established air quality objectives and criteria. Greenhouse gases constitute the major pollutants that drive climate change. Therefore, this indicator is critical in the assessment of this sub-index. A smart city is ideally a pollutant free environment with environmentally-benign processes and operations. Greenhouse gases absorb and emit radiant energy. These gases include water vapor, CO_2, CH_4, and N_2O. the industrial revolution caused for these emissions to rapidly increase at an unprecedented rate. With a digital revolution and the introduction of smart citites, the opportunity is to regulate and control these emissions to cause less harm to the environment and its consequences such as global warming. This indicator is computed by evaluating the GHG emissions per capita for a selected city and comparing it with the GHG emissions per capita in a reference state. The reference values could be that of the surrounding region, provincial state, country, or continent. For Canada, the acceptable levels for air quality as per the Environmental Protection Agency are 12-13 μg/m^3. This indicator is assessed using the following function:

$$\beta_{AQ} = \frac{\delta_{GHG}}{\delta_{GHG_0}} \tag{3.2}$$

where δ_{GHG} is the GHG emissions per capita (kt CO_2eq per capita) for the city, which is compared to the reference state δ_{GHG_0}. This function produces a dimensionless number that can later be computed into the model. Furthermore, percentages or ratios indicating air and environmental protection measures adopted throughout various industries can also be considered for the value of this indicator. Table 3.1 illustrates the various granular data points used to assess this indicator.

Table 3.3 Data points used to assess the air quality indicator

Data Point	**Unit of Measurement**
Total CO_2 Emissions	kt CO_2eq/B$
CO_2 Emissions - Power Sector	g CO_2/kWh
Methane	kt CO_2eq/B$
Nitrous Oxide	kt CO_2eq/B$
Black Carbon	kt CO_2eq/B$
Household solid fuels	*Daily Rate*
$PM_{2.5}$ exposure	μg/m3
$PM_{2.5}$ exceedance	*% population*

3.4.1.2 Water Quality Factor

This indicator encompasses water quality. A smart environment ensures that water remediation and management measures are incorporated in the overall city operation. Water recylcing is also considered in this indicator. Reusing treated wastewater for beneficial agricultural and landscape irrigation or industrial processes enhances a smart environment concept.

Furthermore, water recycling and effective management allows the city to have sufficient water resources for its demand, decreasing the diversion of water from sensitive ecosystems and preventing pollution. This indicator is assessed using the following function:

$$\beta_{WQ} = \frac{\delta_{WQ}}{\delta_{WQ_0}} \tag{3.3}$$

where δ_{WQ} denotes the water conductivity level in Siemens per meter [S/m]. conductivity of substances is an indicator of water quality. In fact, conductivity affects the salinity and total dissolved solids (TDS) content, thus affecting the concentration of oxygen levels in the water. This is compared to a reference state δ_{WQ_0}, which is considered the optimal value.

Moreover, percentages indicating improvements in this sector or percentage of wastewater treatment (%) can also be considered for this indicator.

3.4.1.3 Waste Management Factor

Waste comes in various shapes and forms, including residential, commerical, institutional, industrial and municipal waste. This waste could be hazardeous or non-hazardous. Disposal of waste in an irresponsible manner can cause deterementous environmetnal impacts including soil and water contamination.

Furthermore, methane gas emissions from landfills contirbute to global warming. This indicator captures the percentage of reduced consumption of resources due to recycling. The indicator can also be evaluated by assessing the amount of local waste disposal compared to a reference state waste disposal and is computed as follows:

$$\beta_{WM} = \frac{\delta_{WM}}{\delta_{WM_0}} \tag{3.4}$$

where δ_{WM} is the amount of waste disposal throughout all industries and sectors within a city, that is compared to a reference state δ_{WM_0}. Furthermore, this indicator can also be assessed by determining the recycling rate, which is the percentage of waste being recycled in tonnes per day per year (tonnes/day/yr). Alternatively, the GDP can be divided by waste generated to figure out this rate (tonnes/B$).

3.4.1.4 Ecosystem Turnover Factor

This indicator refers to the preservation of biodiversity and natural habitats. Numerous ecosystems are witnessing considerable changes causing declines in biodiversity. Furthermore, some species have become vulnerable while others are risking extniction. The granual level data points used for this indicator are highlighted in the Convention on Biological Diversity's "Aichi Targets", a set of internationally agreed upon goals for conservation and ecosystem management (Secretariat of the Convention on Biological Diversity, 2014). These data points are: marine protected area, terrestrial biome protection - national weights, terrestrial biome protection - global weights, species protection index, protected area representativeness, and species habitat index. Turnover rates can be defined as the ratio of the quantity of species within a system to their outflow rate. This relationship can be expressed in the following funciton:

$$\beta_{ET} = \frac{\delta_{ET}}{\dot{\delta_{OF}}} \tag{3.5}$$

where δ_{ET} represents the quantity of species within a specific ecosystem within a city with respect to their outflow rates $\dot{\delta_{OF}}$, which is measured at (species/year). Table 3.4 shows these data points in further detail and their respective unit.

Table 3.4 Data points used to assess the ecosystem turnover rate

Data Point	Unit of Measurement
Marine protected area	% of EEZ
Terrestrial biome protection - national weights	% of biomes (capped)
Terrestrial biome protection - global weights	% of biomes (capped)
Species protection index	Dimensionless
Protected area representativeness index	Dimensionless
Species habitat index	Dimensionless

Therefore, the quantity of species is assessed using the following function:

$$\delta_{ET} = \delta_{MPA} + \delta_{TBP} + \delta_{SPI} + \delta_{PARI} + \delta_{SHI} \tag{3.6}$$

where δ_{MPA} is the marine protected area assessed through the percentage of exclusive economic zone, δ_{TBP} is the terrestial biome protection, which is assessed through the percentage of biomes, δ_{SPI} is the species protection index, evaluated by the Environmental Performance Index (2018) along with δ_{PARI} is the protected area representativeness index and δ_{SHI} is the species habitat index, both evaluated in the Environmental Performance Index aforementioned.

This indicator can also asssess the city for its ecological sustainaibility by examining three data points, specifically the GDP per unit of energy use, the enivonrmental performance index as well as number of certificates of conformity with standard ISO 14001 on environmental management systems issued. The 2018 Environmental Performance Index (EPI) ranks 180 countries on 24 performance indicators across ten issue categories covering environmental health and ecosystem vitality. These metrics provide a gauge at a national scale of how close countries are to established environmental policy goals.

The EPI thus offers a scorecard that highlights leaders and laggards in environmental performance, gives insight on best practices, and provides guidance for countries that aspire to be leaders in sustainability. The index ranges from 0 to 100, with 100 indicating best performance. The following function summarizes this indicator:

$$\beta_S = \delta_{GDPE} + \delta_{EP} + \delta_{EC} \tag{3.7}$$

where δ_{GDPE} is the GDP per unit of energy use for a city ($ per kg of oil equivalent), δ_{EP} is the environmental performance index, which is dimensionless, and δ_{EC} is the level of environmental conformorance (number of issued certifications per billion $ GDP).

3.4.2 Economy Index

In order for any city to be considered smart, it must have an outstanding and prosperous economic activity. This stems from effective strategies towards an aspiring vision. Furthermore, a smart economy is one that ensures citizens have better opportunities and sufficient revenue to cover their expenses and enahnce their standards of life. This aspect is assessed by evaluating the indicators using the following function:

$$\gamma_{SEco} = {\beta_{GDP}}^{\omega_{GDP}} \times {\beta_{RD}}^{\omega_{RD}} \times {\beta_{UR}}^{\omega_{UR}} \times {\beta_{GC}}^{\omega_{GC}} \tag{3.8}$$

The economy is a critical domain in a city and for any smart city model to materialize, this domain must be carefully considered. In a smart city concept, the economy flourishes and grows in spirit of all the automation and the system optimizations that take place throughout all domains. This allows for more opportunities, innovative ideas and entrepreneurial platforms to grow and expand. Imports and exports as well as the GDP per capital are indicators for this domain.

3.4.2.1 Gross Domestic Product (GDP) Per Capita Factor

The gross domestic product per capita is a strong indicator that translates how effective the economy is for a given population. In essence, the GDP is the monetary value of all goods and services made within a city or country during a specific period of time. It is valuable as it provides an economic snapshot for a given population, which can be used to evalaute the size of the economy and growth rate. In fact, it is a key tool for policymakers, investors and businesses in strategic decision making. The GDP per capita is the measure of GDP per person in the national populace. Cities with higher GDP per capital enjoy a higher standard of living and a more satisfactory income. A smart city should allow for a sustinable economic growth and a prosperous GDP per capita. Therefore, this indicator is assessed using the following function:

$$\beta_{GDP} = \frac{\delta_{GDP_0}}{\delta_{GDP}} \tag{3.9}$$

where δ_{GDP} is the GDP per capita for a given city, compared to the reference state GDP per capita, which could be the regional, national GDP per capita.

3.4.2.2 Research and Development Expenditure and Innovation Factor

Research and development plays a critical role in the successes of an economy. In fact, it is a cruical component of innovation and a key factor in developing new competitive and alternative advantage. Furthermore, the whole concept of smart cities stemmed from research and development. Many of the technologies and services that have become deeply rooted and integrated in mankind's lifestyles such as cellular phones, internet, or computers are as a result of research and development. The transformation of technology to produce novel products, processes and services is essential in a smart city that thrives on continuous growth. Therefore, cities that have higher expenditure in this sector have higher potential to innovate and create; thus having a smart economy and a smarter city index. This indicator is assessed using the following function:

$$\beta_{RD} = \frac{\sum R\&D\ Expenditure}{\sum GDP} \tag{3.10}$$

Innovation is considered a key indicator for smart cities. As new technologies constantly emerge to optimize and enhance current practices, this indicator coveres a wide range of sectors.

Commercial breakthrough and groundbreaking research is carried out by universities, public institutions and the commerical sector. A smart city is the one that capitalizes on all of these stakeholders to ensure the city prospers.

This indicator assesses the level of creativity and innovativity that a city enjoins. This is assessed by evalauting the bond between academic institutions and industry. Surveys are designed to answer to what extent do businesses and universities collaborate on research and development. The following function is used:

$$\beta_{IC} = \frac{\delta_{IC}}{\delta_{IC_0}} \tag{3.11}$$

where δ_{IC} is the answer to the survey question: In your country, to what extent do businesses and universities collaborate on research and development (R&D)? [1 = do not collaborate at all; 7 = collaborate extensively] and $\delta_{IC_0}$is the total for the answer. In summary, β_{IC} is the average answer to the survey question.

3.4.2.3 Unemployment Factor

Unemployment is a disastrous trend for a city. In fact, cities that have higher unemployment rates have shrinking economies and therefore declining cities. On the contrary, cities with lower unemployment rates have growing economies and smarter cities. It is critical for a city to present its citizens with various types of opportunities, allowing for their skill and talent to be captured in the best of ways.

Furhtermore, this indicator can be used to offset unemployment rate, discussed earlier. Job creation is essential to ignite shared and sustainable economic growth. Job creation leads to lower interest rates and more spending on public works and infrastrucre enhancement. Furthremore, cities that create jobs and provide opportunities for career growth to its citizens, keep them engaged, motivated and productive, thus resulting in a smarter society. This indicator is measured by the following function:

$$\beta_{UR} = \frac{\sum UR}{\sum LF} \tag{3.12}$$

where $\sum UR$ is the total number of unemployed perons compared to $\sum LF$, which is the total labour force including those who work and those who don’t.

3.4.2.4 Gini Coefficient Factor

This indicator is assessed by evaluating applied tarrif rate on productes in addition to the intensity of local market competition. Local market competition is assessed through a survery [1 = not intense at all; 7 = extremely intense]. Furthermore, the domestic market scale is evaluated as measured by the GDP. The domestic market size is measured by gross domestic product (GDP) based on the purchasing-power-parity (PPP) valuation of country GDP, in current international dollars (billions). The following function summarizes the evaluation method for this indicator:

$$\beta_{GC} = \delta_{AT} + \delta_{LMC} + \delta_{DMS} \tag{3.13}$$

where δ_{AT} is the rate of applied tarrifs (%),δ_{LMC} represents the average answer to the survey, and δ_{DMS} is the domestic market scale in (billions \$ GDP).

3.4.3 Society Index

A city without a society is virtually impossible and unrealistic. Society is a major backbone in every city. Therefore, in order for the city to be smart, this aspect must also be competitive, creative, innovative and smart. Therefore, this aspect is considered critical to the assessment of smart cities and is evaluated by computing the different indicators in the following function:

$$\gamma_{SSoc} = {\beta_{EL}}^{\omega_{EL}} \times {\beta_{GE}}^{\omega_{GE}} \times {\beta_{PR}}^{\omega_{PR}} \times {\beta_{HI}}^{\omega_{HI}} \tag{3.14}$$

The normalized values for each indicator will be discussed later in the thesis for each specific indicator. These values will also be analyzed and processed furhter using various aggregation and regression analyses. Another important domain for a smart city concept is health. The wellness and safety of the population is top priority, especially amidst emergence of new technologies and innovations. While the smart city concept heavily relies on the integration of information and communication technologies, it is critical that side effects of these tools be examined to ensure their compliance and safety. Therefore, a smart city is simply a healthy and safe city. In fact, the other domains allow for less environmental pollution, better life standards, economic growth and prosperity as well as physical and mental health. An example of how data can be utilized in this domain is the dispatch of smart healthcare devices to public spaces to provide ongoing health care for patients. Such tools can also be deployed in rural areas. Using technology and data analytics to track immunization and to regularly assess the health and wellness of the population is also possible.

3.4.3.1 Educational Level Factor

A smart society without well-educated and intellectual population is impossible. This indicator measures the level of education that citizens of any given city have. It is logical that a more educated city leads to a smart society that uses rationale, logic and wisdom in their operations. Furthermore, higher education leads to critical thinking, innovation, creativity and reason, which are all features of a smart city. Therefore, this indicator is assessed by evaluating the number of people with postsecondary certificate, diploma or degree in comparison with the total population, In other words, what percentage of the population has postsecondary education. The following function is used for this assessment:

$$\beta_{EL} = \frac{\delta_{EL}}{\sum Pop} \tag{3.15}$$

where δ_{EL} is the number of people with postsecondary certificate, diploma or degree and $\sum Pop$ is the total population. A smart society is one that creates knowledge and enhances the level of science and information available. This inidicator is assessed by a number of data points including the number of resident patent applications filed at a given national or regional patent office; PCT applications by origin; utility models by origin; scientific and technical publications; as well as citable documents H-index. This indicator is assessed using the following function:

$$\beta_{KC} = \delta_{PA} + \delta_{PCT} + \delta_{STP} \tag{3.16}$$

where δ_{PA} refers to the patent applications within the city, δ_{PCT} the patent cooperation treaty applications per resident, and δ_{STP} is the scientific and technical publications.

3.4.3.2 Poverty Factor

Once again, poverty has no place in a smart city. While all socieities may have some level or rates of poverty, a smart living ensures that no one is left below poverty line. The poverty rate is the ratio of the number of people (in a given age group) whose income falls below the poverty line; taken as half the median household income of the total population. The following function is used for this indicator:

$$\beta_{PR} = \frac{\delta_{PR}}{\sum Pop} \tag{3.17}$$

where δ_{PR} is the ratio of the number of people (in a given age group) whose income falls below the poverty line and $\sum Pop$ is the total population.

3.4.3.3 Equity Factor

Equity and human welfare are important indicators to assess a society for its smartness. This concept of human equity is very complex and has many facets including economic progress and quality of life. For this thesis, human welfare and equity are assessed in a unique way, by integrating Maslow's hierarchy of needs. In this model, people with in higher welfare states can achieve higher levels such as esteem and self-actualization, leading to activities such as volunteering and community engagement. Therefore, the economic value of all volunteering activities are captured and assessed. Volunteering activities encompass various sectors including culture and recreation, education and research, health, social services, environment, religion, or business and professional associations. This indicator is evaluated using the following function:

$$\beta_{HW} = \frac{\delta_{HW_0}}{\delta_{HW}} \tag{3.18}$$

where δ_{HW} is the total economic value of all volunteering activities in ($) and δ_{HW_0} is the reference state value for the same indicator.

3.4.3.4 Healthcare Factor

Smart living constitutes healthy lifestyles, both physically, mentally and spiritually. Health and wellness is a critical component to a smart city. Lack of health or wellness deteriorates the city's economy, society and environment. A survey is used to gauge this indicator. Population aged 12 and over who reported perceiving their own health status as being either excellent or very good or fair or poor, depending on the indicator. Perceived health refers to the perception of a person's health in general, either by the person himself or herself, or, in the case of proxy response, by the person responding. Health means not only the absence of disease or injury but also physical, mental and social well-being. Smart living constitutes healthy lifestyles, both physically, mentally and spiritually. Health and wellness is a critical component to a smart city. Lack of health or wellness deteriorates the city's economy, society and environment. A survey is used to gauge this indicator. Population aged 12 and over who reported perceiving their own health status as being either excellent or very good or fair or poor, depending on the indicator. Perceived health refers to the perception of a person's health in general, either by the person himself or herself, or, in the case of proxy response, by the person responding. Health means not only the absence of disease or injury but also physical, mental and social well-being. The survey results are computed to determine the indicator dimensionless value as illustrated in the following function:

$$\beta_{HW} = \frac{\delta_{HW>7}}{\sum Survey} \tag{3.19}$$

where $\delta_{HW>7}$ refers to the number of surveys that submitted a perceived health score of 7 out of 10; divided by the total survey submission $\sum Survey$.

3.4.4 Governance Index

Cities are heavily populated metropolitan areas with municipal or local level of governance. Cities are also impacted by regional or upper-tier municipality or even federal policies. Therefore, it is important for this aspect to be included in the assessmnet to ensure infrastructural improvements, process enhancements and adoption of a shared vision towards a smart city. The main ignitor towards transformation to a smart city is smart governance, which is assessed usign the following function:

$$\gamma_{SGov} = {\beta_{GE}}^{\omega_{GE}} \times {\beta_{GD}}^{\omega_{GD}} \times {\beta_{PP}}^{\omega_{PP}} \times {\beta_{CR}}^{\omega_{CR}} \tag{3.20}$$

This sub-index is limited to three main indicators that encompass many aspects of smart governance including internal processes, corporate strategy, ICT integration, transparency and structure. Governance is another domain that is studied as part of this smart city model. The internal laws and bylaws and the methodology used to govern the city need to be dynamic in response to various changes from decade to another. The social structure must also be studied to ensure equal and fair access to opportunities and resources between all segments of society. Smart kiosk is an example of how government services can be readily available to the public. Furthermore, monitoring of risky areas using sensors and actuators for real-time monitoring can be implemented in risky areas or areas more prone to accidents. These sensors would be connected with the appropriate response agency to ensure timely response and prevention of any harm. Furthermore, smart fire sensors can detect and can be automated to take instant action based on level of severity. These systems can all be interconnected to ensure constant data flow and information between the different departments, that otherwise would not communicate with each other in a conventional setting. Tourism is an important industry for a city, providing regular commerical activity, which creates demand and growth for many more indsutries. Tourism also results in more employment and infrastructure development. Altogethre, yieldign in a smarter city. This indicator is assessed by evaluating the number of non-resident travellers for a given city, compared with the reference mean value for all cities. The following function is used:

$$\beta_{TT} = \frac{\delta_{TT}}{\delta_{TT_0}} \tag{3.21}$$

where δ_{TT} is the ratio of the non-resident travellers and δ_{TT_0} is the weighted mean for the cities involved. Security and safety is an essential component for a smart city. The presence of war or fear for one's life and belongings are not indicators for a smart city. Furthermore, violent and non-violent crimes are also assessed the Crime Severity Index is used to assess this indicator. The crime severity index includes all Criminal Code violations including traffic, as well as drug violations and all Federal Statutes. The Crime Severity Index (CSI) measures changes in the level of severity of crime in Canada from year to year. In the index, all crimes are assigned a weight based on their seriousness. The level of seriousness is based on actual sentences handed down by the courts in all provinces and territories. More serious crimes are assigned higher weights, less serious offences lower weights. As a result, more serious offences have a greater impact on changes in the index.

3.4.4.1 Government Effectiveness Factor

This indicator is assessed by evaluating the perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. Data from The World Bank (2019) is used for this assessment. Representative sources include quality of beureaucracy, quality of overall infrastructure, state failure, which refers to the risk the state is unable to exclusively ensure law and order, and the supply of basic goods such as food, water, infrastructure, and energy, or is unable to respond to or manage current or likely future emergencies, including natural disasters and financial or economic crises. Infrastructure disruption is also considered, which reflects the likelihood of disruption to and/or inadequacy of infrastructure for transport, including due to terrorism/insurgency, strikes, politically motivated shutdowns, natural disasters; infrastructure includes (as relevant) roads, railways, airports, ports, and customs checkpoints. Many other sources are also considered. The questions from the individual data sources are first rescaled to range from 0 to 1, with higher values corresponding to better outcomes. This data is then normalized using the following function:

$$\beta_{GE} = \frac{\delta_{GE} - min}{\delta_{GE_0} - min} \tag{3.22}$$

where δ_{GE} is the score to the individual question, in relation to the maximum score δ_{GE_0} and the minimium score.

3.4.4.2 Government Technology Factor

It is critical for cities to have digital services available to citizens. Integration of technology and utilziation of artifical intelligence, machine learning to drive city business and enhance its oeprations is essential in a digital era. This indicator assesses municipal capacity to provide online services, automation and simplification of transactional processes as well as predictive analytics and data governance.

Connectivity and effective management of outcomes throughout various platforms is also important. This indicator is evaluated using the Open Cities Index (OCI, 2017). The OCI is an appraisal framework to gauge the level of openness in cities across Canada. Furthermore, the OCI serves to audit existing open data initiatives at municipalities and allows participating organizations to compare themselves against their peer groups and track their openness over time based on specific dataset classifications.

The Open Cities Index measures the readiness, implementation, and impact of open data initiatives. Figure 3.9 illustrates the various aspects taken into consideration when assessing this index. The following function also summarizes the evluation method of this inidcator:

$$\beta_{GD} = \frac{\delta_{DS}}{\sum GS} \tag{3.23}$$

here δ_{DS} refers to the number of services that are available digitally compared to the total municipal services carried out in a given year.

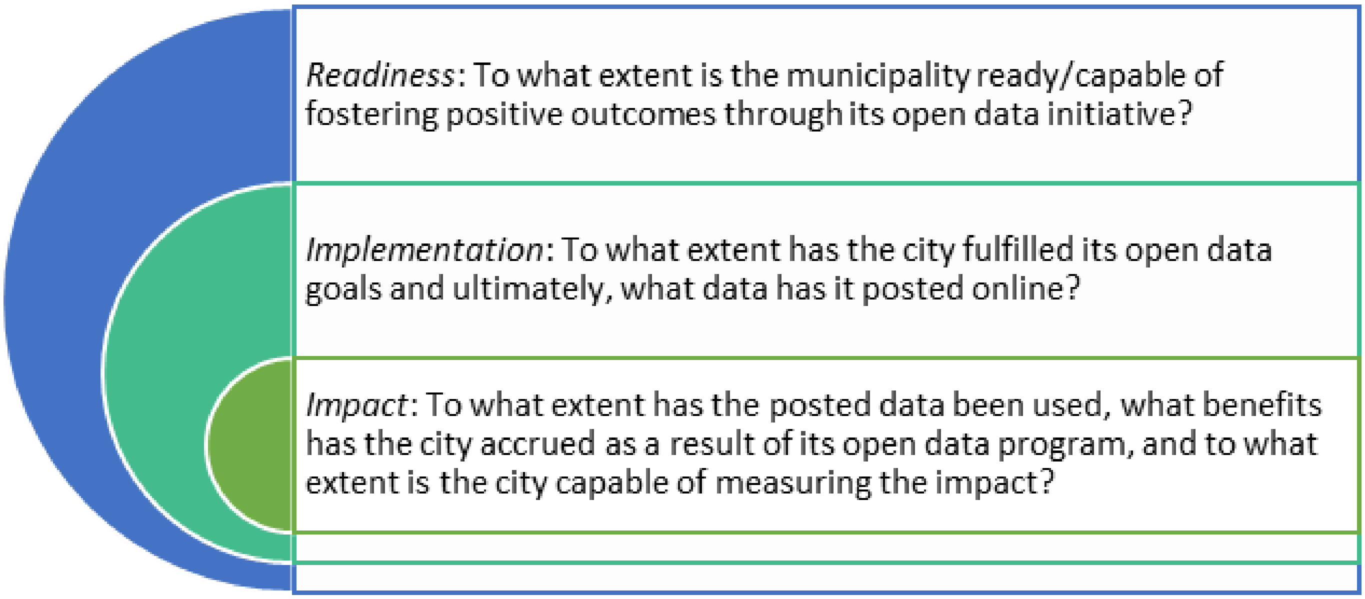


Figure 3.9 Overview assessment criteria using the Open Cities Index

3.4.4.3 Public Participation Factor

This indicator asssess civil society participation based on expert surveys, considering the extent to which the population is engaged in civil society acivities. Electoral participation is also considered denoting the extent to which citizens vote in nantional legislative or executive elections.

Furthermore, local democracy is considered by assessing the extent to which citizens can participate in free elections for influential local governments. Data from International IDEA (2019) is used for this assessment. Expert survey is used to assess this indicator by evaluating the following questions outlined in Figure 3.10. This indicator is assessed by using the following function:

$$\beta_{PE} = \delta_{CS} + \delta_{DD} + \delta_{LD} \quad (3.24)$$

where δ_{CS} is the level of civil society participation gauged through expert surveys, δ_{DD} is the presence of direct democracy including voting and elections; and δ_{LD} refers to the local democracy by figuring out if there are elected local governments, and if so to what extent can they operate without interference from unelected bodies at the local level.

$\beta_{RL} = \frac{\delta_{RL} - min}{\delta_{RL_0} - min}$ (3.24)

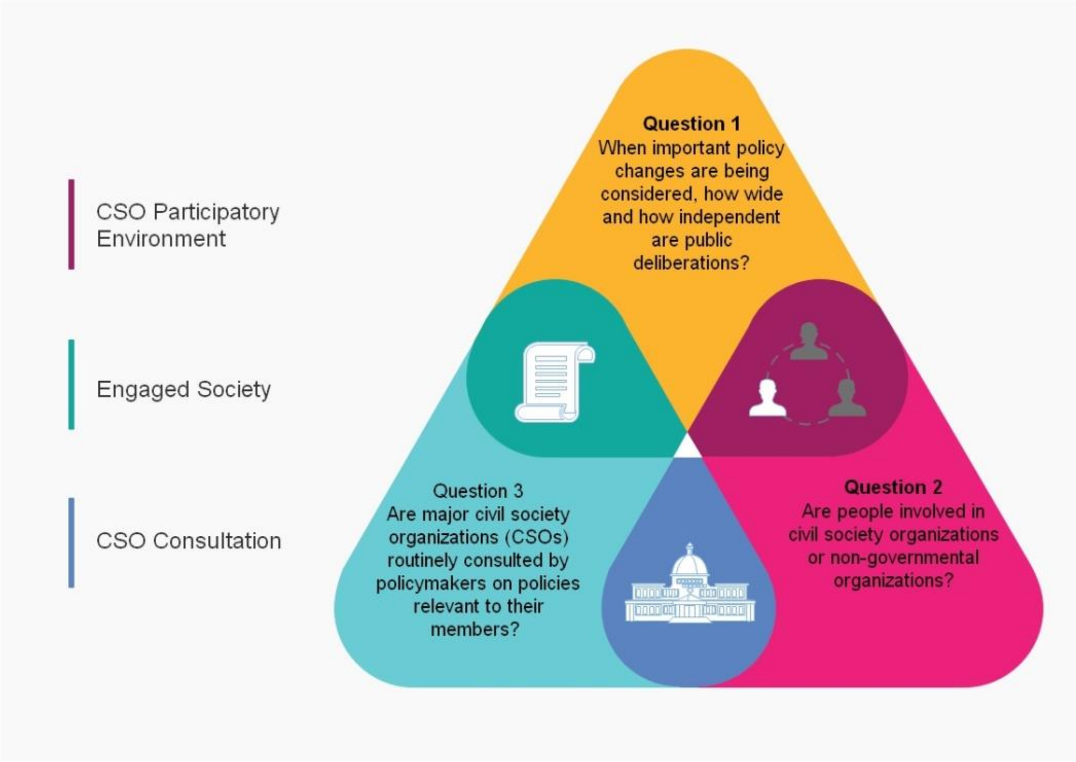


Figure 3.10 Overview of the participatory engagement indicator

3.4.4.4 Corruption Rate Factor

Institutional practice refers to the absence of corruption and the establishment of processes for the ongoing operation of a city. This indicator measures the health of the government within a city. It is evaluated by determining the level of judicial independence within a city. Judicial independence refers to the extent to which the courts are not subject to undue influence from other branches of the government, especially the executive branch.

Rule of law captures perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.

Data sources used to assess this indicator include violent crime, property rights, degree of security of goods and persons, business costs of crime and violence along with many other indicators as set out by the World Bank (2019). The following function is used to quantify this indicator:

$$\beta_{RL} = \frac{\delta_{RL} - min}{\delta_{RL_0} - min} \quad (3.25)$$

where δ_{RL} is the score to the individual question, in relation to the maximum score δ_{RL_0} and the minimium score.

3.4.5 Energy Index

This aspect reflects some of the novelty of this thesis as it has never been considered before in any smart city assessment framework. Energy including electricity and gas or other sources of fossil fuels or renewables and alternative sources constiute the lifeline of a city. Without reliable sources, systems and efficent energy services, any city can virtually shut down and become immobile with significant economic and social catastrophes. Therefore, this aspect is included and evaluated as follows:

$$\gamma_{SEn} = {\beta_{\eta}}^{\omega_{\eta}} \times {\beta_{CEU}}^{\omega_{CEU}} \times {\beta_{ESt}}^{\omega_{ESt}} \times {\beta_{EC}}^{\omega_{EC}} \tag{3.26}$$

The assessment of this aspect will follow the 3S framework and energy will be analyzed from the source, system and service perspectives accordingly. Energy infrastructure in a smart city must be design in an integrated and efficient fashion, where multiple commodities can be achieved through a single system. Currently, cogeneration power plants that provide heat and power, also known as combined heat and power (CHP) are popular.

Similarly, energy systems can be trigenerational, quadgenerational and more if they can provide multiple useful commodities. Therefore, conventional systems for energy generation need to be transformed to allow innovative and more efficient technology to take place in a smart city.

In spirit of data sharing and connectivity, energy generation, distribution and consumption data are shared in real-time to allow for more efficient energy production, distribution and consumption of energy. Figure 3.11 shows the relationship between these aspects and the connectivity throughout the energy life cycle.

Smart metering and various Iot solutions can be used to achieve energy conservation at both the transmission and consumer levels. Conservation and demand management can also be deployed to optimize energy distribution based on consumption patterns. Energy analytics and data can also be accessed over the internet for more public engagement and awareness.

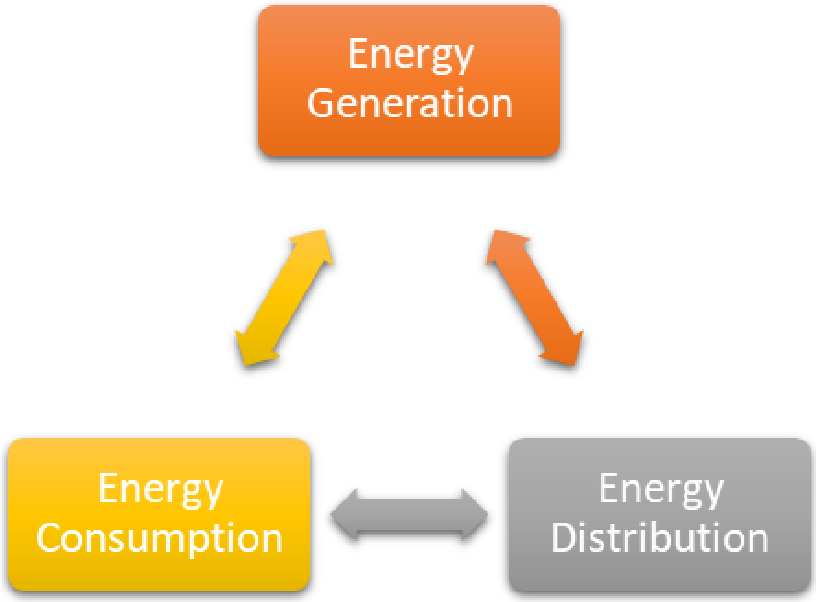


Figure 3.11 Flow of energy and connectivity between each stage in a smart city concept

3.4.5.1 Energy Efficiency Factor

Energy efficiency is a critical indicator to assess this domain. Energy efficient cities have lower energy costs, reduced emissions, improved operating performance and increased asset value. Energy efficiency is the level of performance that describes a process, where more useful output is retrieved from the lowest possible input.

Efficiencies can be qunatified using thermodynamic and mathematical models for energy systems, buildings or other sectors. Energy efficiency is directly correlated to the first law of thermodynamics. Thus, energy efficiency refers to the ratio of useful energy output in relation to the initial energy input. The following function will be used to evaluate this indicator:

$$\beta_\eta = \frac{1-\delta_{EE_0}}{1-\delta_{EE}} \tag{3.27}$$

where δ_{EF_0} refers to the target energy efficiency, which is the upper and reversible energy efficiency of the system and δ_{EF} refers to the actual energy efficiency achieved by the system. the term $1-\delta_{EE_0}$ represents the minimum amount of unavailable energy, while $1-\delta_{EE}$ represents the actual amount of incoming energy not utilized.

Furthermore, this indicator can be assessed by determining the ratio of energy management and efficiency improvements for a given city.

3.4.5.2 Exergy Efficiency Factor

Exergy efficiency is another important indicator that gives a more detailed assessment on effieciency than that of energy. Exergy efficiency highlights that losses and internal irreversibilities are to be evaluated in order to improve performance. Higher exergy efficiency reflects finer energy quality within an energy system, which consequently make the system more sustainable, while lower exergy efficiencies reflect energy losses and internal irreversible reactions. Exergy efficiency is calculated using the following function:

$$\beta_{\psi} = \frac{1-\delta_{ExE_0}}{1-\delta_{ExE}} \tag{3.28}$$

where δ_{ExE_0}represents the reversible exergy efficiency of the system, while δ_{ExE} represents the actual exergy efficiency of the system. Exergy destruction refers to the the sum of exergy destructions in all internal devices (i.e., condensers, evaporators, compressors and expansion valves) within an energy system. It is an important indicator to assess the energy domain as it assesses the quality of energy and the systems' efficiencies and reliability. Exergy destruction is calculated using the following function:

$$\beta_{E\dot{x}D} = (1-\psi) \times \dot{E}x_{in} \tag{3.29}$$

where $\dot{E}x_{in}$ is the total exergy input to the system and ψ is the system's exergy efficiency.

3.4.5.3 Clean Energy Utilization Factor

Sources of energy vary greatly, from fossil-based fuels to renewables; and from fuels in gaseous and liquid states to fuels in solid states. Primary energy sources inclue fossil fuels such as coal, oil and natural gas; nuclear; and renewables such as wind, geothermal, hydropower and solar. These primary sources are converted into secondary energy sources such as electricity, which can be utilzied for various reasons. The transportation sector is a heavy consumer of energy. In fact, the transportation sector is the second largest sector in terms of energy use after the industrial sector in Ontario, accounting for 30% of the energy demand. Therefore, for a smart city, clean fuel must be utilized for transportation for more sustainable growth, economic propserity and environmental protection. Currently, the transportation sector relies significantly on diesel and gasoline for fuel. Enviornmentally-benign energy sources lead to healthier enviornments, and a more prosperou economy, and thus a smarter city. Currently, the base load energy demands for many cities are fossil fuels because of their economic advantage and availability. However, disadvantageous outcomes result from using such sources including pollution, social disruptions, global climate change and political conflicts. Based on the 3S model, smart cities should use sources that are clean, abundant, cheap, and available. Therefore, this indicator will be assessed by evaluating the ratio of renewable fuels in relation to the total energy mix for a given city by using the following function:

$$\beta_{ESo} = \frac{\delta_{RE}}{\sum EM} \tag{3.30}$$

where δ_{RE} denotes the percentage of renewable fuels including ethanol, biodiesel, biogas, biochar, hydrogen, solar, wind, geothermal and hydropower, whereas $\sum EM$ is the total energy mix for the given city.

3.4.5.4 Energy Storage Factor

Energy storage is the capture of energy produced at a certain time for later use at another time. Energy storage is essential in order to actualize the smart city concept. Employing renewables as the energy source, storage becomes critical. In fact, the 3S model integrates storage between the source and the system as well as the between the system and the service. Furthermore, energy storage comes in many forms including mechanical, thermal, electrochemical, and other chemical methods. A city that has abundant energy storage solutions have a smarter energy. This indicator is assessed by the evaluating the amount of energy stored in relation to the total energy demand for a given city:

$$\beta_{ESt} = \frac{\delta_{ESt}}{\sum ED} \tag{3.31}$$

where δ_{ESt} is the energy storage capacity, compared to the total energy demand $\sum ED$.

3.4.5.5 Energy Cost Factor

The cost of energy is also another critical indicator that shapes this domain. Cities with lower cost of energy are considered smarter than cities charging more for energy. In this case, the levlized cost of electricty (LCOE) will be used to quantify this indicator [$/kWh]. The following function is used:

$$LCOE = \frac{\sum_{i=0}^{N}[\frac{I_i+O_i+F_i-TC_i}{(1+r)^i}]}{\sum_{i=0}^{N}[\frac{E_i}{(1+r)^i}]} \tag{3.32}$$

where I_i is investment costs in year I , O_i represent the operation and maintenance costs in year i, $F_i$represents the fuel costs in year i, TC_i represents the total tax credits in year i, E_i represents the energy generated in year i, r is the real discount rate, and N is the economic lifetime of the system. Utilities are essential in any city as they distribute and manage the most essential commodities such as water, electricity, and gas. This domain is optimized and integrated with data analytics and optimization tools to ensure the most efficient and profitable design when distributing these commodities. For example, water monitoring is deployed to ensure the quality of water is within acceptable range along with chemical leakage sensors to avoid water contamination by identifying leakages and wastes of factories in rivers or neighboring water bodies. Water outflows and detecting liquid presence outside tanks and pressure variations along pipes also allows for better management of the water network in a smart city model. As for electricity, grid management and real-time electricity consumption allow for optimization of the grid by utilizing demand and response management. Since the grid was originally designed for one-way electron flow and with the emergence of various renewable energy sources that feed into the grid, the grid operation must be upgraded to allow for this two-way communication within the network. Similarly, gas or other fossil-based fuels are usually used for heating purposes. Data monitoring of gas consumption throughout all sectors such as industrial, residential and institutional sectors allow for better utilization and management of gas lines and demand control.

3.4.6 Infrastructure Index

This aspect is also novel and never used before in any assessment. Assessing the reosurces in a city, especially the essential infrastructur such as water and food to determine the leve lof smartness of a city is considerd critical. While the smart envionrment sub-index focuses on preservation of natural resources, this sub-index assesses the consumption and reliability of available resources. For example, does a city rely on importing essential goods or is it self-sufficient. This aspect is assessed using the following function:

$$\gamma_{SRes} = {\beta_{II}}^{\omega_{II}} \times {\beta_{SI}}^{\omega_{SI}} \times {\beta_{SDP}}^{\omega_{SDP}} \times {\beta_{WR}}^{\omega_{WR}} \tag{3.33}$$

Since this aspect is novel to the assessment of smart cities framework, its impact and relevant will be analyzed and evaluated in depth later in this thesis. Infrastructure is one of the most critical components for cities. Facilities belonging to various sectors such as residential, industrial, commercial and institutional facilities are major components of cities' infrastructure. Moreover, cites' infrastructure also constitutes of various energy systems that are designed to meet the energy and commodity demand for the population. In fact, electricity, air and water heating and cooling as well as fresh water can be considered some of the essential commodities that any civilized city requires. Lastly, urbanization and efficient management of streets and lands within a city is crucial to realizing a smart city model. Throughout this domain, flow of information from the end user to the backend analysis unit is important. For example, facilities can have various monitoring solutions to help detect various issues such as forest fire detection to help monitor combustive gases and preemptive fire conditions, allowing for early defining of alert zones. Controlling CO_2 emissions of industrial facilities is achieved through various control processes. Other monitoring options could include snow level monitoring, landslide and avalanche avoidance, earthquake early detection, liquid presence to prevent breakdowns and corrosion, radiation level detection as well as explosive and hazardous gases to avoid gas leakages in industrial or chemical factories. On the other hand, smart cities allow institutional facilities to utilize various systems that ensure the safety and security of the facility as well as maintenance of assets and overall health of the surroundings. Implementing remote biometrics or wireless alarms can govern the access control and to detect authorized personnel from those who are non-authorized. Water access can be controlled using interconnected technologies to allow for accurate water use in various seasons. Furthermore, smart heating, lighting and ventilation can be attained by monitoring various parameters such as temperature, pressure, and humidity. Collected data is used to optimize the HVAC systems, improving their efficiencies and overall facility performance. Buildings are responsible for the majority of the greenhouse gas (GHG) emissions in urban areas (Morvaj, Lugaric, & Krajcar, 2011). Therefore, one of the major challenges in buildings is to reduce consumption while maintain occupant comfort. In fact, (Moreno, Zamora, & Skarmeta, 2014) explored the energy performance of buildings and the role they play from a city perspective. They also proposed various energy efficiency management systems integrated with building automation control systems. Their approach resulted in 20% savings for heating, translating to an energy savings of 8% in the energy consumption of buildings at a city level. The use of intelligent modeling and control techniques such as the Building Information Modeling (BIM) allows for more data access from buildings and external environments, which can be used to develop Artificial Neural Network (ANN) algorithms. Such models yield in significant reduction in energy consumption with potential savings of approximately 30% (O'Dwyer et al., 2019). Furthermore, the actualization of energy efficiency in buildings from a city perspective involves a number of stages including the building design and structure, building envelope, energy systems and equipment, construction processes, performance monitoring and management and end of life. At each of these stages, a set strategy must be followed in order to achieve energy efficiency. The design must be a holistic, integrated and multi-targeted design. The structure of the building must also provide features such as sustainability, adaptability and affordability (Moreno et al., 2014). Moreover, the building envelope must include multifunctional and adaptive components and must ensure efficient energy and environmental performance. Purchased equipment for heating, cooling, power generation as well domestic hot water and other commodities must rely on sustainable sources. Under this, various technologies such as photovoltaic thermal (PVT) systems and other integrated systems can be utilized such as cogeneration, trigeneration and multigeneration energy systems. Besides, the construction processes must be improving the energy performance delivered and use automated construction tools. In addition, energy systems must be maintained regularly through constant monitoring and the utilization of smart energy management systems. Finally, at the end of life stage, retrofit possibilities must be explored prior to the decommissioning of buildings. The conclusion behind the work done by (Moreno et al., 2014) suggests modest energy savings by applying various building automation control systems while utilizing real-time data. On the other hand, while building automation and control systems are capable of saving 20%-30% of the total energy consumption for a building, it does take a nonresponsive approach. In fact, buildings have the potential to be more efficient and environmentally benign by transforming from passive consumers of energy to an active participant in the power system (Karnouskos, 2011). This paradigm shift can be actualized by incorporating real-time demand-response schemes. Intelligent controls and concepts of smart cities can have an evident impact on the shorter-time scale events, with real-time data providing the basis for automated decisions. Collected information from user activity and receiving input to guide the load management will certainly reduce the energy consumption. This methodology for energy conservation does not conflict with the passive approach. In fact, the passive approach can remain as part of the energy plan as it helps to preserve and distribute thermal energy equally within the building and upkeeps the thermal insulation for instance. Furthermore, Near-Zero-Energy-Buildings (NZEB) or Zero-Energy-Buildings (ZEB) are also expected to be widespread in smart cities as they call for meeting their energy demand using nonpolluting renewable sources. In smart cities, streets resemble an interconnected, synergetic network of data flow to optimize services such as smart lighting, smart parking, and smart mobility. Data gathering will resolve many challenges in a smart city such as traffic congestion, road blockages, and roadworks and will ensure efficient management of resources to enhance public transportation and urban landscape.

3.4.6.1 Technology Infrastructure Factor

The level of investment within a city mirrors its willingness to improve and enhance its services as well as face current challenges. Cities that do not invest in their internal infrastructure are not considered smart, whereas cities that always optimize their internal infrastructure are more smart. This indicator is evaluated by assessing the amount spent on infrastructure investments. Therfore the function used to assess this indicator is as follows:

$$\beta_{IV} = \frac{\delta_{IV}}{\sum GDP} \tag{3.34}$$

where δ_{IV} refers to the investments made within a city in ($) and GDP is the gross domestic product for that city.

3.4.6.2 Green Space Factor

As cities expand and become hubs for civilizations and metropolitan areas, urban planning becomes most necessary. This indicator is evaluated by assessing the number of airports per city as well as the percentage of green public areas in respect to the total city area. Cities that have higher green areas in comparison to metropolitan areas are considerd more smart than cities that do not. This indicator is assessed by the following function:

$$\beta_{GS} = \frac{\delta_{GS}}{\sum Area} \tag{3.35}$$

where δ_{GS} refers to the area of green spaces available within a city in (km^2) in relation to the total city area.

3.4.6.3 Smart Device Penetration Factor

In a digital world, this indicator assesses the percentage of people owning smart devices in each country. It is assumed that having higher smart device penetration will result in smarter cities. This is because of the opportunities that smart devices provide to residents. The following function can be used to assess this indicator:

$$\beta_{SDP} = \frac{\delta_{SDP}}{\sum Pop} \tag{3.36}$$

Where δ_{SDP} refers to the percentage (%) of the population with posession of smart devices. The global Cybersecurity index is used for this indicator. It is a trusted reference that measures the commitment of cities to cybersecurity at a global level. The index is assessed through the presence of legal measures, technical measures, organizational measures, capacity building nad cooperation. A question-based online survey, which further allowed for the collection of supporting evidence was used. Through consultation with a group of experts, these questions were weighted in order to arrive at an overall GCI score. The following function summarizes the method for evaluating this indicator:

$$\beta_C = \delta_{Legal} + \delta_{Technical} + \delta_{Organizational} + \delta_{Capacity} + \delta_{Cooperation} \tag{3.37}$$

where legal measures authorize a nation state to set up basic response mechanisms through investigation and prosecution of crimes and the imposition of sanctions for non-compliance or breach of law. Technical aspect is the primary frontier of defence against cyber threats (including the use of computer emergency or incident response teams, standards plementation framework, technical mechanisms and capabilities deployed to address spam, child online protection, etc.). Furthermore, organizational measures include national strategies, responsible agencies, and cybersecurity metrics. Capacity building include public awareness campaigns, framework for certification and accreditation of cybersecurity professionals, professional training courses in cybersecurity, educational programmes or academic curricula. Lastly, cooperation refers to the use of a multi-stakeholder approach when dealing with cybersecurity.

3.4.6.4 Water Resources Factor

Water is the most critical commodity on earth. In fact, it is the source of life for all organisms and species on this planet. Water consumption, therefore is critical. In a smart city, water consumption is not extravegant nor immoderate. On the contrary, smarter societies conserve less water, in a manner that is sustainable and comfortable. The average person worldwide consumes 742 m3 of water. This indicator is assessed by comparing the global average to the m3 consumption per capita for a given city, using the following function:

$$\beta_{WC} = \frac{\delta_{WC}}{\delta_{WC_0}} \tag{3.38}$$

where δ_{WC} is the water consumption per capita for a given city, while δ_{WC_0} is the global average consumption per capita. In order for a city to be smart and sustainable, it must be self-sufficient in terms of water resources. Therefore, water production is an indicator used to assess this domain of smart resource utilization. The larger capacity for water production is always advantageous to a city. On the other hand, cities that do not produce water or do not have self-regulated processes for water prodcution are not considered smart. The amount of water produced is compared to the mean across the participating cities in this study. The following function is used:

$$\beta_{WP} = \frac{\delta_{WP}}{\delta_{WP_0}} \tag{3.39}$$

where δ_{WP} is the ratio of the water produced and δ_{WP_0} is the weighted mean for the cities involved.

3.4.7 Transportation Index

Mobility and transportation is one of the main features of a city. The fact that all services are interconnected and being heavily populated inspired cities to develop various transportation solutions. This includes efficient urban planning to using environmentally benign transportation solutions. This aspect is assessed based on the following function:

$$\gamma_{SMob} = {\beta_{TE}}^{\omega_{TE}} \times {\beta_{TI}}^{\omega_{TI}} \times {\beta_{TC}}^{\omega_{TC}} \times {\beta_{AC}}^{\omega_{AC}} \tag{3.40}$$

This domain is explored by assessing a number of indicators including transport efficiency, technology integration in the transportation sector, multi-modal mobility, clean fuel utilization and accessibiltiy in the sector. In a smart city concept, efficient and smooth mobility is essential in light of projected skyrocketing of the world's population. Therefore, transportation is a key domain for a smart city concept.

The main elements for this domain are clean, efficient and free mobility. In a smart city concept, modes of transportation are environmentally benign, pollution-free, easily accessible and uses sensors, metric and analytics to provide the most efficient and timely service for the consumers. Transportation of people and goods is designed in a hyper-connected manner to avoid obstacles and challenges. There are various technologies for transportation, which utilize clean and alternative fuel sources as opposed to the conventional fossil fuel-based modes.

Furthermore, self-sufficient, and economically viable transportation options that ensure the welfare of the population are other important features as part of the smart city concept.

3.4.7.1 Transport Efficiency Factor

This indicator assess the level of efficiency for the transportation sector at any given city. A smart city is one where mobility is very efficient, with no congestions or delays. The use of technology as well as efficient and effective planning and management should allow for citizens to move around the city in a very smooth, timely and comfortable manner.

Threfore, this indicator is a very important one when assessing the smart mobiltiy domain. This indicator is evaluated by determining the commute duration for the employed labour force to their place of employment.

Once again, this sample is a reflective sample of the transport efficiency. The commute durations of less than 30 minutes were deteremined and compared t othe total commuting durations for a given city. The following function is used:

$$\beta_{TE} = \frac{\sum CD_{<30}}{\sum CD} \tag{3.41}$$

where $\sum CD_{<30}$ is the sum of all commuting durations less than 30 minutes and $\sum CD$ is the total commuting durations in the sample data.

3.4.7.2 Technology Integration Factor

The integration of technology and ICT is critical to the prosperity of any city as well as the enhancements of the mobility sector. This indicator assesses the use of advanced or emerging technologies in the transportation sector for a given city.

Emerging technologies are those with the potential for rapid growth, significant opportunities, estabkished capabilities, which can make any given city competitive globally. Furhtermore, such technologies include the use of advanced materials, artifical intelligence, cyber resilience, space systems, and remotely-piloted systems and autonomous technologies.

This indicator is assessed by determinig the percentage of advanced technology use in the transportation sector. This indicator is assessed using the following function:

$$\beta_{TC} = \frac{\sum EV}{Area} \tag{3.42}$$

where $\sum EV$ is the total number of EV charging stations in a city divided by the total city area.

3.4.7.3 Traffic Congestion Factor

A smart city is one that is congestion-free. This indicator measures how bad traffic is in a given city. The congestion level percentages represent the measured amount of extra travel time experienced by drivers across the entire year.

To evaluate this indicator, a baseline of travel times during uncongested, free flow conditions across each road segment in each city is established. Then, travel times across the entire year (24/7) for each city is analyzed and compared against free flow periods to derive extra travel time. The following function explains the relationship:

$$\beta_{TC} = \frac{\sum Congestion}{\sum Free\ Flow} \tag{3.43}$$

Where $\sum Congestion$ is the amount of extra time in a year [hr/yr] due to congestion within the city while $\sum Free\ Flow$ is the baseline of travel times during uncongested, free flow conditions across each road segment in each city.

3.4.7.4 Accessibility Factor

Accessbility in transport planning refers to a measure of ease of reaching destinations or activities throughout the city. The level of accessibility in a given city tells a much larger story about that city. In fact, the economic properity of cities in part, depends on people being able to move around in an efficient, inclusive and sustainable manner. Fast development in cities ignite and inspite mobility solutions that are more accessible and efficient. For this indicator, the Deloitte City Mobility Index is used to quantify accessibility for a given city. The following function is used to assess this indicator:

$$\beta_{ACC} = \frac{\sum Accessible\ Route}{Total\ Length} \tag{3.44}$$

where $\sum Accessible\ Route$ represents the total length of the accessible routes in (km) compared to the total length of the transportation system in any given city.

3.4.8 Pandemic Resiliency

The impact of COVID-19 and the global pandemic on the energy sector dynamics. Hourly electricity demand data was collected and analyzed for the province of Ontario. It is evident that health-related pandemics have a detrimental and direct influence on the concept of the smart city. This is manifested through various social, economic, environmental, technological and energy-related changes. This factor revolves around assessing the city's resiliency to pandemics by assessing four district indicators, composed using the following function:

$$\gamma_{PResil} = {\beta_{RR}}^{\omega_{RR}} \times {\beta_{DT}}^{\omega_{DT}} \times {\beta_{CC}}^{\omega_{CC}} \times {\beta_{IC}}^{\omega_{IC}} \tag{3.45}$$

Where the response rate β_{RR} indicator is evaluated by assessing daily test per million of population. The death toll within that city is also taken into consideration using β_{DT} indicator. The numebr of confirmed cases β_{CC} reflects the city's preventative and strategic measures to counteract local, regional and international pandemics. Finally, the infrastructure capacity β_{IC} is evaluaed either by the number of bed capacity or by the ratio of physician per patient.

The overall electricity demand of the province for the month of April of this year amidst pandemic conditions declined by 14%, totaling 1,267 GW. A unique trend of reciprocating energy demand exists throughout the week. The post-COVID-19 indicates higher energy demand in the earlier part of the week and a lower demand in the latter part of the week. Pre-pandemic, the days of highest electricity demand were in the latter part of the work week (Wed-Fri) in addition to the weekend. Post-pandemic, the highest electricity demand occurred in the earlier part of the week (Mon-Tue). Hourly electricity demand shows a clear curve flattening during the pandemic, especially during peak hours of 7 – 11 in the morning and 5 – 7 in the evening, resulting in significant demand reductions during these periods. Lastly, due to COVID-19, GHG emission reductions of 40,000 tonnes of CO_2eq were achieved along with savings of $131,844 for the month of April (Abu-Rayash & Dincer, 2020b). Furthermore, the flattening of the energy demand curve is evident in Figure 3.12. The blue and grey shades are the days of April of 2019, while the yellow and orange shades show the days of April of 2020. The flattening of the energy demand curve is clear during peak hours. A significant reduction in off-peak hours is also observed. While prior health crises, such as SARS, impacted the transportation sector, the COVID-19 pandemic is unprecedented, resulting in exceptional impacts on this sector. Canadian Civil Aviation activities dropped by 71%, compared to business as usual, whereas military aviation activities declined by 27%. As of the end of June 2020, cities with higher than 50% mobility index include Brussels, Singapore, Stockholm, Lyon, Paris, Moscow, and Hong Kong with the highest mobility index of 76%. American cities have the lowest mobility indexes as of the end of June with mobility indexes lower than 20%. It is expected and reasonable to assume that the public's response to COVID-19 will exceed that of SARS. While Britons and Canadians are the biggest supporters of keeping the economy and businesses shut until COVID-19 is fully contained, the Chinese, Russians, Indians, and Italians find it vital to restart the economy regardless. Results show that the majority of the world is in a state of mental distress and will face nervousness and anxiety issues post-COVID-19.

This sentiment is strongest in India, Japan, China, the U.K., Brazil and Canada, ranging between 68%-78%. The trucking industry is the main contributor to the greenhouse gas (GHG) emissions of the Canadian transportation sector, accounting for more than 62% of the total emissions in 2019. Given the impact of COVID-19, forecasted GHG emissions of the Canadian transportation sector for 2020 is evaluated to be 93 megatonnes of carbon dioxide equivalents(Abu-Rayash & Dincer, 2020a).

Mobility and transportation are some of the main essential services of any given city. The fact that all services are interconnected and being heavily populated, inspires cities to develop various transportation solutions. This includes everything from efficient urban planning to use environmentally benign transportation solutions. The impacts of COVID-19 on all transportation modes has been evident throughout the world. Figure 3.13 shows the impacts of COVID-19 on different transportation modes globally.

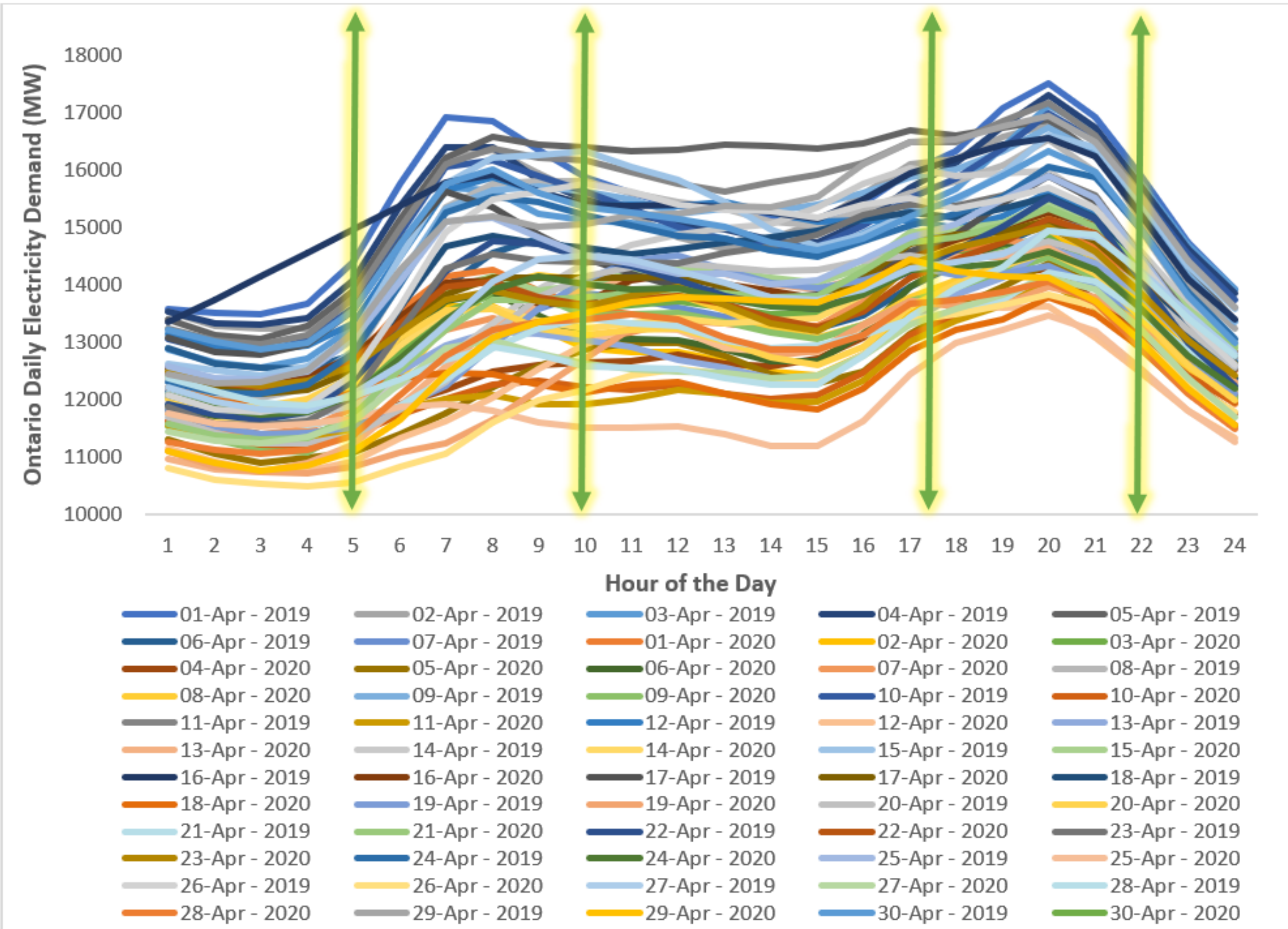


Figure 3.12 Hourly electricity demand for the days of April of 2019 and 2020 [Adopted from(Abu-Rayash & Dincer, 2020b)]

The COVID-19 global crisis is extraordinary in its magnitude. Therefore, the consequent impacts are also unparalleled. Global mobility has halted since the pandemic outbreak and the utilization of transportation means for passenger and freight purposes has been limited due to restrictions imposed by authorities throughout the world. Figure 3.14 shows the Citymapper Mobility Index results for selected cities across the world. These cities were selected in specific because they are considered major cities and because of data availability on the transportation sector for these cities. The Citymapper Mobility Index is calculated by comparing trips planned in the Citymapper app to a recent typical usage period. The mobility reductions of 50% is observed from China and Japan prior to March 2020. The wave triggered the rest of the world after that of China's. Thus, the mobility is rapidly reduced throughout the world as of the start of March 2020. During that week, many jurisdictions halted public transport and other means of non-essential transportation, resulting in a severe depression in the mobility index to unprecedented low levels. The transportation sector was virtually non-existent for the months of March, April and May, after which restrictions loosened and cities started to resume public transport with extra precautions and care. Figure 3.14 also shows how the mobility index of China never went below 30%, whereas the rest of the world went to near 0%. This is attributed to effective management of the wave and accurate timing for transport closure and restriction. As the rest of the world just shut down their transportation, China started to revive and increase its mobility. As of June 2020, Hong Kong, followed by Moscow and Istanbul are the cities with the highest mobility index worldwide. It is also observed that loosening of the transportation restrictions in Moscow and Hong Kong is happening incrementally and gradually, whereas other cities are following a more gradual and steadier rate.

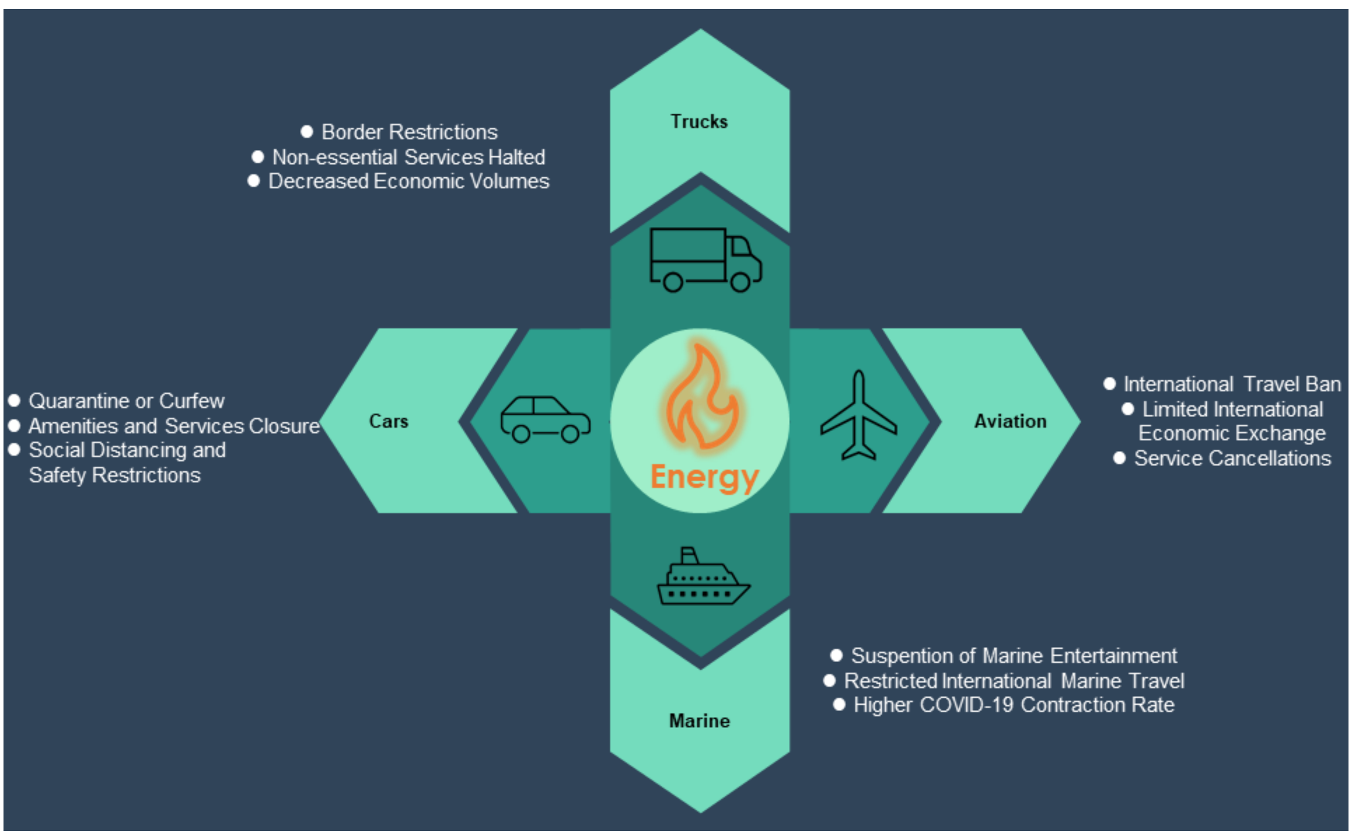


Figure 3.13 Overview of the COVID-19 impacts on the transportation sector [Adopted from (Abu-Rayash & Dincer, 2020a)]

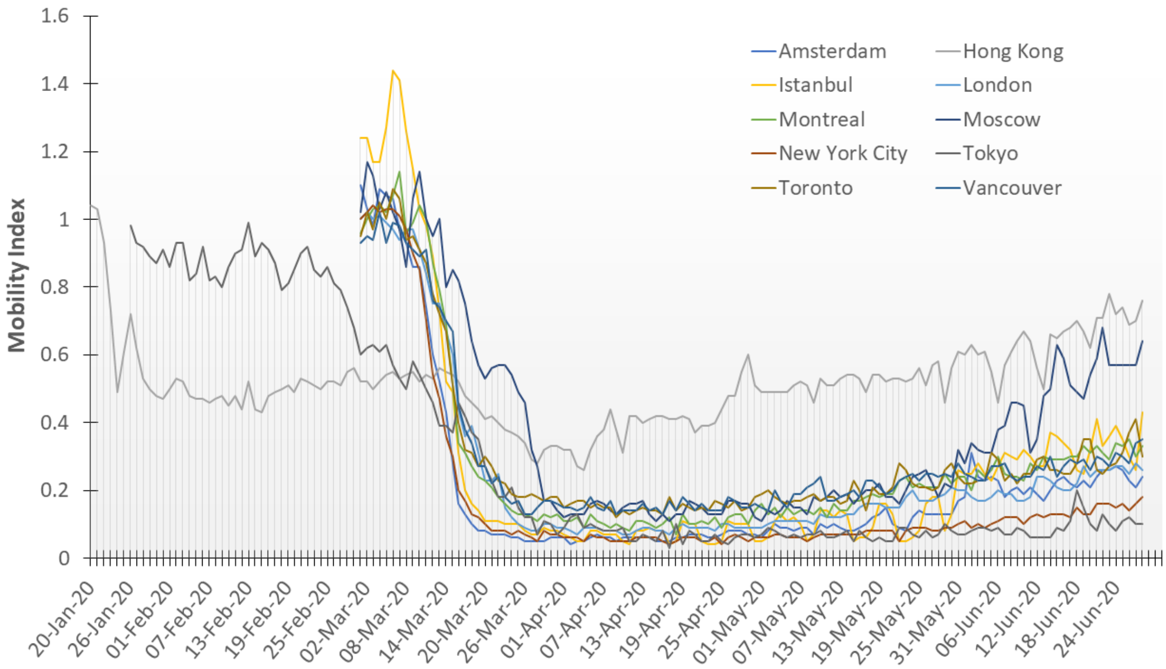


Figure 3.14 Global mobility trends in response to COVID-19 pandemic (Adopted from: (Abu-Rayash & Dincer, 2020a))

3.5 Guiding Principals Process

Once data is collected for each indicator under each domain, the data is processed in a specific methodology to ultimately result in an actionable smart city model. Figure 3.15 shows the methodology that data sharing follows in this model. Using this methodology, data is firstly collected using various sensory intake tools and information communication technology tools.

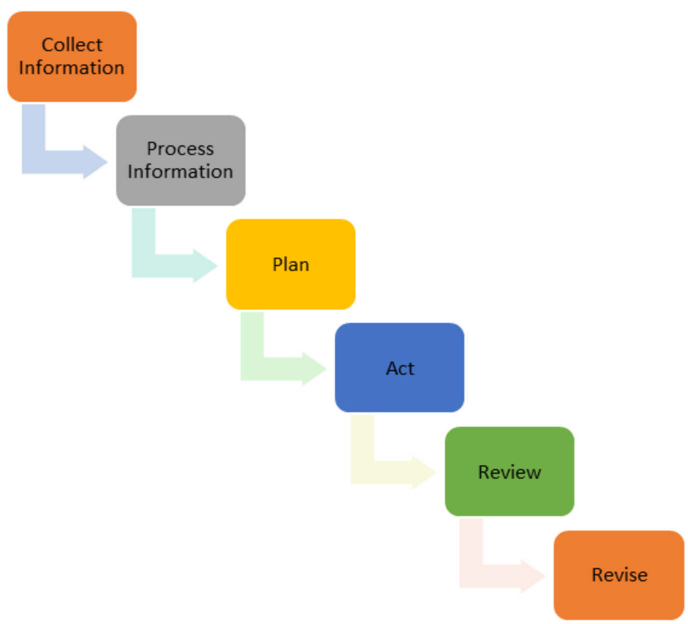


Figure 3.15 Verification and validation methodology for the smart city concept

Data is then processed and integrated with various related domains to identify the right course of action. The plan of action is subsequently developed by using the optimized scenario. Action based on the plan is carried out and the relative domains or stakeholders are notified. Review and reassessment of the action is necessary to learn from mistakes or to address errors, which lead to the final step, which is to revise the action that had been carried out in case of faults.

3.6 Aggregation and Weighting

In this thesis, the weighted geometric mean will be used as the main aggregation method to aggregate the values of the indicators within a single sub-index. Weighted geometric is a type of statistical mean that indicates the central tendency of a group of values using the product of these values rather than their sum (arithmetic mean).

3.6.1 Weighted Geometric Mean Aggregation

From previous research in energy sustainability, it was found that this type of aggregation was most meaningful and effective when compared to other types of aggregations such as the weighted arithmetic mean. The weighted geometric mean is illustrated using the following function:

$$WGM_{(\gamma,\omega)} = \prod_{i=n}^{m} {\gamma_i}^{\omega_i} \tag{3.46}$$

where γ represents the dimensionless normalzied value for the respective domain and ω represents the weight associated with each domain.

3.6.2 Panel Weighting Method

Different weighting schemes will be carried out to avoid any subjectivity in the assessment. Weighting schemes include the individualist, hierarchist, egalitarian, panel and equal weighting methods. Many of the indicators' reference state use the weighted mean of the values of all cities. To consolidate the various indicators, normalized ratios were obtained and then computed for each measure. The final index score for each indicator is the ratio of one city's indicator to the weighted mean across all cities. This method provides a comparison of how each city is doing against others while permitting a wide variety of measures to be used.

3.7 Data Analysis

In this thesis, three regression predictive modelling techniques will be utilized. Such modelling methodologies investigate the relationship between a dependent and an independent variable(s). Furthermore, they are used to forecast and find casual effect relationships between variables. In relation to this thesis, the influence of the air quality parameter or the social cost parameter on the overall smart city index will be investigated. Similarly, the impact of a sub-index on the smart city index will also be assessed. The most suitable regression analysis will be used for each relationship in study depending on the nature of the parameters. The benefits of using regression modeling can be summarized in the following points:

- Regression modelling indicates the significant relationships between dependent and independent variables.
- The strength of the impact of multiple independent variables on a dependent variable can be assessed.

Multiple Linear Regression Modeling is the most common methodology in data sciences. Linear regression modeling is used for predictive modeling where the dependent variable is continuous, and the independent variables can be discreet or continuous. The nature of the regression line in this case is linear, and thus the relationship between both variables is illustrated using a best-fit straight line, known as the regression line. The following function summarizes this methodology further:

$$\gamma_i = \alpha + \beta_1 x_i + \varepsilon_i, \; i = 1, \dots, n \tag{3.47}$$

where γ_i is the linear regression, α is the intercept, β_1 is the slope and ε_i is the error term. The fact that there are multiple independent variables causes this regression methodology to suffer from multicollinearity, autocorrelation, and heteroscedasticity. Furthermore, linear regression is very sensitive to outliers, which can affect the regression line and subsequently the forecasted values. Multicollinearity can increase the variance of the coefficient estimates and make them very sensitive to minor changes in the model. This results in the instability of the coefficient estimates. Multiple Logistic Regression Modeling is usually used when there is one nominal variable, which in this case is the smart city index and two or more measurement variables, which in this case are all the six sub-indexes along with their respective indicators. Simply, the objective is to know how the measurement variables affect the nominal variable. The modeling can be used to predict probabilities of the dependent nominal variable or can be used to suggest the degree of influence of each independent variable on the dependent variable. The model can be illustrated in the following function:

$$logit\ (\gamma) = \ln\left(\frac{\gamma}{1-\gamma}\right) = \alpha + \ \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \ldots . \beta_k x_k \qquad (3.48)$$

where the logistic function $logit\ (\gamma)$ is the function used for this binomial distribution. This methodology is widely used for classification problems and does not require linear relationship between the dependent and independent variables. In fact, it is able to handle various types of relationships because it applies a non-linear logistic transformation to the predicted ratios. Ridge Regression Modeling is used for analyzing multiple independent variables that suffer from Multicollinearity. In the case of the smart city index, all the sub-indexes are highly multicollinear. Therefore, ridge regression adds a degree of bias to the regression estimates and reduces the standard errors. The final results are usually more reliable estimates. The following function is used for this modeling:

$$\gamma = \alpha + \ \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \ldots . \beta_k x_k + \varepsilon \qquad (3.49)$$

3.8 Limitations and Assumptions

Every research or novel model has limitations and restrictions. For this thesis, the smart city concept is limited to the eight domains that are described at length in this chapter. While these domains could have been limited to say five or four or even nine, the eight domains remain a limitation to this model. Furthermore, several data imputations were conducted due to data unavailability. For example, when the data for a specific parameter cannot be found for a given city, the value adopted for that country is considered a suitable replacement after the data point has been processed accurately. Various data points were collected from internationally adopted databases such as the World Bank. These data points include the GDP per capita, cost of electricity for an average residential load, and unemployment ratings. The clean energy utilization ratio was assumed based of the electricity production from renewable sources from the city. Furthermore, while the denominator for the majority of factors was 100, in order to normalize the value between 0 and 1, the average was taken for some, including the GDP per capita, government effectiveness ratio, pandemic resiliency indicators and energy cost.

Chapter 4: System Development

The main commodities that are necessary for a city include electricity, heating, cooling, and domestic hot water. A mixture of energy sources, primarily fossil fuels, currently supply the demand for these commodities. The integration of renewable energy sources is on the rise, given a rapid decrease in cost and increase in efficiency and performance. The current business as usual (BAU) scenario for cities include generating electricity from a variety of sources, primary fossil fuels. In Ontario, electricity is generated from nuclear energy (58%), gas (10%), and renewable sources (32%) for the year 2016 (IESO, 2017). Furthermore, heating, domestic hot water and drying commodities are fulfilled using natural gas (100%), which is imported from Alberta. In this thesis, four novel and integrated energy systems are designed, assessed and analyzed to achieve a net zero energy smart city concept. Each system is distinct by the following features:

- Each system utilizes distinctive energy storage options.
- Each system meets the energy demand by using different energy sources.
- The four systems provide a variety of energy source combination to mimic real scenarios

Table 4.1 summarizes all systems and describes each system and their components.

Table 4.1 Summary of proposed systems and their subcomponents

Component | System	System 1 (BAU)	System 2	System 3	System 4	System 5
Source	Nuclear, Natural Gas, Hydro	CSP, PVT	PTD, Wind	PVT, Geothermal, Hydro	Nuclear, Biomass
System	Conventional RTUs and Chillers	ORC, ARC, District Heating/Cooling	Compressed Air Energy System, ORC, ARC, District Heating/Cooling	Quintuple Geothermal, ARC,	Biomass Gasification, Vapor Compression Refrigeration
Storage	Hydro Storage	TES, Battery Storage	CAES, TES, Battery	TES, Hydro,	TES
Service	Electricity, Heating, Cooling, Domestic Hot Water				

4.1 System I

This system is considered the reference system, which is the current business as usual. In Ontario, electricity is generated through hydropower from Niagara Falls and various nuclear stations distributed across Southern Ontario as part of the Ontario Power Generation (OPG). Therefore, nuclear and hydropower will be the main sources of energy for electricity and cooling in this system. Furthermore, heating, and domestic hot water is achieved through the combustion of natural gas using conventional boilers. Natural gas is imported from Alberta through various gas lines and further distributed through Enbridge Gas to cities in Ontario.

While renewable and alternative energy sources are present with modesty in Ontario, they will not be considered in this system as a mere assumption. Figure 4.1 illustrates this system in detail. In fact, the trilogy of nuclear energy coupled with hydropower and natural gas is a good representation of a conventional energy system in a modern city today. The combination of fossil fuels (natural gas), renewable (hydropower), and alternative fuels (nuclear energy) makes this system unique. Once again, this system is designed as the reference system, illustrating the current energy system in Ontario.

4.1.1 Source I

Fossil fuels, primarily oil and gas are the most popular forms of energy in the world today. In fact, 63% of the world's generated electricity in 2014 was from coal and natural gas, while nuclear accounted for 11% and hydropower for 16%. Other sources such as renewable accounted for only 6% and oil accounting for 4%. In Ontario, nuclear energy and hydropower are the main sources of electricity generation. Natural gas imported from Alberta is also the main energy source for heating and domestic hot water.

4.1.2 System I

Conventional energy systems are currently being deployed to provide basic heating and cooling commodities. Cooling is achieved by deploying single unit chillers or combined cooling systems. Similarly, heating is achieving through combustion or gasification by the use of boilers or other heating equipment.

4.1.3 Service I

The main commodities are assembled in this system as electricity, heating, cooling and domestic hot water. Cities vary in their capacities and needs for each commodity. Furthermore, some cities have higher demand per capita than other cities and thus requiring higher energy input.

4.2 System II

This system utilizes the sun as a primary source of energy. A 40 MW solar PVT farm is developed, to produce electricity and heated water. The electricity generation is used to directly fulfill the electricity demand of the city. Excess electricity is stored in battery storages, which offset the mismatch between demand and supply as required. Another main output from the PVT is hot water, which is directed to a low-grade thermal energy storage (TES) tank. The second energy input is through concentrated solar power (CSP). Mirrors reflect the solar energy and concentrate it onto a power tower collector, where molten salt is heated and sent back to the high-grade TES. The thermal energy storage acts as a buffer and an intermediate source of energy for the processes to come. Heated molten salt from the high-grade TES acts as an input to an Organic Rankine Cycle (ORC), which generates electricity. Waste heat from the ORC is further utilized to operate an absorption refrigeration plant, which ultimately provides cooling in the form of district cooling. Similarly, heated molten salt from the high-grade thermal energy storage is used for the purpose of district heating. Lastly, the low-grade thermal energy storage is used to heat water for domestic use. Figure 4.2 illustrates this system in further detail. In this system, solar energy is utilized for both power generation and heating applications while developing storage solutions as it is an intermittent energy source. Both district cooling and district heating are introduced in this system. The organic Rankine cycle is utilized in this system to provide cooling and power for the city. Battery storage is also utilized in this system.

4.2.1 Source II

Between 2006 and 2016, the global solar capacity increased from 5762 MW to 301 GW. This exponential increase in the past decade accounts for 5132% in the global solar capacity. There is no doubt that a solar revolution will take place soon. Solar power can be utilized for power generation and heating applications. This is in fact one of the limitations of this system as it solely relies on the intermittent solar energy, yet compliments that with thermal and battery energy storage solutions.

4.2.2 Service II

Energy services introduced in this smart energy system are quite different form conventional systems. District heating and district cooling are both utilized. Electricity and domestic hot water remain unchanged from conventional systems. However, domestic hot water is also heated centrally and distributed in a district fashion. District energy solutions introduce the ideal of a thermal grid, similar to the electricity grid. This solution utilizes thermal energy storage for charging or discharging energy as required. Heat from the TES is also used to power the absorptions refrigeration system, which is the component responsible for the district cooling. While this system is aggressive in approach, an intermediate phase can be implemented where conventional energy infrastructure such as boilers and chillers can augment this system.

4.3 System III

This system primarily uses wind turbines for electricity generation. A wind farm feeds into the grid to meet the electric demand of the city. Excess electricity is stored using compressed air storage. During peak demand as well as absence of wind power generation, compressed air energy storage (CAES) is utilized to supply electricity to through the grid to the city. Figure 4.3 illustrates this system in further detail. Solar energy is harvested through concentrated solar power (CSP) using parabolic trough dishes. The heat generated is preserved in a thermal energy storage for further processing. The TES acts as a gateway, providing district heating, and domestic hot water to the city. District cooling is achieved by utilizing the electricity from the wind turbines or CAES to operate a Carnot refrigeration plant that delivers cooling in the form of district cooling to the city.

4.3.1 Source III

This system utilized both solar and wind sources, both renewable and intermittent. Storage solutions are also integrated to offset the intermittency nature of these energy sources. Wind energy is also rapidly adopted worldwide. The global capacity for wind energy between 2006 and 2016 was 74008 MW and 469 GW consecutively. This accounts for an increase of 534% in global wind capacity in the past decade.

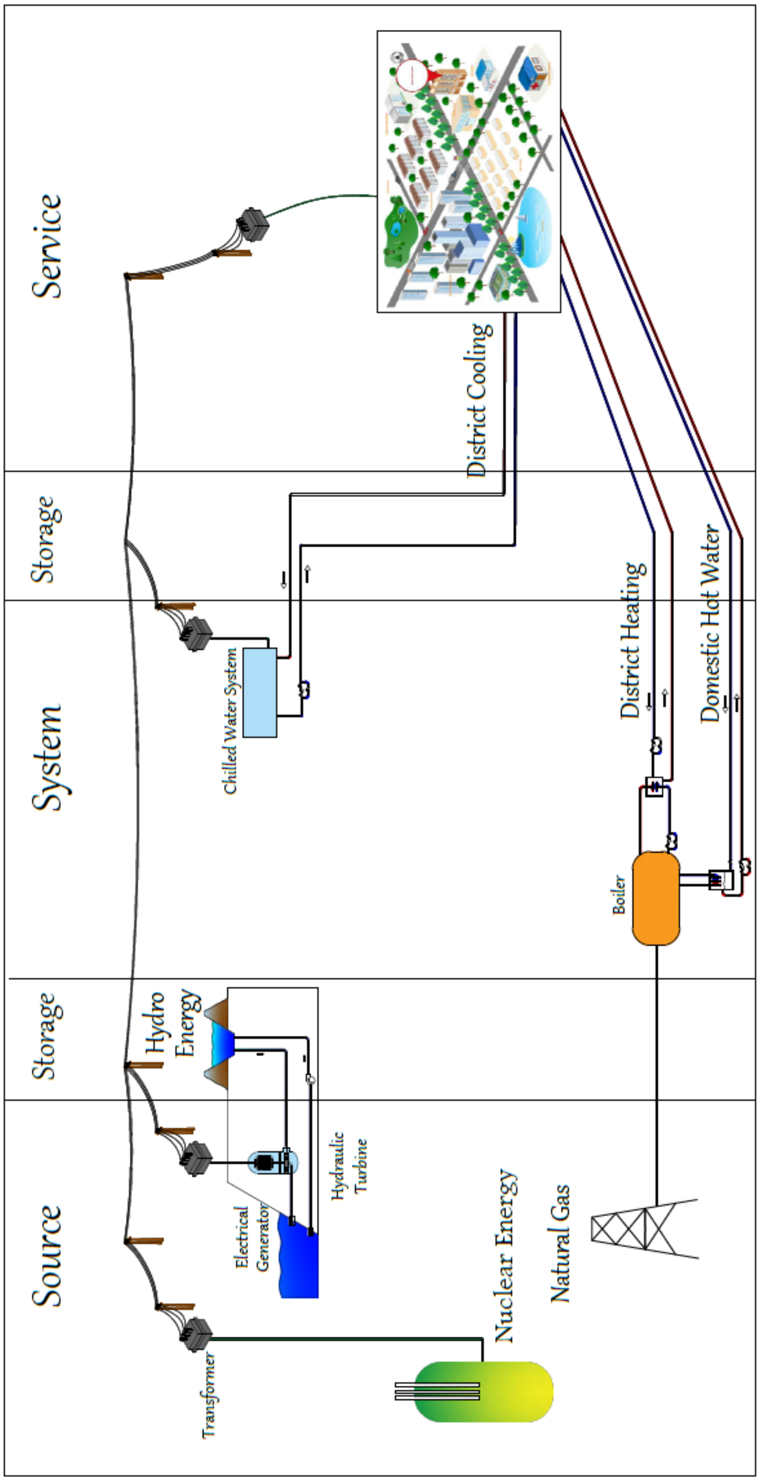


Figure 4.1 Reference energy sources, systems and

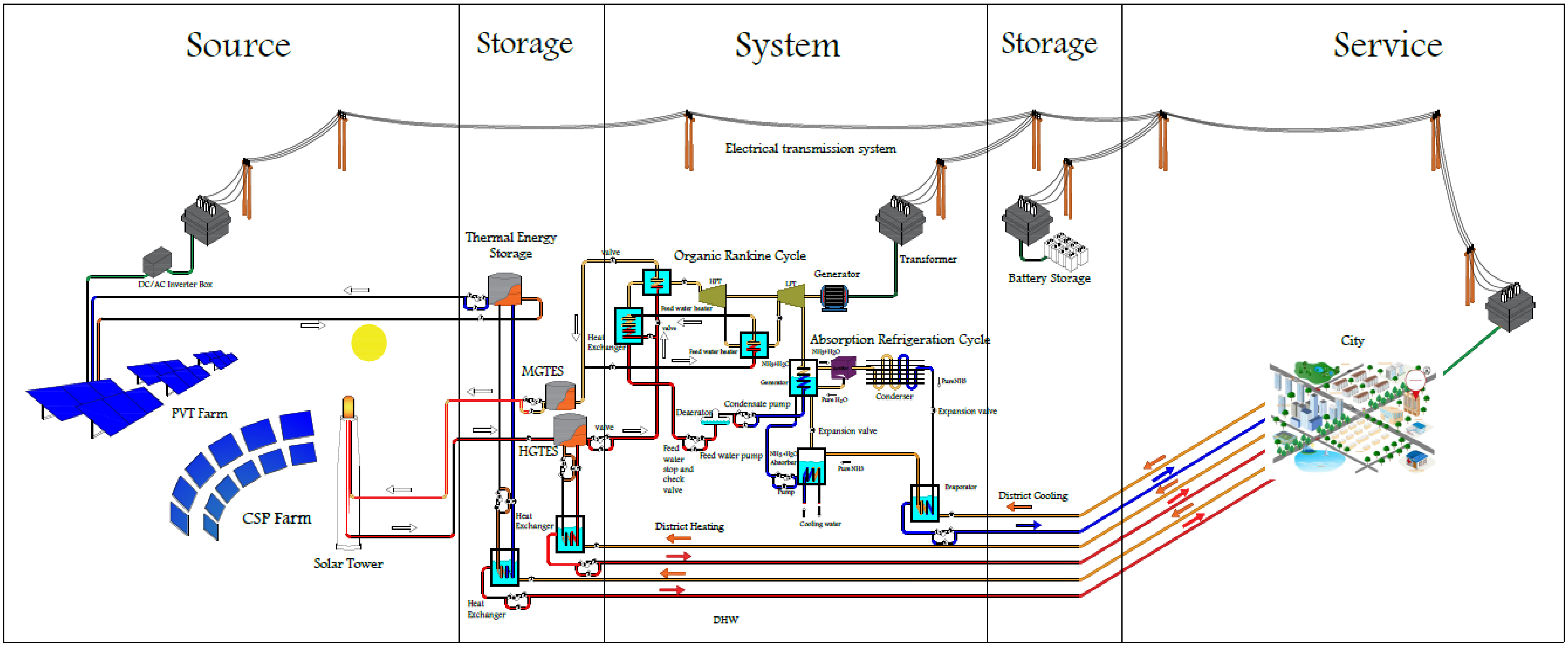


Figure 4.2 All components for system II including sources, systems and energy services

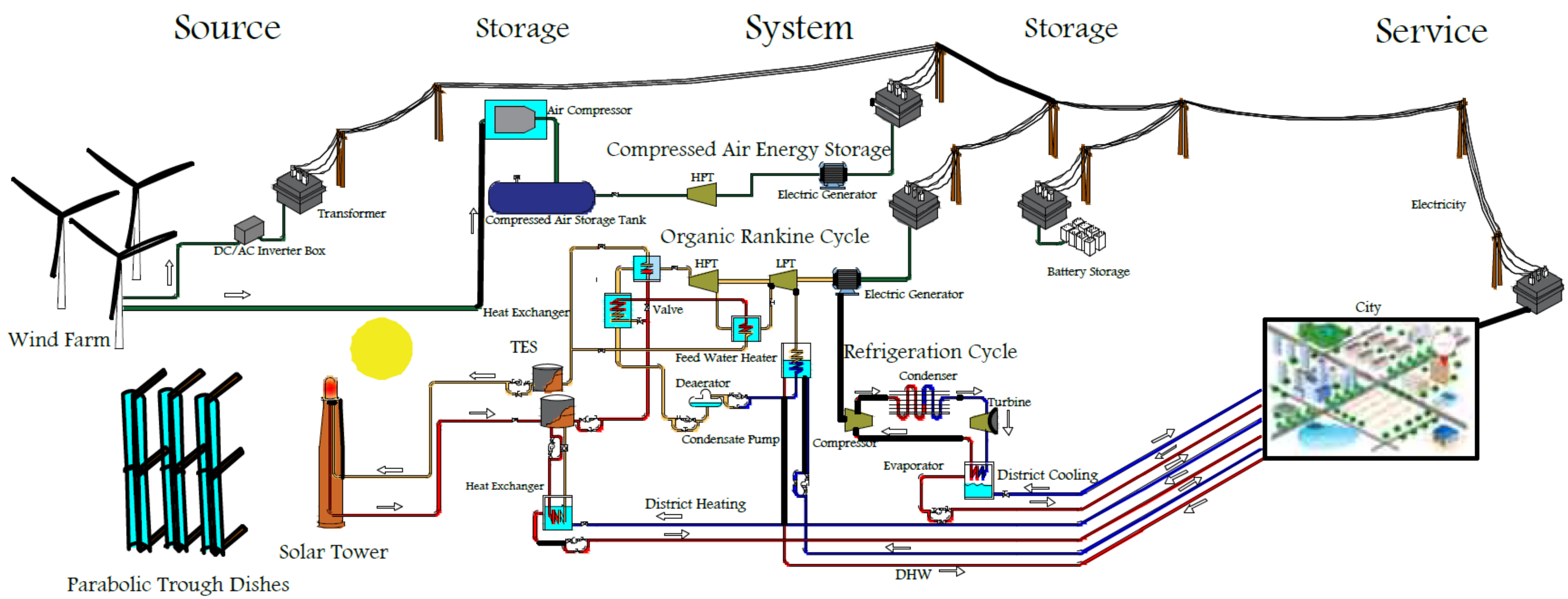


Figure 4.3 All components for system III including sources, systems and energy services

4.3.2 System III

Besides the organic Rankine cycle for cooling and power generation, the system also utilized parabolic trough solar dishes to concentrate heat onto a solar tower that captures the heat and saves it in a thermal energy storage, which is then used for heat distribution. Furthermore, the system features another energy storage solution, which compressed air energy storage to store excess electricity from the wind turbines. Battery storage is also used in this system.

4.3.3 Service III

The services remain unchanged throughout the systems. As elaborated earlier, electricity, heating, cooling and domestic hot water are all delivered to the city in the capacities outlined in Table 4.1, earlier in the section.

4.4 System IV

This system uses three renewable sources to meet the energy demand of the city. The availability of two of the sources however are geographically dependent. Hydro energy is utilized for power generation at a rate of 40MW to meet the majority of the electric demand of the city. Figure 4.4 illustrates this system in further detail. Pumped hydro energy storage is used as the storage medium in this case. On the other hand, heat is extracted using a quintuple geothermal system. Heat is transferred to a TES, which is then further used for district heating and domestic hot water (DHW). The geothermal system also produces electricity, which feeds into the grid as well. The PVT system also produces 10MW of electricity as well as thermal energy, which is used to operate an absorption refrigeration plant to provide the required cooling supply for the city.

4.4.1 Source IV

This system features the addition of both geothermal and hydro energy as renewable energy sources. Hydropower has been rapidly adopted across the globe, growing from 698 Mtoe in 2006 to a global consumption of 910 Mtoe from hydropower alone. This accounts for a 30.5% increase in global adoption of hydropower. Furthermore, geothermal adoption is also increasing. The world consumed 62 Mtoe of geothermal and biomass in 2006 and 127 Mtoe in 2016, accounting for a 106% increase in the past decade.

4.4.2 System IV

The geothermal system is comprised of a quintuple flash geothermal cycle, producing electricity and heat, which is captured in a thermal energy storage that is used for district heating and cooling. An absorption refrigeration cycle is used to fulfill the cooling demand. Hydro storage is also utilized in this system.

4.4.3 Service IV

District heating and domestic hot water are obtained from the geothermal energy through a thermal energy storage. Cooling is achieved through the absorption refrigeration cycle, which is powered through the PVT farm. Electricity is generated from hydropower, PVT farm and the geothermal system.

4.5 System V

The fifth system combines nuclear energy with biomass. Small modular nuclear reactors produce 100MW of electricity, which feeds the grid and meets the city's electric demand. Excess electricity is used to run a vapor-compression refrigeration plant, which meets the cooling demand. Figure 4.5 illustrates this system in further detail. Waste heat from the nuclear plant is utilized for domestic hot water and district heating. Biomass utilizes the city's wastes and solid wastes to generate heat through gasification, which is used for district heating.

4.5.1 Source V

While nuclear energy experienced a slight decline in global consumption by 7%, its relevance and use remain widely spread. In specific, small modular nuclear reactors are favorable because of their simplicity and easy deployment. Furthermore, biomass and geothermal together have been highly adopted globally. The biomass system uses gasification instead of combustion to generate the heat, which is then stored in the thermal energy storage. Nuclear energy is utilized as the main source of electricity, which also powers a vapor compression refrigeration cycle for cooling. Waste heat from the nuclear reactors is also utilized in the thermal energy storage.

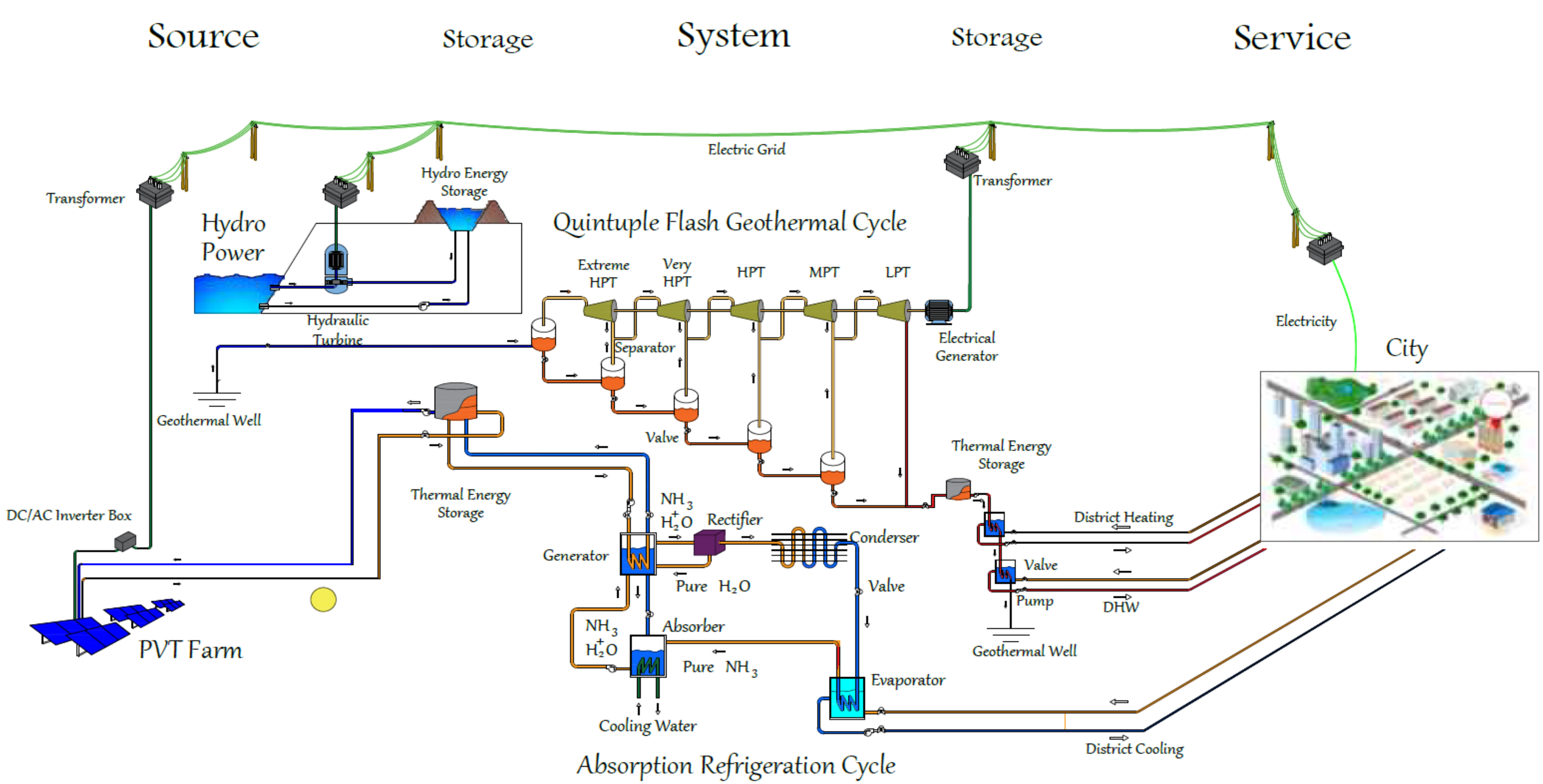


Figure 4.4 All components for system IV including sources, systems and energy services

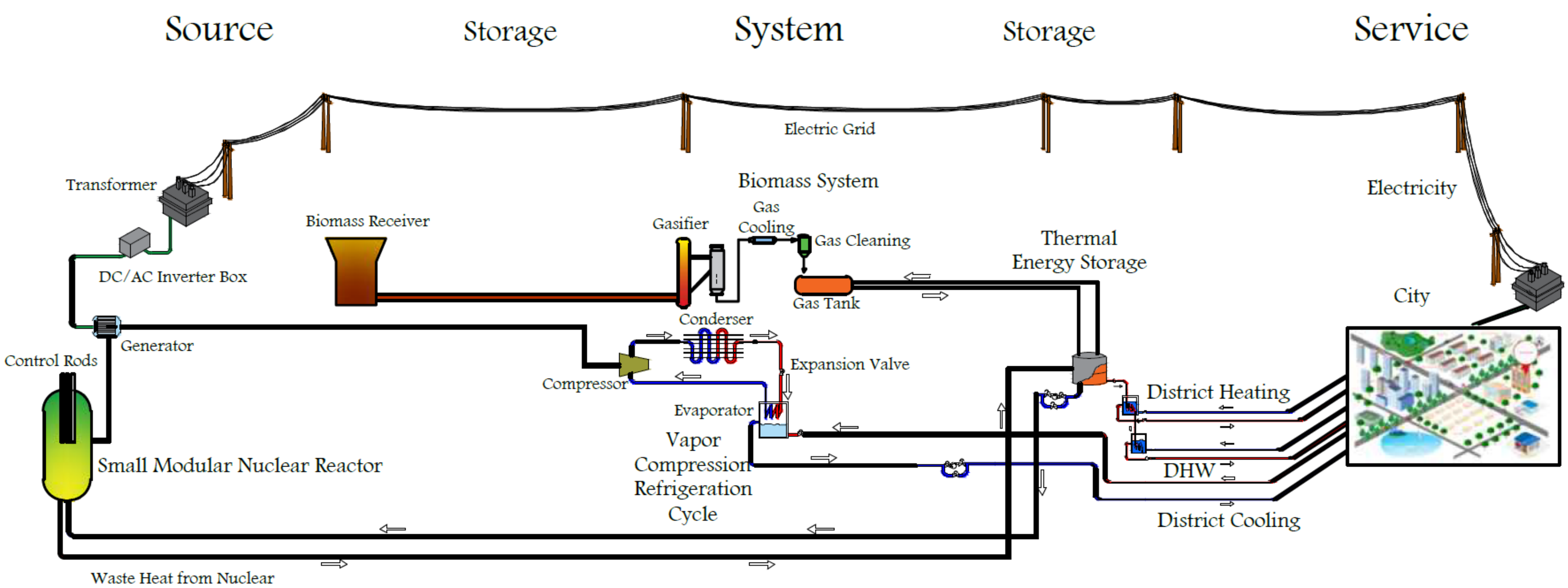


Figure 4.5 All components for system V including sources, systems and energy services

4.5.2 System V

The district energy system is typically run as a thermal utility by a company that operates all the plants and networks, ensures service quality, and manages the metering and billing of the heating services. The network allows for reduced energy consumption and GHG emissions, since generating heat and cooling in a few larger plants is more efficient than having thousands of boilers, furnaces and air conditioners heating and cooling individual buildings. It also enables valuable energy currently wasted in electricity generation and industrial processes to be cheaply captured and delivered to consumers. The heating network enables a wide range of heat sources to be mixed together, many of which have lower costs, lower emissions and adds reliability to the overall heating supply. Heat can be captured and added to the network from any process that produces waste heat including power generation, industrial processes, solar thermal panels, biomass tri-generation and geothermal processes.

4.5.3 Service V

The sole source of electricity in this case is nuclear energy. Electricity also powers the cooling cycle for district cooling. Biomass gasification provides the heat required for district heating and domestic hot water. Waste heat from the nuclear reactors are also inputs to the thermal energy storage. District heating networks transport heat efficiently up to 30 kilometers from any single heat source. When multiple heat sources are combined, networks can be hundreds of kilometers long. This allows for heating and cooling services to be established across neighborhoods, industrial areas, entire cities and regions. Networks can balance the supply and generation of heat by time and location. As the heat demands change throughout the day for residential, commercial, industrial and public buildings, the heat network matches and manages these changing patterns, while ensuring the most efficient and lowest cost mix of heat sources are used. Seasonal patterns can also be managed.

Chapter 5: Analysis and Modeling

This chapter outlines all the analyses, assessment and modeling that are conducted on all five systems. The first part outlines the thermodynamic studies to assess system performances comparatively. Energetic and exergetic efficiencies are evaluated as well.

Furthermore, exergoeconomic analysis is used to assess the developed systems from an economic perspective. Furthermore, a lifecycle assessment is conducted to evaluate and compare the energy consumption, resource utilization and environmental impacts between the assorted products and processes. Lastly, optimization studies will be detailed outlining preferred system parameters to achieve the objective function.

5.1 Thermodynamic Analysis

Assuming kinetic, potential and chemical energies are negligible; the general mass balance equation of a non-steady system is denoted as follows:

$$\sum_{in} \dot{m}_{in} = \sum_{out} \dot{m}_{out} \tag{5.1}$$

Similarly, the energy balance equation, representing the thermal energy rates, the work rates as well as the energy associated with the mass entering and exiting the system is as follows:

$$\sum \dot{Q}_{in} + \sum \dot{W}_{in} + \sum_{in} \dot{m}_{in} h_{in} = \sum \dot{Q}_{out} + \sum \dot{W}_{out} + \sum_{out} \dot{m}_{out} h_{out} \tag{5.2}$$

The entropy balance equation is assessed using the following function:

$$\sum_{in} \dot{m}_{in} s_{in} + \sum_{in} \dot{m}_{in} \frac{q_{in}}{T_{source}} + \dot{S}_{gene} = \sum_{out} \dot{m}_{out} s_{out} + \sum_{out} \dot{m}_{out} \frac{q_{out}}{T_{source}} \tag{5.3}$$

Moreover, exergy is the maximum useful output that a process can generate. Thermodynamic irreversibilities are detected through exergy analysis, which can be assessed using the following function:

$$\sum \dot{E}x_{\dot{Q}_{in}} + \sum \dot{E}x_{\dot{W}_{in}} + \sum \dot{E}x_{flow_{in}} = \sum \dot{E}x_{\dot{Q}_{out}} + \sum \dot{E}x_{\dot{W}_{out}} + \sum \dot{E}x_{flow_{out}} + \dot{E}x_d \tag{5.4}$$

Thermal exergy can be further assessed using the following function:

$$\dot{E}x_Q = \left(1 - \frac{T_0}{T_i}\right) \times \dot{Q} \tag{5.5}$$

Similarly, exergy associated with work is assessed using the following function:

$$\dot{E}x_w = \dot{W}_{cv} + P_0 \frac{dV_{cv}}{dt} \tag{5.6}$$

Exergy generated with a steady stream is assessed through the following function:

$$\sum_{in} \dot{m}_{in}[(h_{in} - h_0) - T_0(s_{in} - s_0)] = \sum_{out} \dot{m}_{out}[(h_{out} - h_0) - T_0(s_{out} - s_0)] \tag{5.7}$$

Furthermore, exergy destruction, which has a linear relationship with entropy generation is assessed using the following function:

$$\dot{E}x_d = T_0 \times \dot{S}_{gen} \tag{5.8}$$

The overall energy efficiency of the system is defined as the ratio of useful output to the energy input and can be evaluated using the following function:

$$\eta_{en} = \frac{\sum Useful\ Energy\ Output}{\sum Energy\ Input} = 1 - \frac{\sum Energy\ Loss}{\sum Energy\ Input} \tag{5.9}$$

Similarly, the exergy efficiency can be evaluated using the following function:

$$\eta_{ex} = \frac{\sum Useful\ Exergy\ Output}{\sum Exergy\ Input} = 1 - \frac{\sum Exergy\ Loss + Exergy\ Destruction}{\sum Exergy\ Input} \tag{5.10}$$

5.1.1 Organic Rankine Cycle Analysis

The Organic Rankine Cycle is composed of a high-pressure turbine and a low-pressure turbine that add to the electric mix. The thermal output from the condenser is used to fulfill the domestic hot water demand for the city. Table 5.1 shows all the mass, energy, entropy, and exergy balance equations for all the main components in this cycle.

Furthermore, the energy and exergy efficiencies of the ORC can be expressed as follows:

$$\eta_{en,ORC} = \frac{\dot{W}_{net,ORC}}{\dot{m}_{ORC} \times (h_{HPT} - h_{pump})} \tag{5.11}$$

$$\eta_{ex,ORC} = \frac{\dot{W}_{net,ORC}}{\dot{m}_{ORC} \times (ex_{HPT} - ex_{pump})} \tag{5.12}$$

Table 5.1 Balance equations for all major components in the ORC

Component/Balance Equation	Mass Balance Equation	Energy Balance Equation	Entropy Balance Equation	Exergy Balance Equation
Pump	$\dot{m}_1 = \dot{m}_2$	$\dot{m}_1 * h_1 + \dot{W}_{pump,in} = \dot{m}_2 * h_2$	$\dot{m}_1 * s_1 + \dot{S}_{gen} = \dot{m}_2 * s_2$	$\dot{m}_1 * ex_1 + \dot{W}_{pump,in} = \dot{m}_2 * ex_2 + \dot{E}x_{D,Pump}$
Boiler	$\dot{m}_2 + \dot{m}_4 = \dot{m}_3 + \dot{m}_5$ $\dot{m}_2 = \dot{m}_3$ $\dot{m}_4 = \dot{m}_5$	$\dot{m}_2 * h_2 + \dot{m}_4 * h_4 + \dot{Q}_{in} = \dot{m}_3 * h_3 + \dot{m}_5 * h_5$	$\dot{m}_2 * s_2 + \dot{m}_4 * s_4 + \frac{\dot{Q}_{in}}{T} + \dot{S}_{gen} = \dot{m}_3 * s_3 + \dot{m}_5 * s_5$	$\dot{m}_2 * ex_2 + \dot{m}_4 * ex_4 + Ex^{\dot{Q}_{in}} = \dot{m}_3 * ex_3 + \dot{m}_5 * ex_5 + \dot{E}x_{D,Boiler}$
High Pressure Turbine	$\dot{m}_3 = \dot{m}_4$	$\dot{m}_3 * h_3 = \dot{m}_4 * h_4 + \dot{W}_{turb,out,H}$	$\dot{m}_3 * s_3 + \dot{S}_{gen} = \dot{m}_4 * s_4$	$\dot{m}_3 * ex_3 = \dot{m}_4 * ex_4 + \dot{W}_{turb,out,I} + \dot{E}x_{D,HPT}$
Low Pressure Turbine	$\dot{m}_5 = \dot{m}_6$	$\dot{m}_5 * h_5 = \dot{m}_6 * h_6 + \dot{W}_{turb,out,L}$	$\dot{m}_5 * s_5 + \dot{S}_{gen} = \dot{m}_6 * s_6$	$\dot{m}_5 * ex_5 = \dot{m}_6 * ex_6 + \dot{W}_{turb,out,II} + \dot{E}x_{D,LPT}$
Condenser	$\dot{m}_6 = \dot{m}_1$	$\dot{m}_6 * h_6 = \dot{m}_1 * h_1 + \dot{Q}_{out}$	$\dot{m}_6 * s_6 + \dot{S}_{gen} = \dot{m}_1 * s_1 + \frac{\dot{Q}_{out}}{T}$	$\dot{m}_6 * ex_6 = \dot{m}_1 * ex_1 + Ex^{\dot{Q}_{out}} + \dot{E}x_{D,Condenser}$

5.1.2 Photovoltaic Thermal System Analysis

The solar PVT subsystem proposed in this study is composed of south facing panels, which are both roof mounted and ground mounted. The following assumptions are considered in this study:

- The cell temperature for the solar PVT panels is 60 °C
- The solar irradiance is considered at 1000 W/m^2
- The solar PVT panels are of 1.056 m length and 2.38 m width
- The overall collector absorber efficiency is 82.4% while the panel efficiency is 15%
- The maximum power point current (Impp) is 6.48 A
- The maximum power point voltage (Vmpp) is 30.4 V

The incoming solar energy can be evaluated using the following equation:

$$\dot{Q}_{in} = \frac{A_{PVT} \times R_a \times N_{PVT}}{1000} \tag{5.13}$$

where A_{PVT} refers to the area of the PVT system in (m^2), R_a is the irradiance of the sun depending on the geographic location in (W/m^2), and N_{PVT} is the number of PVT panels in this system. On the other hand, the thermal solar energy is evaluated using the following equation:

$$\dot{Q}_{thermal} = \dot{m}_1 \times C_p \times (T_3 - T_2) \tag{5.14}$$

The energy efficiency of the PVT system is defined as:

$$\eta_{en,pvt} = \frac{I_{MPP} \times V_{MPP}}{R_a} \times A_{PVT} \tag{5.15}$$

Similarly, the exergy efficiency of the PVT system is derived from the division of the useful output of the system by the system inputs. Therefore, the exergy efficiency of the PVT is calculated as follows:

$$\eta_{ex,pvt} = \frac{\dot{W}_{electric} \times \left(1 - \frac{T_0}{T_{cell}}\right)}{\dot{Q}_{in} \times \left(1 - \frac{T_0}{T_{sun}}\right)} \tag{5.16}$$

where $\dot{W}_{electric}$ refers to the electric output from the PVT in (kW), T_{cell} is the cell temperature, which is assumed at 60 °C, and T_{sun} is the sun's temperature of 5505 °C.

5.1.3 Absorption Refrigeration Cycle Analysis

Absorption refrigeration cycles utilize inexpensive thermal energy sources at temperatures ranging between 100 to 200 °C. The system involves the absorption of a refrigerant by a transport medium. The ammonia-water system is the most commonly used refrigeration system, where (NH_3) is the refrigerant and (H_2O) is the transport medium. The coefficient of performance for the absorption refrigeration system is evaluated using the following function:

$$COP_{en} = \frac{\sum Desired\ Output}{\sum Required\ Input} = \frac{\dot{Q}_L}{\dot{Q}_{gen} + \dot{W}} \tag{5.17}$$

where $T_L, T_0, and\ T_s$ are the thermodynamic temperatures of the refrigerated space, the environment, and the heat source, respectively.

The exergetic COP is also assessed as follows:

$$COP_{ex} = \frac{\dot{Ex}_{eva}}{\dot{Ex}_{des}+\dot{W}} \tag{5.18}$$

5.1.4 Compressed Air Energy Storage Analysis

This energy storage has three phases, charging, storing and discharging. The mass balance, energy balance, and exergy balance equations for this storage system are illustrated in Table 5.2.

Table 5.2 Balance equations for all phases in the CAES

Component/ Balance Equation	Charging	Storing	Discharging
MBE	$m_{s1} + \dot{m}_5 \Delta t_{charg} = m_{s2}$	$m_{s2} = m_{s3}$	$m_{s3} = m_{s4} + \dot{m}_6 \Delta t_{discharg}$
EBE	$m_{s1}u_{s1} + \dot{m}_5 h_5 \Delta t_{charg} = m_{s2}u_{s2} + W_b$	$m_{s2}u_{s2} = m_{s3}u_{s3}$	$m_{s3}u_{s3} + W_b = m_{s4}u_{s4} + \dot{m}_6 h_6 \Delta t_{discharg}$
EXBE	$m_{s1}ex_{s1} + \dot{m}_5 ex_5 \Delta t_{charg} = m_{s2}ex_{s2} + W_b + Ex_{d,charg}$	$m_{s2}ex_{s2} = m_{s3}ex_{s3} + Ex_{d,stor}$	$m_{s3}ex_{s3} + W_b = m_{s4}ex_{s4} + \dot{m}_6 ex_6 \Delta t_{discharg} + Ex_{d,discharg}$

5.2 Exergoeconomic Analysis

The exergoeconomic analysis is a tool that incorporates exergy analysis at the system component level into the laws of economics. As a result, this provides useful information to design and operate energy systems at the most cost-effective level. Furthermore, this tool provides a technique to evaluate the costs of inefficiencies and individual process streams. Exergy costing depends on the exergy balance of the system multiplied by the allocated cost defined ($/kWh). The following functions are used to conduct the exergoeconomic analysis:

$$\dot{C} = \sum_i c \times \dot{Ex} = \sum_i c \times \dot{m}_i[(h_i - h_0) - T_0(s_i - s_0)] \tag{5.19}$$

where c is the cost ($/kWh) and $\dot{Ex}$ is given in kW. The capital cost rates of the components are given in $/h. Typical cost rate balance for a component (neglecting thermal energy interactions) is given as:

$$\sum_i \dot{C}_{in} + \dot{Z} + c_{Q_{in}} Ex^{\dot{Q}_{in}} + c_{w_{in}} \dot{W}_{in} = \sum_{out} \dot{C}_{out} + c_{Q_{out}} Ex^{\dot{Q}_{out}} + c_{w_{out}} \dot{W}_{out} \tag{5.20}$$

where $\dot{C}_{in}$ and $\dot{C}_{out}$ represents the total costs of exergy flows entering and leaving the component. $\dot{Z}$ is the capital maintenance and operations costs of the component while $c_{w_{in}}$ and $c_{w_{out}}$ are the total costs associated with work input and output.

The ratio of exergy losses of the system $\dot{L}$ to the capital costs $\dot{Z}$ of the system is identified as R using the following function:

$$\mathrm{R} = \dot{\mathrm{L}}/\dot{\mathrm{Z}} \tag{5.21}$$

$\dot{L}$ is further illustrated as follows:

$$\dot{L} = \dot{Ex}_d + \dot{Ex}_{loss} \tag{5.22}$$

where $\dot{Ex}_{loss}$ represents the total exergy losses from the systems boundary. In addition, the exergoeconomic factor, f_k of the component k is can be written as:

$$f_k = \dot{Z}_k/[\dot{Z}_k + c_{F,k}(\dot{Ex}_{d_k} + \dot{Ex}_{loss})] \tag{5.23}$$

Here, $c_{F,k}$ is the exergy unit cost of the fuel supplied to the studied part.

5.3 Life Cycle Assessment

Life cycle assessment (LCA) is a comprehensive methodology to assess the environmental or economic impact of a system and its sub-processes. This assessment methodology is globally adopted by ISO as it serves a number of needs including:

- Improving performance of systems and services
- Enables stakeholders to make informed decisions
- Selection of relevant indicators
- Supports marketing strategy and claims

The LCA is intended to be relative, iterative, transparent, comprehensive, and based on scientific methodology. LCAs can be process-based, input-output based or hybrid, which combines both types. Process based LCA provides detailed flows of processes, bottom up analyses, which makes it data and time intensive. On the other hand, input-output LCA is includes a more aggregated analysis, top-down approach and is generally faster. Life cycle refers to the phases of a system or product from the point of extraction of natural resources to the end life and disposal of its waste. Therefore, the LCA is a valuable tool for scientists, engineers, and policy makers as it assesses and compares energy and material use, emissions and wastes, and well as environmental and economic impacts for various processes or systems.

fact, assessing the environmental performance of a system during operation phase only does not reflect the true environmental footprint of the system. Therefore, impacts related to plant construction, utilization, dismantling phases are considered within the analysis. LCA has four main stages summarized in Figure 5.1. The LCA analysis methodology and the details on each stage are explained further in the following subsection.

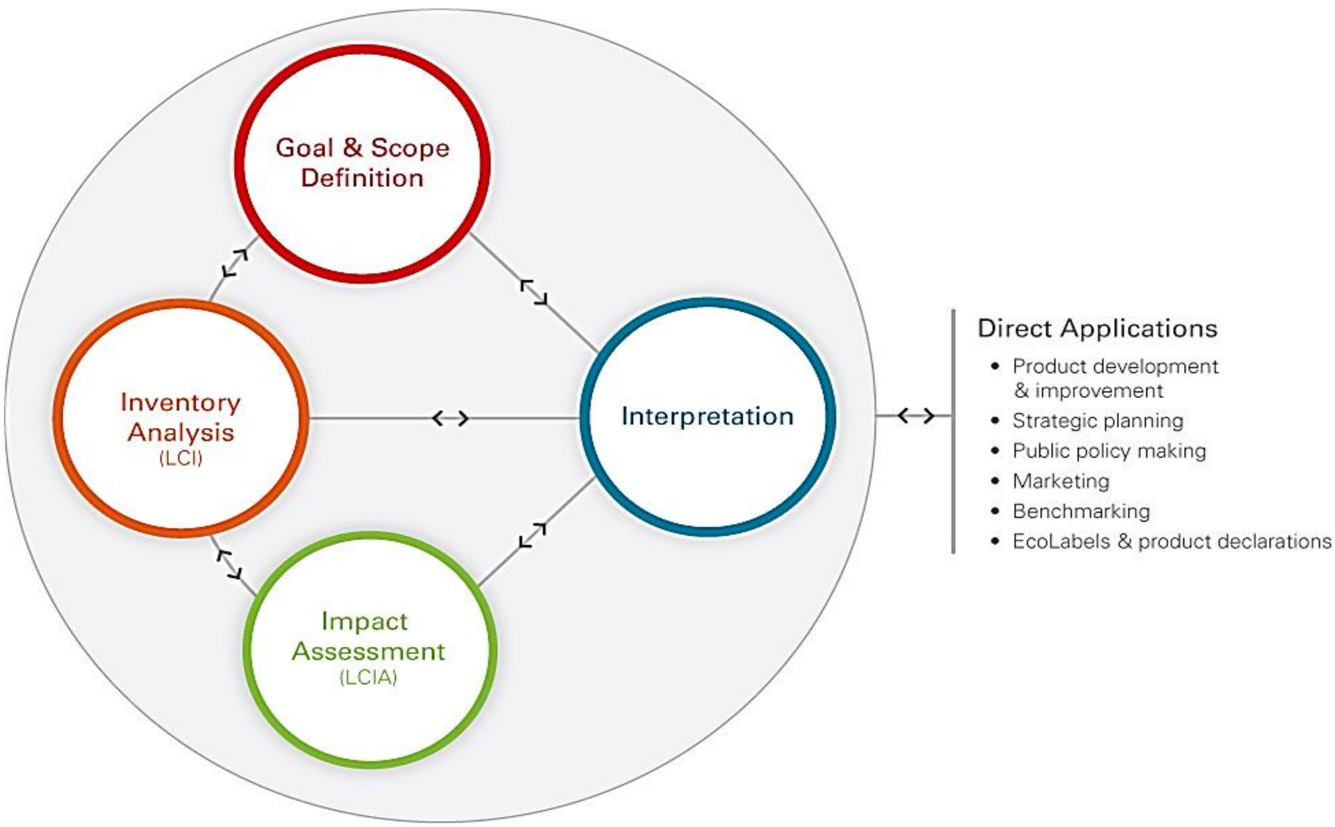


Figure 5.1 LCA framework for assessing the energy systems in this thesis

5.3.1 Goal and Scope Definition

The goal and scope are series of parameters to be qualitatively and quantitatively described for an LCA study, which is also referred to as the study design parameters (SDPs). In this stage, high level aspects for the study are collected. Furthermore, the scope items, product system, product boundary, functional unit, inventory inputs and outputs as well as LCIA methods are outlined in this section.

5.3.2 Inventory Analysis

This stage constitutes the main time-intensive part of the LCA analysis. Various data points such as energy, emissions, waste data and raw materials are collected. This data is further analyzed to calculate the total emissions from the system. Inputs and outputs of interest such as energy, resources, emission and wastes are considered as well. The materials and energy flows of the system will be determined within the overall system boundaries. Environmental impact is also assessed at this stage along with in-depth investigation at each process. Furthermore, in this stage, high quality control and quality assurance is implemented to ensure data credibility and result validation.

5.3.3 Impact Assessment

In this stage, results from the inventory analysis is further processed to consider the he actual effects on humans, ecosystems, and resources, instead of merely tracking quantities like tons of emissions or gallons of fuel consumed as a result of production. Indicators for impacts are used such as GHG emissions for global warming and SOx emissions for acidification. Some impact categories are considered local, while others are considered global or regional as illustrated in Table 5.3. In the LCIA, the focus is on the impacts as a function of that specific normalized quantity. This is achieved through a number of steps, which are ordered as follows:

<u>Selection</u>: this step features the selection of impact categories, their indicators and characterization models. The impact categories selected must be consistent with the scope and goal of the work.

<u>Classification</u>: this step includes taking huge list of inventory flows and making smaller and more manageable piles. For example, GHGs can all be considered one pile. Energy demand can also be classified to renewable and non-renewable sources. One limitation in this step is that depending on the scope, there might be no flows (or too few) to classify into LCIA methods.

Characterization: this step transforms classified flows into impact category indicators via characterization factors. Impact category indicators are relevant to resources, ecosystems, and human health. Characterization factors are the result of separate scientific studies on impact assessment.

Normalization: this is an optional step in LCA, but very much recommended. It is done by dividing by a selected reference value. Normalization occurs against a baseline.

Table 5.3 Summary of impact categories with scale and examples (EPA, 2006)

Impact Category	Scale	Examples of LCI Data (i.e. classification)
Global Warming	Global	Carbon Dioxide (CO_2), Nitrous Oxide (N_2O), Methane (CH_4), Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Methyl Bromide (CH_3Br)
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Halons, Methyl Bromide (CH_3Br)
Acidification	Regional, Local	Sulfur Oxides (SO_x), Nitrogen Oxides (NOx), Hydrochloric Acid (HCl), Hydrofluoric Acid (HF), Ammonia (NH_4)
Eutrophication	Local	Phosphate (PO_4), Nitrogen Oxide (NO), Nitrogen Dioxide (NO_2), Nitrates,Ammonia (NH_4)
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish
Human Health	Global, Regional, Local	Total releases to air, water, and soil.
Resource Depletion	Global, Regional, Local	Quantity of minerals used, Quantity of fossil fuels used
Land Use	Global, Regional, Local	Quantity disposed of in a landfill or other land modifications
Water Use	Regional, Local	Water used or consumed

5.3.4 Interpretation

This last stage constitutes the interpretation of the results and providing feedback for improvement of the system and making informed decisions. Critical phases can be highlighted by the LCA, where sub-systems or selected processes changes could significantly decrease the impacts.

5.3.5 Assessment Method

TRACI assessment methodology will be used in this thesis to assess the impacts of the energy systems. TRACI is an environmental impact assessment tool used in Life Cycle Assessments. Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) provides characterization factors for Life Cycle Impact Assessment (LCIA), sustainability metrics and industrial ecology. Impact categories that TRACI encompass include:

- Ozone Depletion
- Climate Change and Global Warming
- Acidification
- Eutrophication
- Smog Formation
- Human Health Impacts
- Ecotoxicity

Characterization factors quantify the potential impacts that inputs have on specific impact categories that share the equivalence units.

The traditional pollution categories were included in TRACI. The category of human health was further explored to include cancerous, noncancerous, and criteria pollutants. Furthermore, smog formation is considered a critical environmental issue in the USA and has specific regulations to address its prevention.

TRACI functions by a provided inventory of stressors from the user. Such gate-to-gate analysis and inventory data can be available from various facilities, suppliers and LCA databases. The heart of the TRACI assessment tool is characterizing each impact category. The underlying methodologies within TRACI utilize the amount of the chemical emission or resource used and the estimated potency of the stressor. Best available data and models for each impact category form a basis for estimated potency. Relative potency for some impact categories is pre-determined because of an international consensus. This consensus includes ozone depletion potentials and global warming potentials for example. For other impact categories, the relative potency may be dependent on models related to chemical and physical principles and/or experimental data (EPA, 2012). Emission related categories are summarized in Table 5.4.

Table 5.4 Emission related categories covered by TRACI

Impact Category	Media
Ozone Depletion	Air
Global Warming	Air
Acidification	Air, Water
Eutrophication	Air, Water
Smog Formation	Air
Human Health Particulate	Air
Human Health Cancer	Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil, Agricultural Soil
Human Health Non-cancer	Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil, Agricultural Soil
Ecotoxicity	Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil, Agricultural Soil

5.4 Optimization Analysis

Optimization problems are ubiquitous in science and engineering. An optimization problem has a real function which has to be maximizing or minimizing by systematically choosing input values and by fulfilling the given constraint and computing the value of the function. The generalization of optimization theory and techniques to other formulations comprises a large area of applied mathematics.

More generally, optimization includes finding "best available" values of some objective function given a defined domain, including a variety of distinct types of objective functions and several types of domains. There is various type of algorithm available which can be used to solve the problem in order to optimize it.

5.4.1 Particle Swarm Optimization

The particle swarm concept originated as a simulation of simplified social system. The original intent was to graphically simulate the choreography of birds in a bird block or fish school. However, it was found that particle swarm model can be used as an optimizer. As stated before, PSO simulates the behaviors of bird flocking.

Suppose the following scenario: a group of birds are randomly searching for food in an area. There is only one piece of food in the area being searched. All the birds do not know where the food is, but they know how far the food is in each iteration. So, what's the best strategy to find the food? The effective one is to follow the bird which is nearest to the food.

PSO learned from the scenario and used it to solve the optimization problems. In PSO, each single solution is a "bird" in the search space. We call it "particle". All particles have fitness values which are evaluated by the fitness function to be optimized and have velocities which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles.

PSO is initialized with a group of random particles (solutions) and then searches for optima by updating generations. In every iteration, each particle is updated by following two "best" values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called p_{best}. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population.

This best value is a global best and called gbest. When a particle takes part of the population as its topological neighbors, the best value is a local best and is called pbest. After finding the two best values, the particle updates its velocity and positions with following equation (a) and (b).

v[] = w*v[ ] + c1 * rand( ) * (pbest[ ] - present[ ]) + c2 * rand( ) * (gbest[ ] -present[ ])

present[ ] = present[ ] + v[ ]

v[ ] is the particle velocity, present[ ] is the current particle (solution). pbest[ ] and gbest[ ] are defined as stated before. Rand () is a random number between (0,1). c1, c2 are learning factors, usually c1 = c2 = 2. The following weighting function for w is utilized:

$$w = wMax-[(wMax-wMin) * iter]/maxIter \tag{5.24}$$

where wMax= initial weight, wMin = final weight, maxIter = maximum iteration number, iter = current iteration number.

The pseudo code of the procedure is as follows:

```
For each particle
    Initialize particle
END
Do
  For each particle
    Calculate fitness value
    If the fitness value is better than the best fitness value (pBest) in history
    set current value as the new pBest
End
Choose the particle with the best fitness value of all the particles as the gBest
For each particle
    Calculate particle velocity according to equation (a)
    Update particle position according to equation (b)
End
While maximum iterations or minimum error criteria is not attained
```

Figure 5.2 Framework for particle swarm algorithm

5.4.2 Genetic Algorithm Optimization

In last two decades, optimization algorithms have been improved significantly and have received increasing attention by the research community as well as the industry. Genetic algorithm (GA) is an optimization technique based on natural genetics. GA was developed by Holland to understand the adaptive processes of natural systems. GA proved to be a robust optimization technique. The term robust denotes the ability of the GA for finding the global optimum, or a near-optimal point, for any optimization problem and keep a good solution even if there is a small change in the input parameters. Figure 5.3 shows the process that GA takes in the analysis. The basic steps for the GA are described as follow. An initial set of solution is created randomly, and each single solution will be converted into a string that is coded (initial population). The size of the population may vary from tens to several hundreds.

Increasing the number of populations does not results in solution improvement, a good number of population can be determined after several runs. Then, each solution is tested and evaluated on the objective function to show how good a solution is (fitness value). After that selection criteria are applied to do the crossover and mutation operations. Next, a new population is created after the applied operations and replace the old population. A stopping criterion is applied for the algorithm to decide wither to continue for another iteration or stop. The number of generations is considered as the stopping criteria, a good number of generations is in the range of 200-500. The solutions should be coded when doing the operations but decoded when evaluating the fitness values.

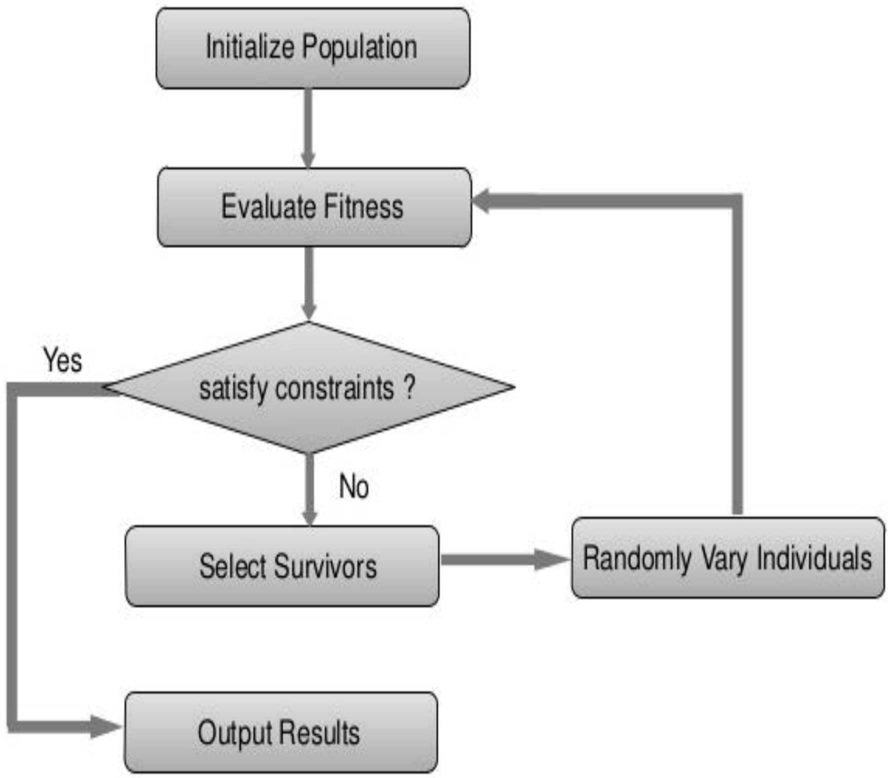


Figure 5.3 Framework for genetic algorithm

Chapter 6: Results and Discussion

This chapter presents the research findings and results. The relationship between indicators and how they impact each other is first presented. Secondly, the smart city index for 20 cities worldwide are presented and analyzed based on the developed methodology, followed by more analysis and discussion.

6.1 Principal Components Analysis (PCA) Results

In this section, the relationship between variables are visualized in order to have a greater understanding of the impacts they have on each other. This is especially key when analyzing numerous variables at once, in which case, plots and correlation coefficients can quickly uncover patterns and reduce a large amount of data to a summarized subset of key relationships. Principal component analysis (PCA) is suitable for datasets that have random variables with standard deviations that are reflective of the relative significance for their application. This is due to the fact that PCA relies on both the correlations between random variables and the standard deviations of those random variables. Changing the standard deviation while the correlation remains the same, therefore results in a change in the principal components.

Due to the enormous number of variables in the data set, it becomes harder to comprehend all of the relationships between the variables using a scatter plot or correlation matrix. Using a data reduction technique such as principal components analysis (PCA) reduces the dimensionality of the dataset whilst retaining as much of the variability in the data as possible. In fact, the first few components retain most of the variation in the original variables, and to ease the interpretation, they can be used to describe the relationships between the original variables and similarities between observations. PCA is a mathematical technique that reduces dimensionality by creating a new set of variables called principal components. The first principal component is a linear combination of the original variables and explains as much variation as possible in the original data. Each subsequent component explains as much of the remaining variations as possible under the condition that is uncorrelated with the previous components. Table 6.1 shows the variance analysis for the sub-indexes in this model. Table 1 shows the amount of variance in the original data explained by each principal component. Because the data was standardized, a principal component with a variance of 1 indicates that the component accounts for variation equivalent to one of the original variables. Also, the sum of all the variances, equals the number of the original variables (8 sub-indexes). The first two principal components account for nearly 78% of the variance in the original twirl variables.

Table 6.1 Variances analysis for each principal component

Component	Variance	Proportion	Cumulative proportion
1	5.735	0.717	0.717
2	0.831	0.104	0.821
3	0.534	0.067	0.887
4	0.325	0.041	0.928
5	0.309	0.039	0.967
6	0.152	0.019	0.986
7	0.096	0.012	0.998
8	0.018	0.002	1.000

Correlations refers to the strength between two variables. The correlation coefficient is a value that ranges between -1 and 1, where positive 1 reflects a strong and perfect positive linear relationship and negative 1 indicates a perfectly negative linear relationship. Values around zero indicate that variables are uncorrelated, and a linear relationship is absent. Table 6.2 shows the relationship between the different domains using Pearson's R, Spearman's RS and Kendall's Tau values. Dark color gradient indicates stronger relationship between the two variables, whereas lighter color gradient indicates a weaker relationship. Pearson's R value is a statistical correlation coefficient, which measures bivariate correlation. It is the most widely used coefficient to assess the relationship between two variables and it follows the same principle as described above with values ranging between -1 and 1.

On the other hand, Spearman's Rank Correlation Coefficient R_s, is a statistical measure of the strength of a link or relationship between two sets of data. The answer will always be between 1.0 (a perfect positive correlation) and -1.0 (a perfect negative correlation). A value of 0 indicates no association between ranks. Kendall's T coefficient is a measure of rank correlation, assessing the similarity of the orderings of the data when ranked by each of the quantities. The Kendall correlation between two variables will be high when observations have a similar (or identical for a correlation of 1) rank (i.e. relative position label of the observations within the variable: 1st, 2nd, 3rd, etc.) between the two variables, and low when observations have a dissimilar (or fully different for a correlation of -1) rank between the two variables.

Table 6.2 Correlation coefficients between the different domains used for the smart city index

Domain	Environment	Society	Energy	Governance	Economy	Infrastructure	Pandemic Resiliency	Transportation	
Environment	-	0.742	0.870	0.867	0.509	0.899	0.712	0.726	Pearson's r
	-	0.715	0.800	0.895	0.687	0.789	0.767	0.523	Spearman's rs
	-	0.546	0.629	0.750	0.561	0.630	0.583	0.370	Kendall's tau
Society	0.742	-	0.707	0.718	0.340	0.744	0.502	0.622	Pearson's r
	0.715	-	0.668	0.781	0.543	0.736	0.551	0.578	Spearman's rs
	0.546	-	0.497	0.579	0.413	0.567	0.355	0.403	Kendall's tau
Energy	0.870	0.707	-	0.870	0.521	0.845	0.649	0.788	Pearson's r
	0.800	0.668	-	0.795	0.704	0.850	0.705	0.742	Spearman's rs
	0.629	0.497	-	0.620	0.548	0.674	0.570	0.585	Kendall's tau
Governance	0.867	0.718	0.870	-	0.427	0.821	0.583	0.668	Pearson's r
	0.895	0.781	0.795	-	0.691	0.814	0.682	0.549	Spearman's rs
	0.750	0.579	0.620	-	0.579	0.611	0.477	0.394	Kendall's tau
Economy	0.509	0.340	0.521	0.427	-	0.525	0.275	0.627	Pearson's r
	0.687	0.543	0.704	0.691	-	0.724	0.424	0.662	Spearman's rs
	0.561	0.413	0.548	0.579	-	0.582	0.348	0.483	Kendall's tau
Infrastructure	0.899	0.744	0.845	0.821	0.525	-	0.565	0.901	Pearson's r
	0.789	0.736	0.850	0.814	0.724	-	0.570	0.843	Spearman's rs
	0.630	0.567	0.674	0.611	0.582	-	0.436	0.710	Kendall's tau
Pandemic Resiliency	0.712	0.502	0.649	0.583	0.275	0.565	-	0.512	Pearson's r
	0.767	0.551	0.705	0.682	0.424	0.570	-	0.465	Spearman's rs
	0.583	0.355	0.570	0.477	0.348	0.436	-	0.330	Kendall's tau
Transportation	0.726	0.622	0.788	0.668	0.627	0.901	0.512	-	Pearson's r
	0.523	0.578	0.742	0.549	0.662	0.843	0.465	-	Spearman's rs
	0.370	0.403	0.585	0.394	0.483	0.710	0.330	-	Kendall's tau

The economy index is strongly correlated with the energy and infrastructure indexes, followed by a good correlation with the transportation, environment, and governance indexes. However, the economy index is weakly correlated with the pandemic resiliency and society indexes. Figure 6.1 shows the positive relationship of the economy index with the indexes abovementioned. The correlation values are composed of the granular level data, collected for the 20 cities, and computed to form the total index value in their respective domain. The infrastructure index has the highest Spearman's Rs value with the economy index, which means that the higher the smart infrastructure value, the greater the smart economy value as well. Similarly, with the transportation and environment indexes. The transportation index is highly correlated as well with the infrastructure index along with the energy index, followed by the economy index. Pandemic resiliency index has the weakest correlation with the transportation index, followed by the governance environment and society indexes. Figure 6.2 shows the relationship of key indexes with the transportation index.

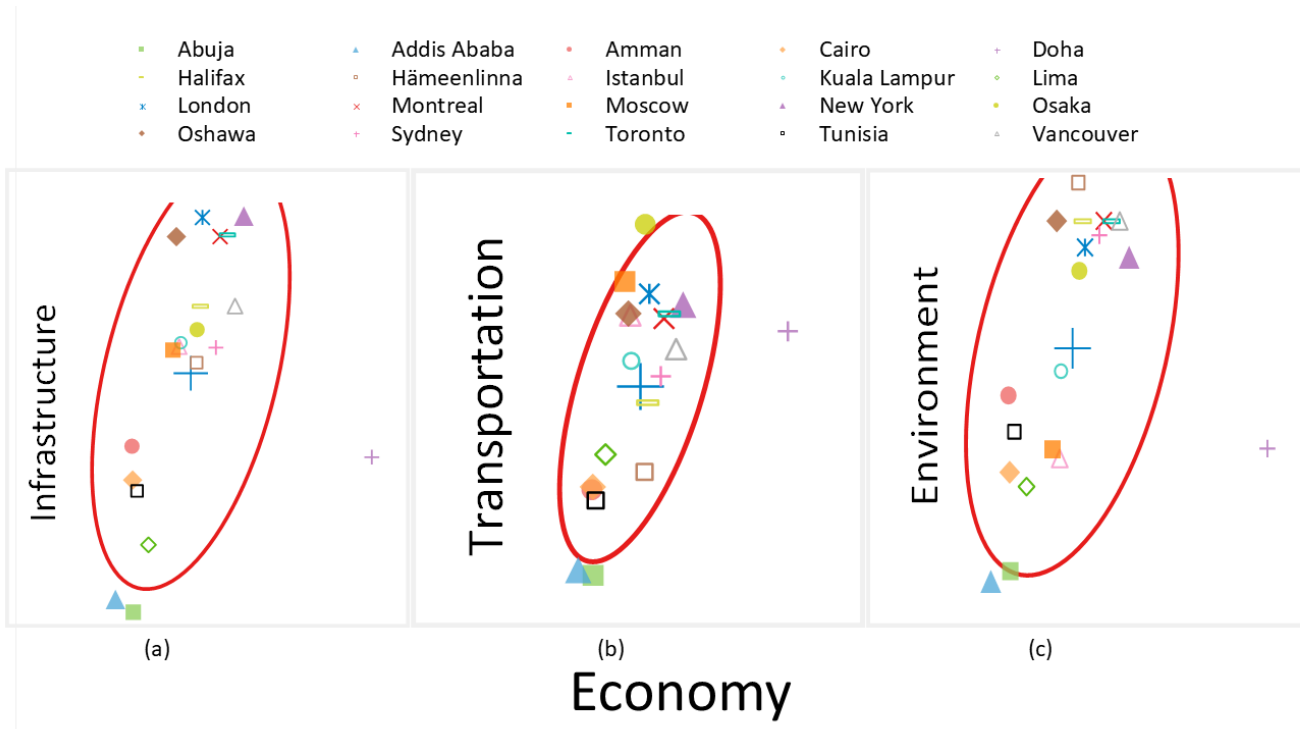


Figure 6.1 Relationship of the economy index with other key indexes

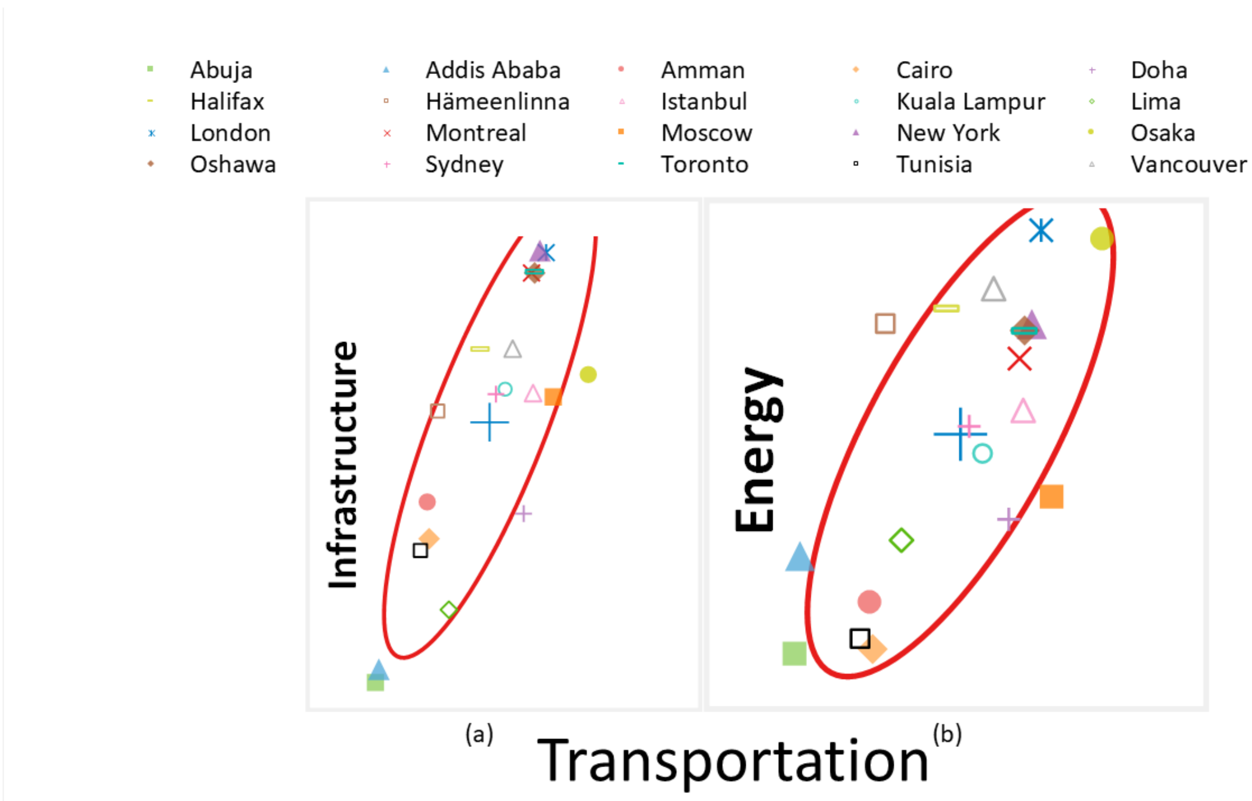


Figure 6.2 Relationship of the transportation index with other key indexes

The energy index is strongly correlated with the infrastructure, environment and governance indexes in sequence. It is weakly correlated with the pandemic resiliency and society indexes. Figure 6.3 shows the key correlations associated with the energy index. Relatively, the energy index has the second highest correlation with the pandemic resiliency index, after the environment index.

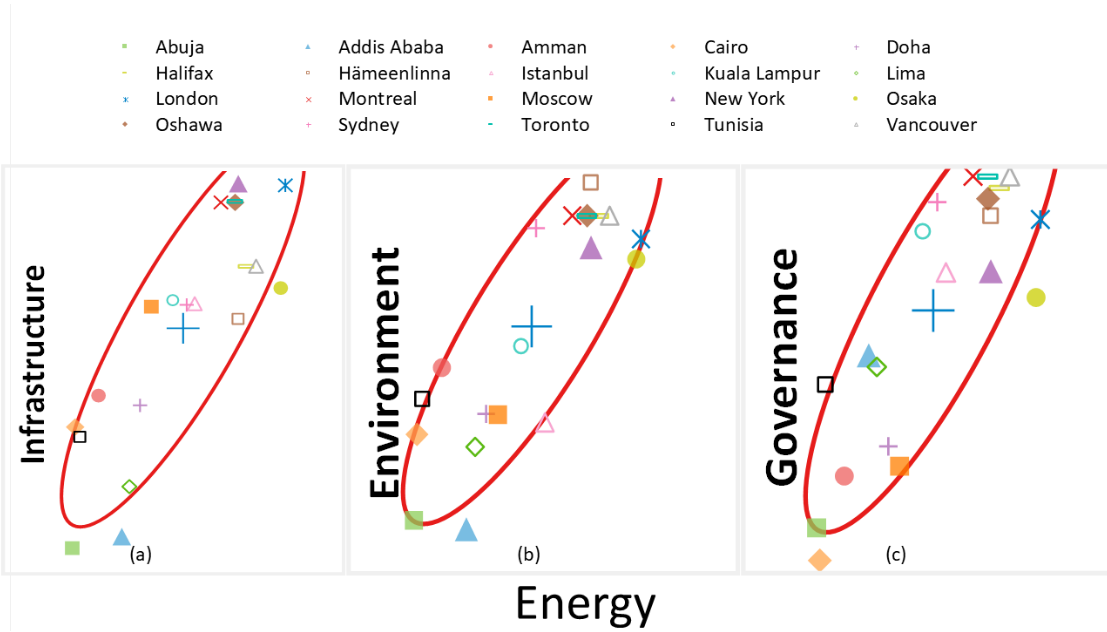


Figure 6.3 Relationship of the energy index with other key indexes

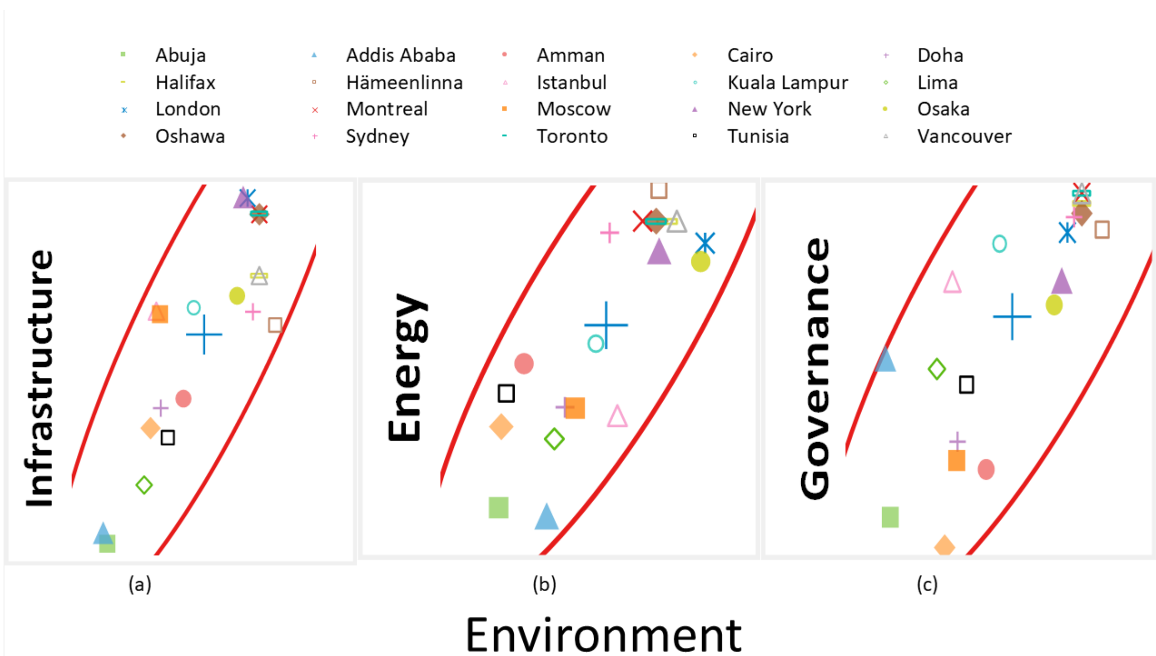


Figure 6.4 Relationship of the environment index with other key indexes

The environment index is strongly correlated with the infrastructure index, followed by the energy and governance indexes. It is weakly associated with the economy, transportation and society indexes. Notably, it has the highest correlation with the pandemic resiliency index. Figure 6.4 illustrates key correlations related to the environment index.

The governance index is strongly correlated positively with the energy and environment indexes. It also has influence on the pandemic resiliency index. However, the governance index is weakly correlated with the economy, transportation and society indexes. Figure 6.5 illustrates key correlations related to the governance index.

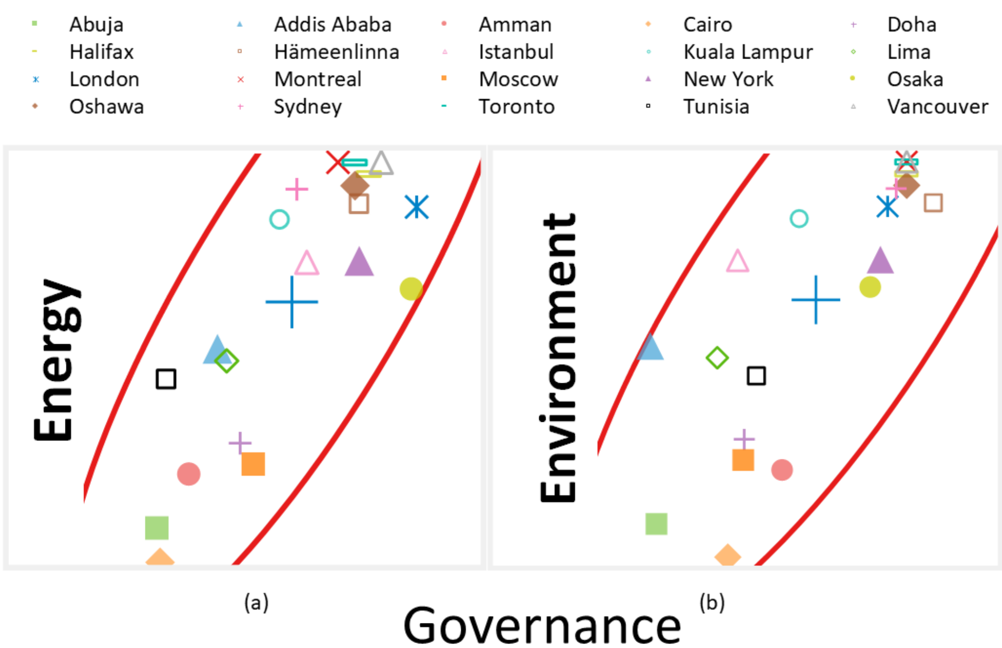


Figure 6.5 Relationship of the governance index with other key indexes

The smart society index is strongly correlated with governance, infrastructure, environment and energy indexes. Economy, transportation and pandemic resiliency indexes have a weaker correlation with the society index on the other hand. Figure 6.6 illustrates the key correlations related to the society index. The infrastructure index is positively correlated with many other indexes, more strongly with the transportation, energy and environment indexes and slightly strongly with the governance, society and economy indexes. Figure 6.7 illustrates the key correlations related to the infrastructure index. The last index, pandemic resiliency is interesting strongly correlated with the environment, energy and the governance indexes. It is weakly correlated with the economy and transportation indexes. Figure 6.8 shows these highlighted relationships

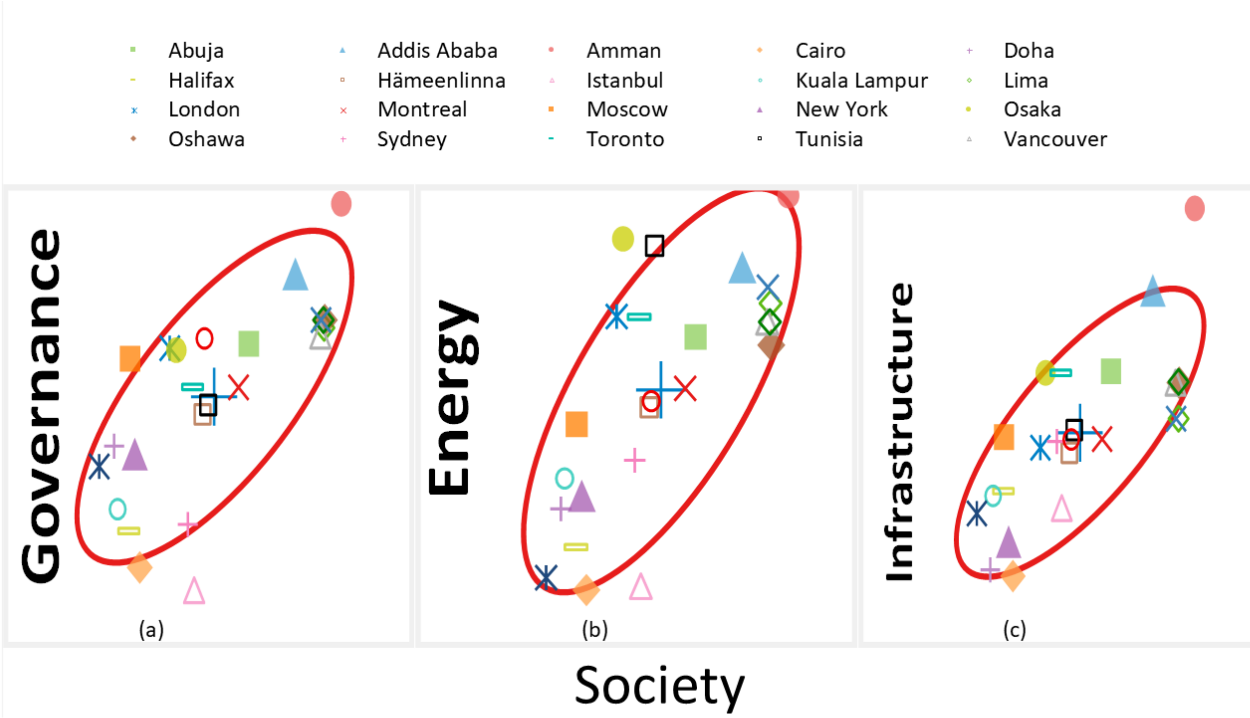


Figure 6.6 Relationship of the society index with other key indexes

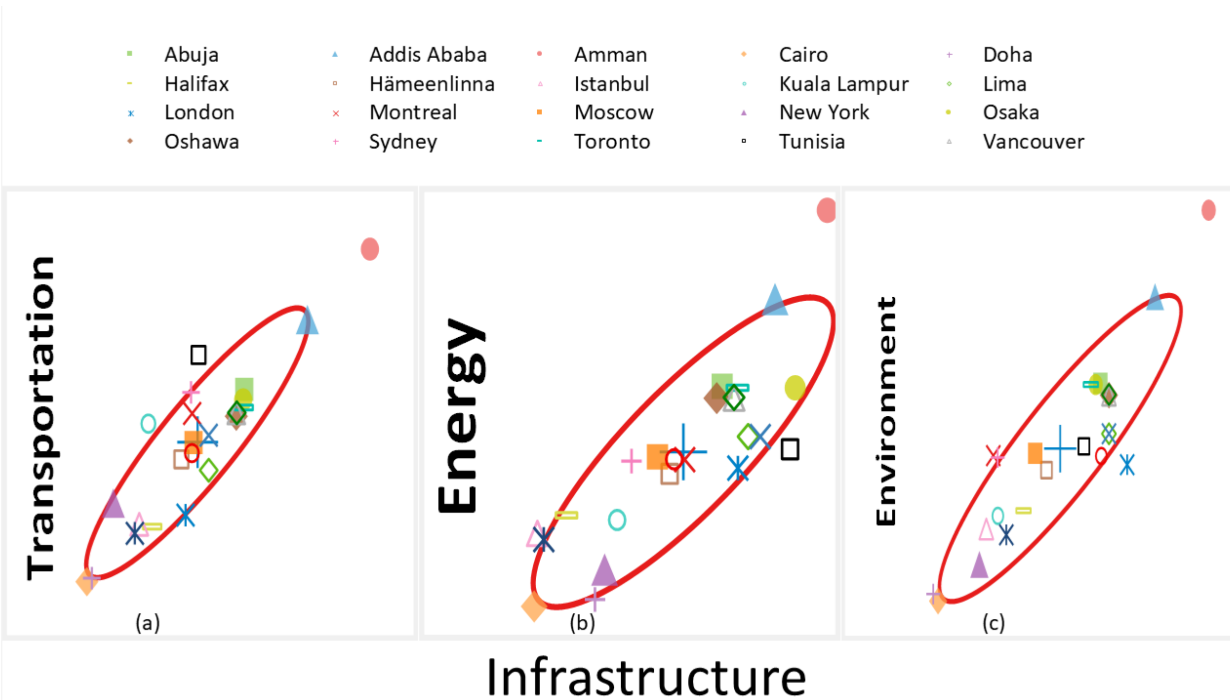


Figure 6.7 Relationship of the infrastructure index with other key indexes

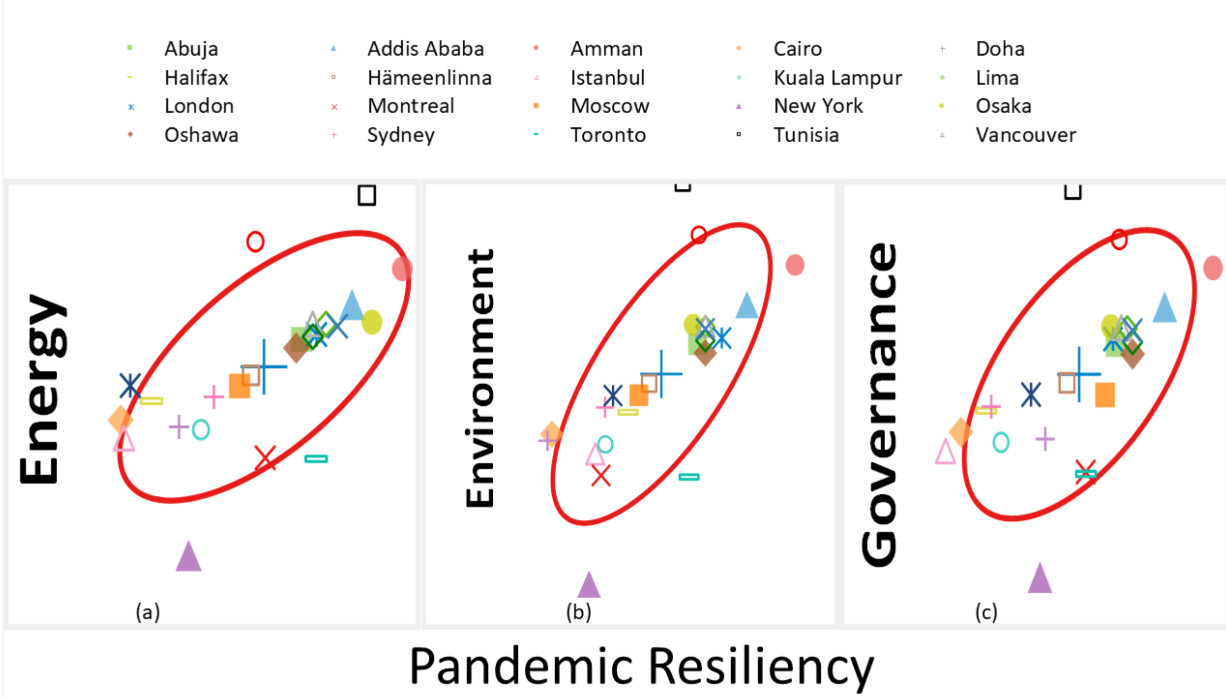


Figure 6.8 Relationship of the pandemic resiliency index with other key indexes

Overall, the relationships between the 8 indexes are illustrated in Figure 6.9, showing the degree of influence and correlation between each index. For instance, the environment index is more positively correlated with the society, energy, governance and infrastructure indexes. The eclipse circle shows the data distribution and how the values are spread out throughout the different cities in the model. Values that are better clustered show a stronger correlation, whereas values that are more spread out reflect more variation. On the other hand, the economy index is poorly correlated throughout all indexes, other than the transportation index. The 25%, 50%, and 75% averages refer to the values above the average value in each index. For instance, the 25% average of the economy index means to 25% increase from the average economy index value. As discussed in the model development, weighting and aggregation are critical in computing a composite model. For this thesis, given the multi-disciplinary aspect and variety of indicators, a multi-criterial decision analysis is considered, along with the principal component analysis. A two-dimensional monoplot of the coefficients of the first two principal components can visualize the relationships between the variables. This monoplot shows vectors pointing away from the origin to represent the original variables. The angle between the vectors approximates the correlation between the variables. A small angle indicate that the variables are positively correlated, whereas an angle of 90 degrees indicate that variables are not correlated.

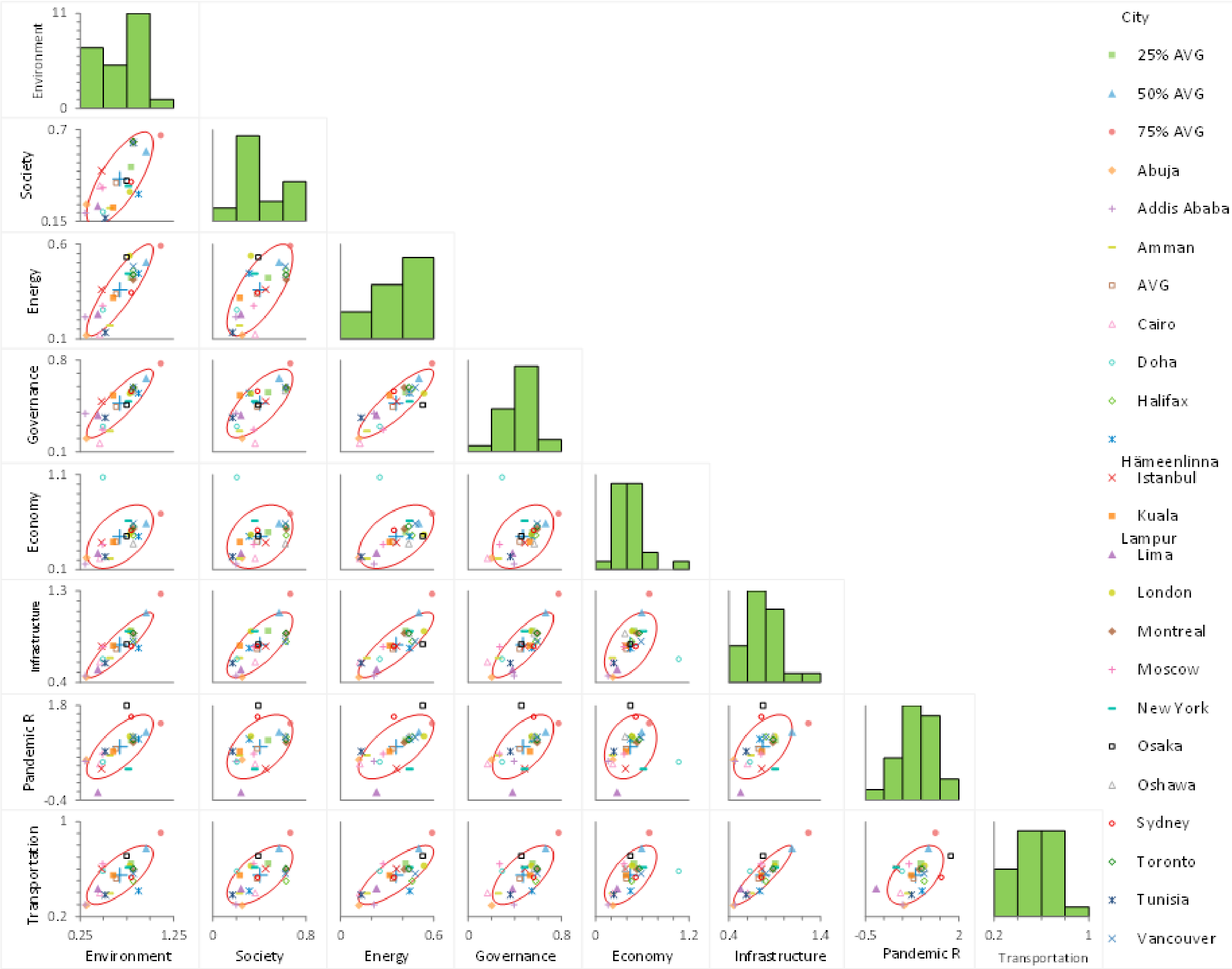


Figure 6.9 Correlation of the indexes with each other

Similarly, an angle of 180 degrees show that variables are negatively correlated. Table 6.3 show the coefficients of the different sub-indexes in association with the principal components.

Table 6.3 Coefficients of the sub-indexes in association to the principal components

Sub-Index	**Component**							
	1	2	3	4	5	6	7	8
Environment	0.395	-0.131	0.058	0.135	-0.159	0.595	-0.412	0.506
Society	0.336	-0.224	-0.483	0.376	0.667	-0.129	0.018	0.011
Energy	0.391	-0.045	0.004	0.005	-0.316	-0.628	-0.574	-0.147
Governance	0.374	-0.170	-0.174	0.264	-0.554	-0.077	0.645	0.056
Economy	0.252	0.793	0.286	0.449	0.099	0.030	0.054	-0.104
Infrastructure	0.395	0.056	-0.201	-0.376	-0.018	0.425	-0.019	-0.691
Pandemic Resiliency	0.296	-0.421	0.780	-0.027	0.276	-0.056	0.180	-0.124
Transportation	0.363	0.305	-0.057	-0.653	0.192	-0.209	0.222	0.464

The blue boxes, depending on the depth of the shade represent strong correlation, whereas the red boxes, depending on the shade, represent weak correlation. The intensity of the color reflects the magnitude of the correlation. In fact, the results of the principal component analysis reveal interesting relationships between the different sub-indexes as illustrated in Figure 6.10. The graph reveals that pandemic resiliency sub-index is closely correlated with the society. Furthermore, the society, governance and environment sub-indexes are closely correlated to each other. The energy index is correlated closely with the environment and infrastructure sub-indexes. The economy and transportation sub-indexes are isolated and do not correlate well with the rest of the sub-indexes. However, they are no negative correlations between the different sub-indexes. Most of the sub-indexes are associated with the second principal component, whereas the transportation and economy sub-indexes are associated with the first principal component. Absolute values near zero indicate that a variable contributes little to the component, whereas larger absolute values indicate variables that contribute more to the components. The sign of the coefficients is irrelevant and may even differ when the analysis is performed on different models. There isn't a simple interpretable structure to the principal components, because they are created to maximize the amount of variance whilst remaining uncorrelated with the other components. The first component in Table 6.3 is an average of many different variables. The second component mainly represents economy, transportation, and pandemic resiliency. The third component, although it has some reasonably sized contributions from other variables, represents mainly society and pandemic resiliency. The principal components explain the degree of variance and correlation between the different indexes combined. Figure 6.11 shows the proportion of variance that is explained by each dimension. We can see that most indexes are well-explained and represented by the first dimension, whereas economy and pandemic resiliency indexes are better explained using the second dimension. As illustrated in Figure 6.12, there are roughly four main categories for the cities in this study. The first cluster is composed of Abuja, Addis Ababa, Tunisia, Amman, Cairo and Lima. The proximity between these cities indicate their similarity in their portfolio. The second cluster is near the middle of the plot, composed of Moscow, Istanbul, and Kuala Lampur. The third cluster is comprised of Western cities such as Canadian cities, in addition to London, Osaka, Sydney and Hameenlinna. The final cluster are the outliers such as New York and Doha. What makes New York an outlier is its superior infrastructure, economy, and transportation values. As for Doha, its economic index value of 107%, makes it more than double the average. This is due to the fact that Doha has a very small population size, yet disproportionate GDP, making the GDP per capita very significant.

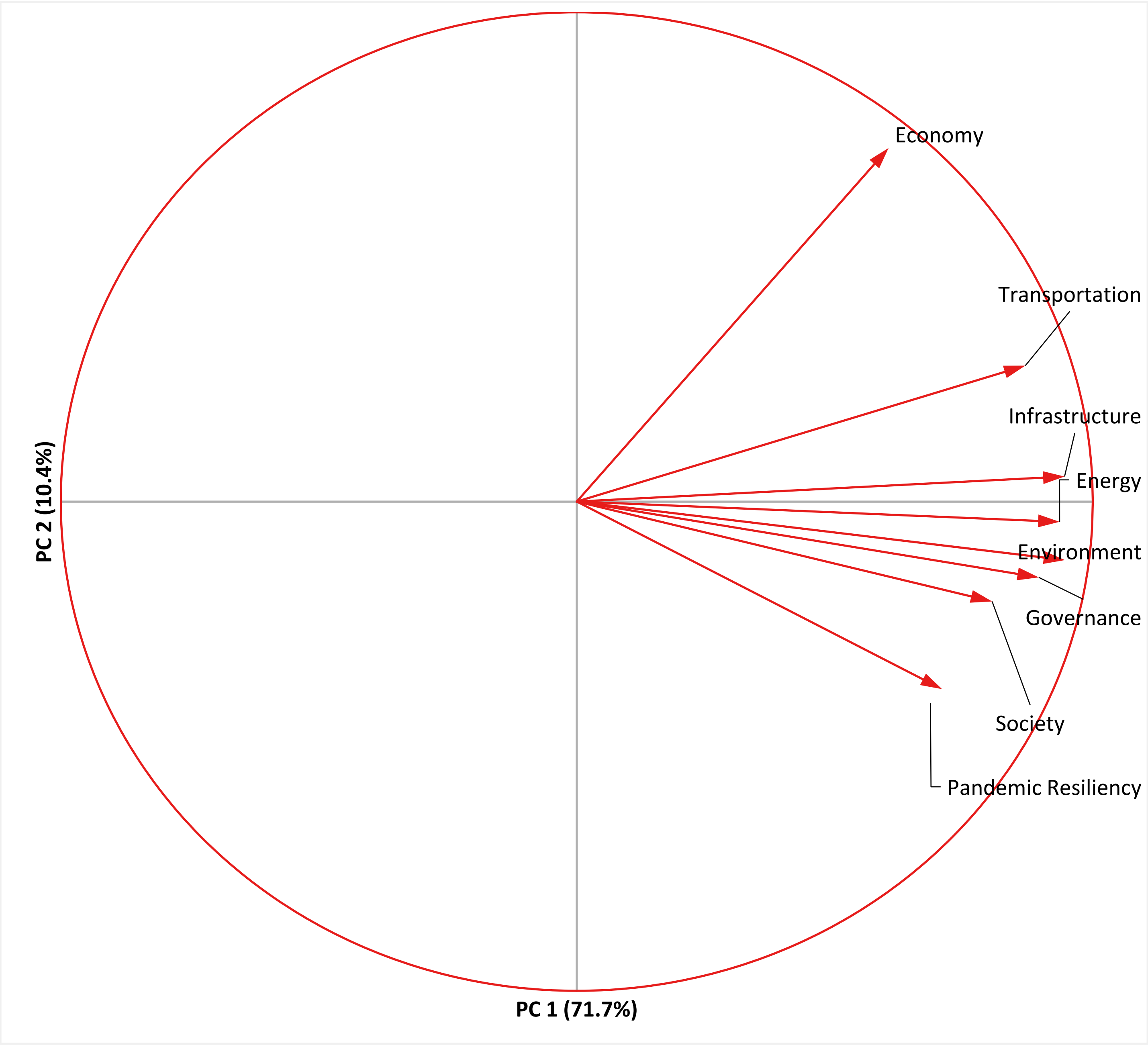


Figure 6.10 Correlation between sub-indexes with the top two principal components

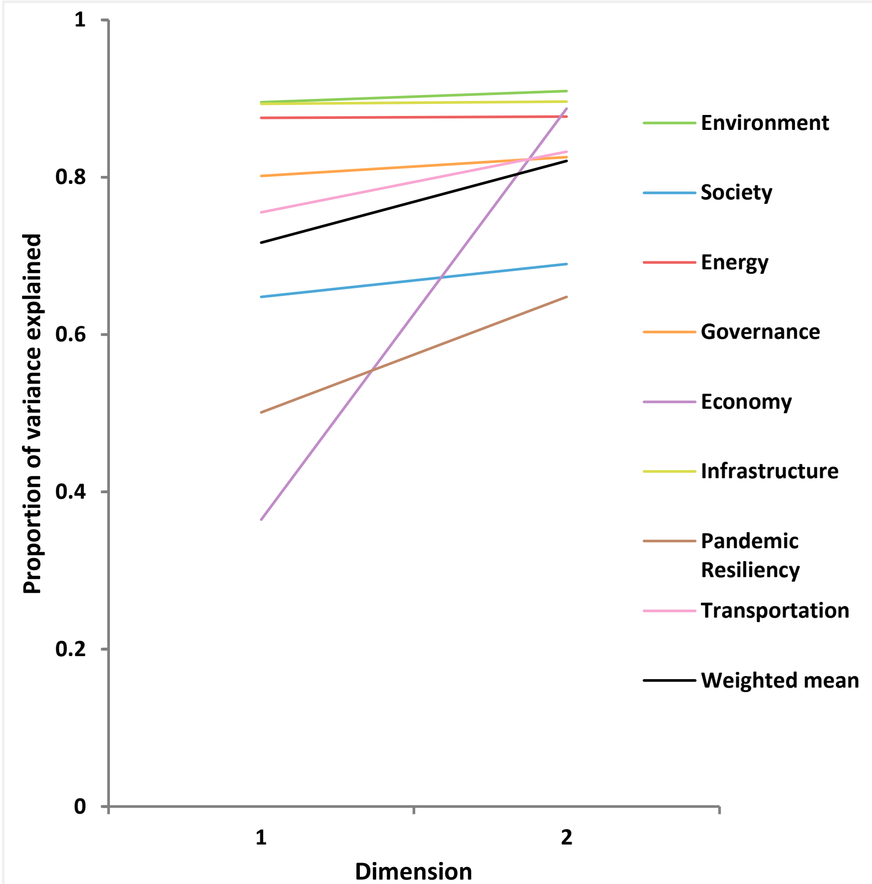


Figure 6.11 Proportion of variance explained for each index by the first two dimensions

In addition to the analysis of the sub-indexes, detailed principal component analysis is also performed on the actual performance indicators used in this model. Statistical assessment was performed on 32 performance indictors as illustrated in Figure 6.13. Results show how correlated each indicator is, in relation to other indicators from other indexes. Under-represented indicators are also highlighted. For example, Gini Coefficient, Energy Cost and Biodiversity and Habitat indicators are under-presented, while GDP per capita, Infrastructure Investment, and Air Quality are well-represented.

Furthermore, the GDP per capita has a negative correlation with Poverty & Unemployment Rates. Similarly, the Healthcare Index has a negative correlation with the Gini Coefficient and Death Toll. The indicators that are neighboring to each other and with minimal angles between them illustrate positive and strong correlation and relationship. Therefore, Government Digitalization under Smart Governance is correlated very strongly with the Response Rate under Pandemic Resiliency.

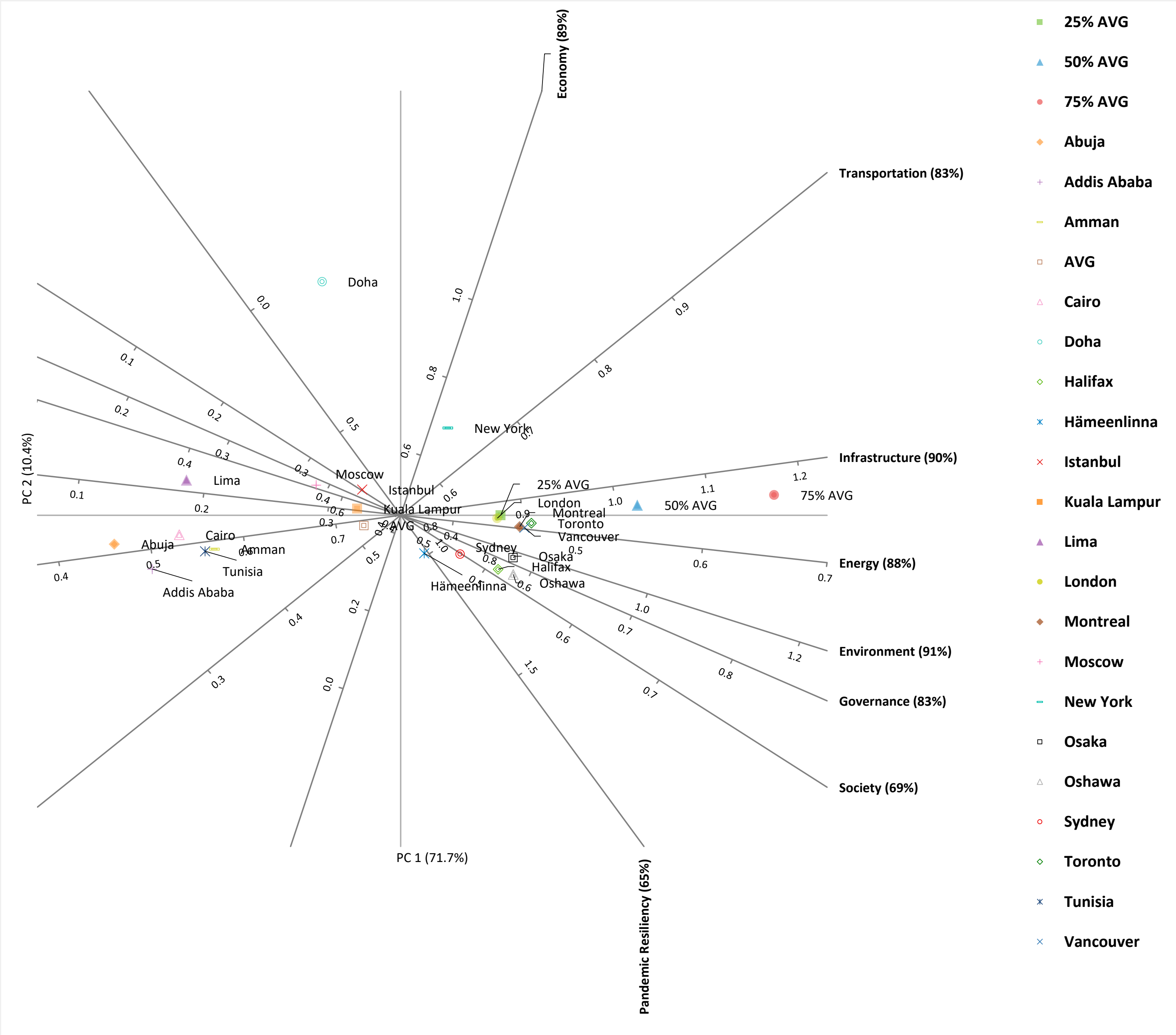


Figure 6.12 Principal component analysis biplot aggregating all domains

Not all performance indicators are illustrated best using the first dimension of the principal component analysis. Some are better illustrated by the second dimension, including the Clean Energy Utilization, Climate Change - GHG Emissions, Confirmed Cases, Corruption Rate, Poverty Rate, Public Participation, and Unemployment Rate. For these indicators, the lines show an increase in the proportion of variance explained from the first dimension to the second as illustrated in Figure 6.14. On the other hand, the majority of performance indicators are well-represented and explained by the first dimension, some more than others, depending on the data quality and correlation between the indicators.

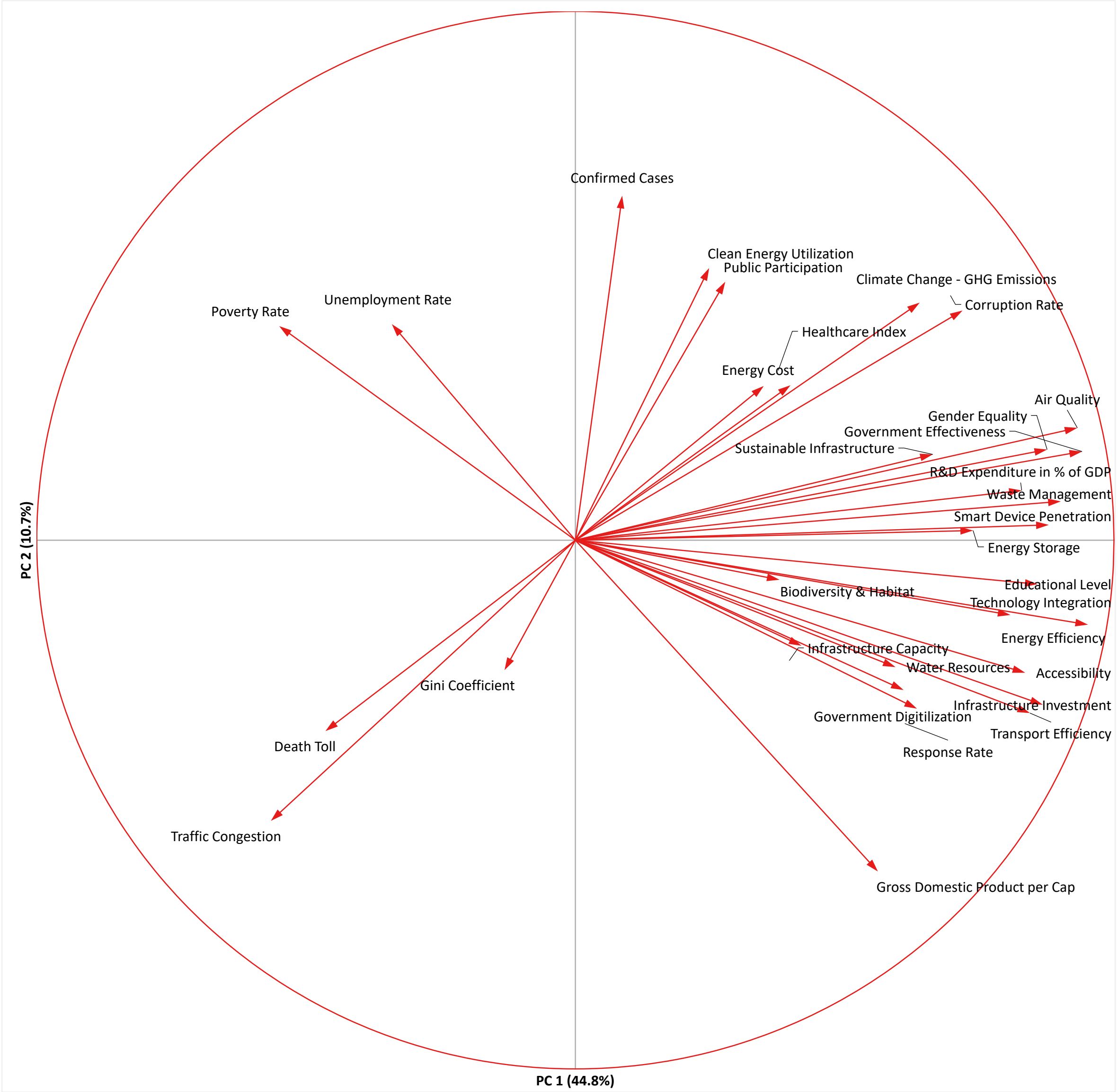


Figure 6.13 Correlation between performance indicators with the top two principal components

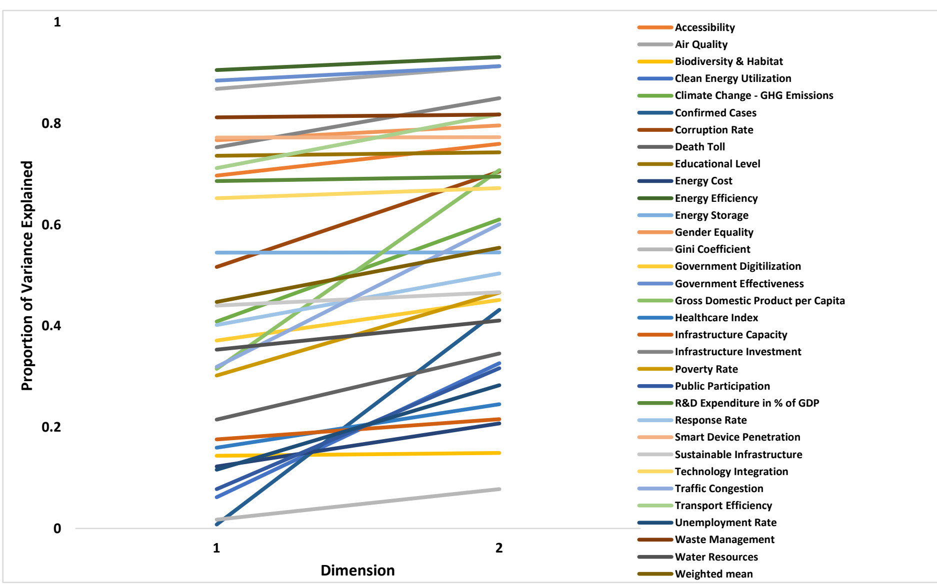


Figure 6.14 Proportion of variance explained for each performance indicator by the first two dimensions

Thirty-two axes are aggregated in Figure 6.15 using the principal component analysis to have a better visual illustration of the performance of the indicators relative to each other. Similar to the index biplot, the clusters remain intact, however the values are a little bit more spread apart than the index values.

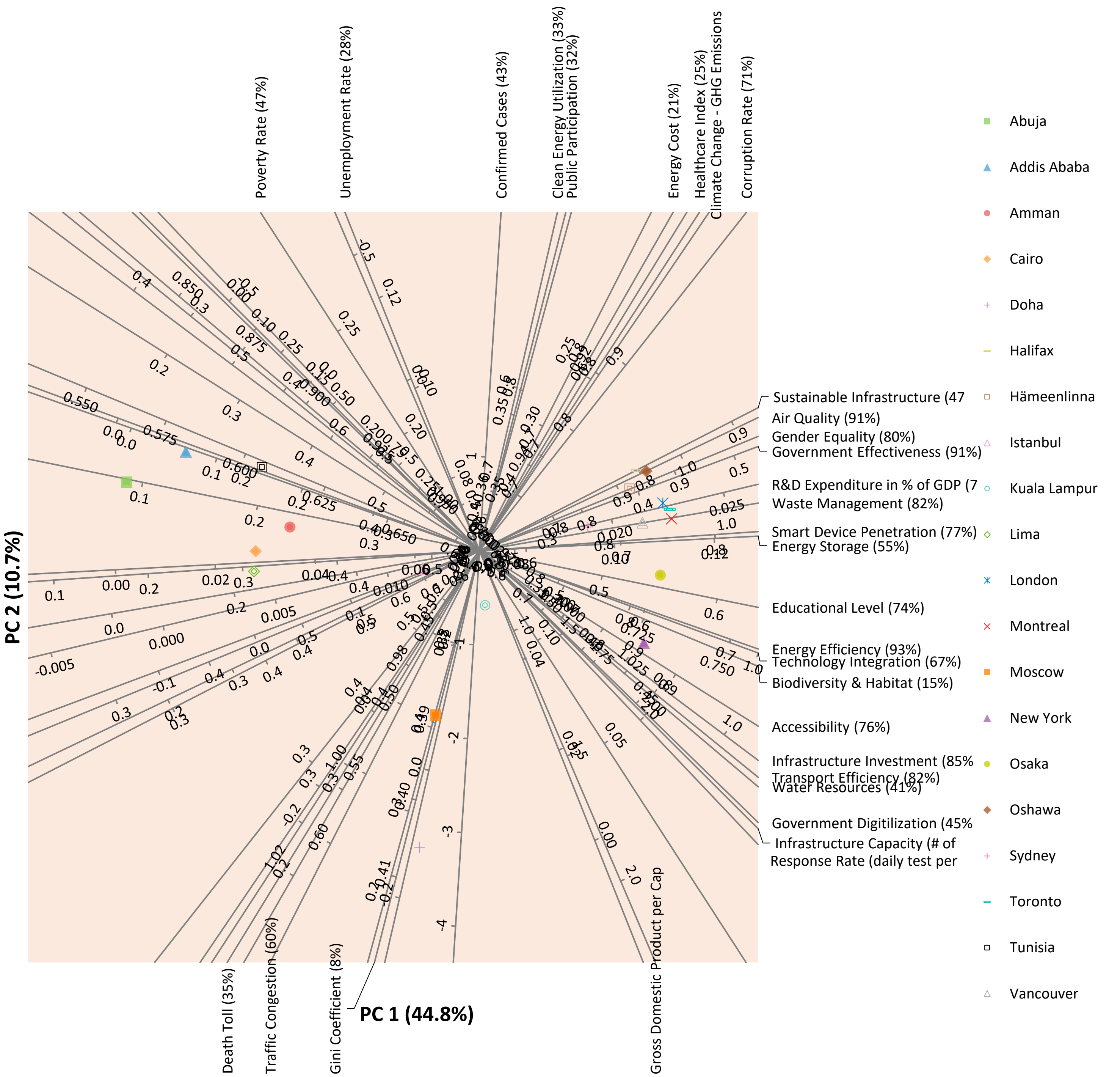


Figure 6.15 Principal component analysis biplot aggregating all performance indicators

The first component represents approximately 45% of the variation whereas the second component accounts for only 11% of the indicator variations. The biplot represents 56% of the original variation in the dataset. Each point on the biplot represents a city and each axis represents a performance indicator. The distance between points reflects the degree of similarity between them. Therefore, cities in close approximation to each other have similar profiles, whereas cities that are far from each other have dissimilar profiles.

6.2 Smart City Index Results

The composition of data relies heavily on weighting. After data normalization of each indicator using methods described in the past chapter, the indicator is given a weight within its compartmentalized index. Each index has four indicators. Table 6.4 shows the weight distribution and scenarios. Each indicator is placed in the corresponding sub-index category and weights based on the four weighing schemes are highlighted. In bold is the 22% ratio that is considered a priority factor for the respective indicator, under the respective weighting scheme.

Using multi-criteria decision making (MCDA), the indicator values are summed to compose the unweighted index value γ. This value undergoes four different weighting schemes, through which each index has the opportunity to be weighed at 7%, 13% and the maximum of 22%. The four weighing schemes proposed in this model are described in detail in Figure 6.16.

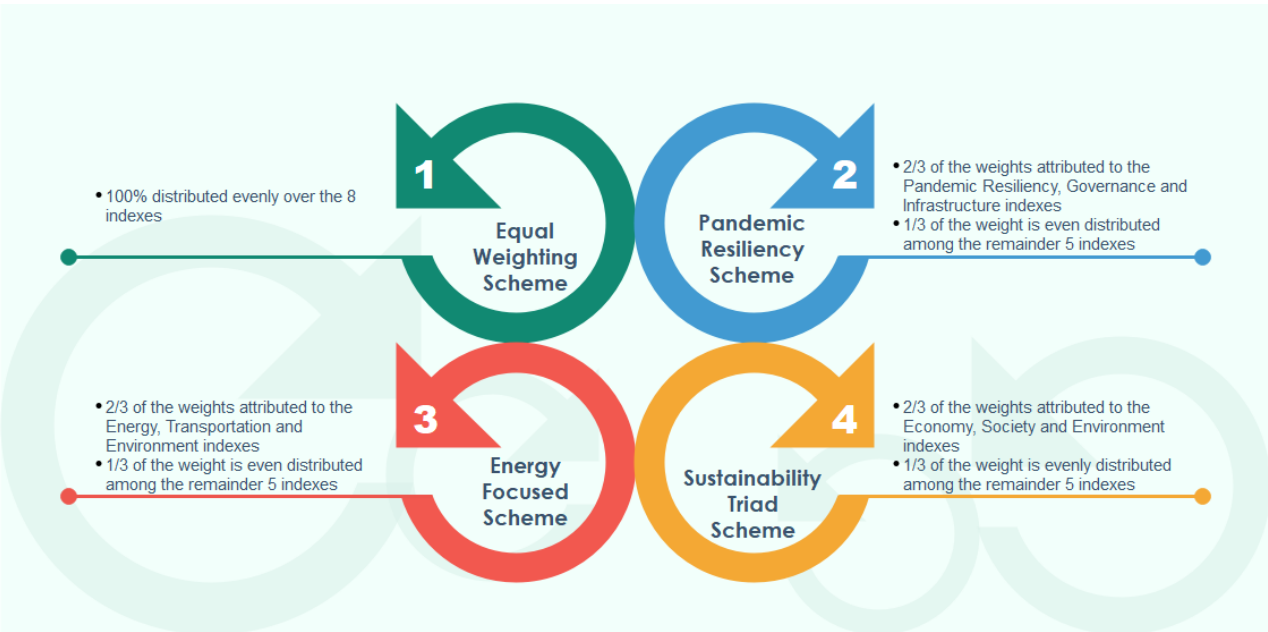


Figure 6.16 Weighting schemes used in this study

Table 6.4 Weighting schemes and scenarios for performance indicators and indexes

Sub-Index	Indicator	Indicator Weight (ω)	(γ) Equal Weighting	(γ) Sustainability Triad	(γ) Energy Focused	(γ) Pandemic Focused
Smart Environment	Air Quality	0.25	0.13	**0.22**	**0.22**	0.07
	Climate Change - GHG Emissions	0.25				
	Waste Management	0.25				
	Biodiversity & Habitat	0.25				
Smart Economy	Gross Domestic Product per Capita	0.4	0.13	**0.22**	0.07	0.07
	R&D Expenditure in % of GDP	0.1				
	Unemployment Rate	0.1				
	Gini Coefficient	0.4				
Smart Society	Educational Level	0.25	0.13	**0.22**	0.07	0.07
	Poverty Rate	0.25				
	Gender Equality	0.25				
	Healthcare Index	0.25				
Smart Governance	Government Effectiveness	0.25	0.13	0.07	0.07	**0.22**
	Government Digitalization	0.25				
	Public Participation	0.25				
	Corruption Rate	0.25				
Smart Energy	Energy Efficiency	0.5	0.13	0.07	**0.22**	0.07
	Clean Energy Utilization	0.13				
	Energy Storage	0.25				
	Energy Cost	0.13				
Smart Infrastructure	Infrastructure Investment	0.25	0.13	0.07	0.07	**0.22**
	Sustainable Infrastructure	0.25				
	Smart Device Penetration	0.25				
	Water Resources	0.25				
Smart Transportation	Transport Efficiency	0.2	0.13	0.07	**0.22**	0.07
	Technology Integration	0.2				
	Traffic Congestion	0.4				
	Accessibility	0.2				
Pandemic Resiliency	Response Rate	0.25	0.13	0.07	0.07	**0.22**
	Death Toll	0.25				
	Confirmed Cases	0.25				
	Infrastructure Capacity	0.25				

The first scheme is the equal weighting scheme, where all eight indexes are given the same weight and degree of significance, when calculating the final Smart City Index score. The second scheme highlights the traditional sustainability pillars of economic, societal, and environmental sustainability. Thus, these three indexes combined account for two thirds of the weights, whilst the last third is distributed evenly among the remainder five indexes, leaving each index to be rated at 7%. Similarly, the third scheme takes an energy focused approach by giving two thirds of the weight to the energy, environment, and transportation indexes, leaving the remainder five indexes with the last third of the weight, evenly distributed among them. Lastly, the pandemic focused scheme gives two thirds of the weight to the pandemic resiliency, infrastructure, and governance indexes, leaving the last third evenly distributed among the remainder indexes in the model. Following this comprehensive methodology, indicator data points have been collected for a total of 20 cities across the world. The cities were selected based on the availability and quality of data. Representation from all continents was carefully planned. Furthermore, cities from both developing and developed countries were included in the study. Figure 6.17 shows the map of the selected cities for this study, while Figure 6.18 shows the results of these cities against each unweighted index. According to the average results, the energy index has the lowest ratio, followed by governance and pandemic resiliency. On the other hand, infrastructure has the highest ratio, followed by the environment, economy, and transportation indexes.

Figure 6.17 World map highlighting selected cities included in this study

Furthermore, the outliers have been removed to ensure a consistent and uniform scale. These outliers include the economic index ratio for Doha. The smart index ratio for the environment index shows three clusters, where two clusters are below average and the last cluster is slightly above average, ranging from 0.75 and 0.86. Most of the cities in this study are below average on the society index. In fact, only the Canadian cities have a smart society index ratio higher than average, ranging between 0.81 and 0.82. The average smart energy index ratio is 0.26, which reflects immense opportunities for improvements in this sector. Half of the cities in the study are below average, while the other half exceed the average smart index ratio for the energy index.

Significant low values stem from the minimal utilization of clean energy, and energy storage as part of the energy infrastructure.

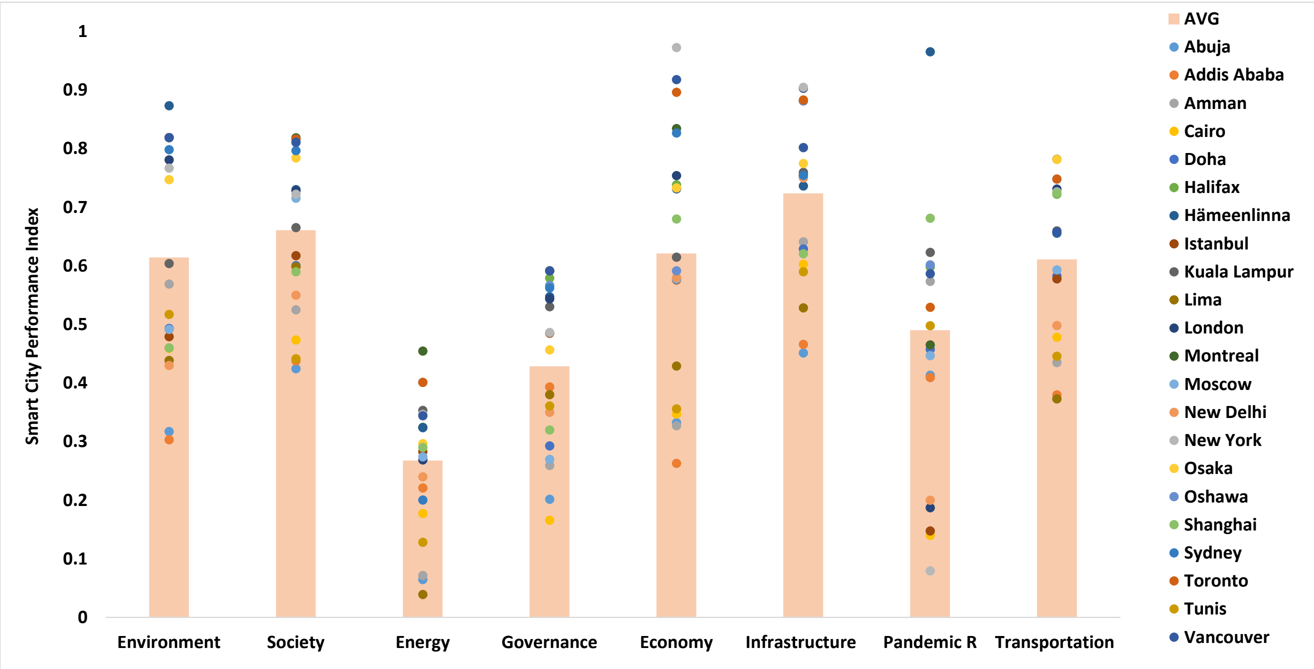


Figure 6.18 Cities performance on various indexes along with the calculated average for each index

The smart governance index ratio is 0.44 and cities vary on this front between 0.17 and 0.59. Montreal is the City with the highest smart governance index ratio, whereas Cairo has the lowest. Disparity in the economy index is evident as clusters of cities can be grouped based on the results. The value of Doha of 1.72 was excluded because it is considered an outlier. This significantly high value stems from the substantial GDP that Doha enjoys with very minimal population, making the GDP per Capita indicator considerably high. New York, Toronto, and Vancouver scored more than 0.9 on this index. Pandemic resiliency results also show considerable variation as some are performing very poorly with scores that are less than 0.2, while others are hitting the average, which is 0.45. Three cities were excluded from this averaging as they were considered outliers, including Lima, Osaka and Sydney. Figures 6.19 to 6.22 shows the SCI results based on the four different weighting schemes. Based on the equal weighting scheme, the city with the highest SCI is Sydney at 0.72, whereas the city with the lowest SCI is Lima at 0.26. On the other hand, based on the sustainability triad scheme, the city with the highest SCI is Toronto at 0.77, whereas the city with the lowest SCI is Abuja at 0.31. Toronto, Vancouver, and Montreal remain part of the top 5 cities in the equal weighting, sustainability triad and energy focused schemes. In fact, the energy focused scheme places four Canadian cities at the highest SCI, with Montreal at the top, scoring 0.7 and Oshawa at 0.66. The lowest in this scheme remains Lima with a SCI score of 0.26. From a pandemic focused scheme, Sydney, Osaka, followed by Hämeenlinna score the highest with SCI scores of 0.81, 0.79, and 0.7 respectively. While the energy focused scheme resulted in the most conservative and pessimistic SCI for the cities, the pandemic focused scheme resulted in the most optimistic SCI values. The biggest difference among the highest SCI scores between the different schemes is 0.11, whereas the biggest difference among the lowest SCI scores is 0.12. Table 6.5 lists all cities alphabetically along with the SCI based on each separate weighting scheme.

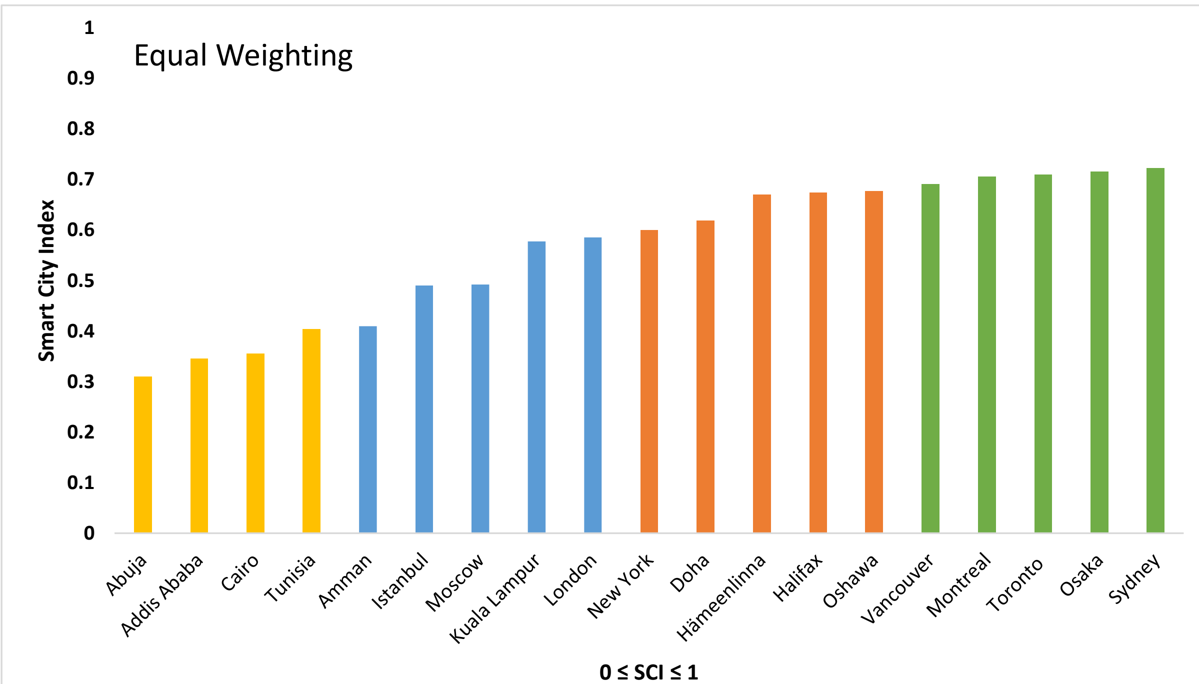


Figure 6.19 Smart City Index results based on the equal weighting scheme

For Doha, the Sustainability Triad scheme makes it the fourth highest, as it factors in its strongest suite, the economy index. However, equal weighting brings it to the 9th place with 0.619. The other schemes do not take the economy index into consideration, bringing Doha to 0.546 and 0.549 based on the Pandemic Focused and Energy Focused schemes, respectively. Figure 6.23 illustrates these results further. The average SCI is relatively remarkably similar among the four different weighting schemes, which reflects the accuracy and resiliency of the model. The Energy Focused scheme results in a more compacted results set with pessimistic results, whereas the Pandemic Focused scheme results in the most optimistic results for all cities except for the City of Lima. Furthermore, Figure 6.24 shows the variation of the SCI results for each city as a function of the weighting scheme.

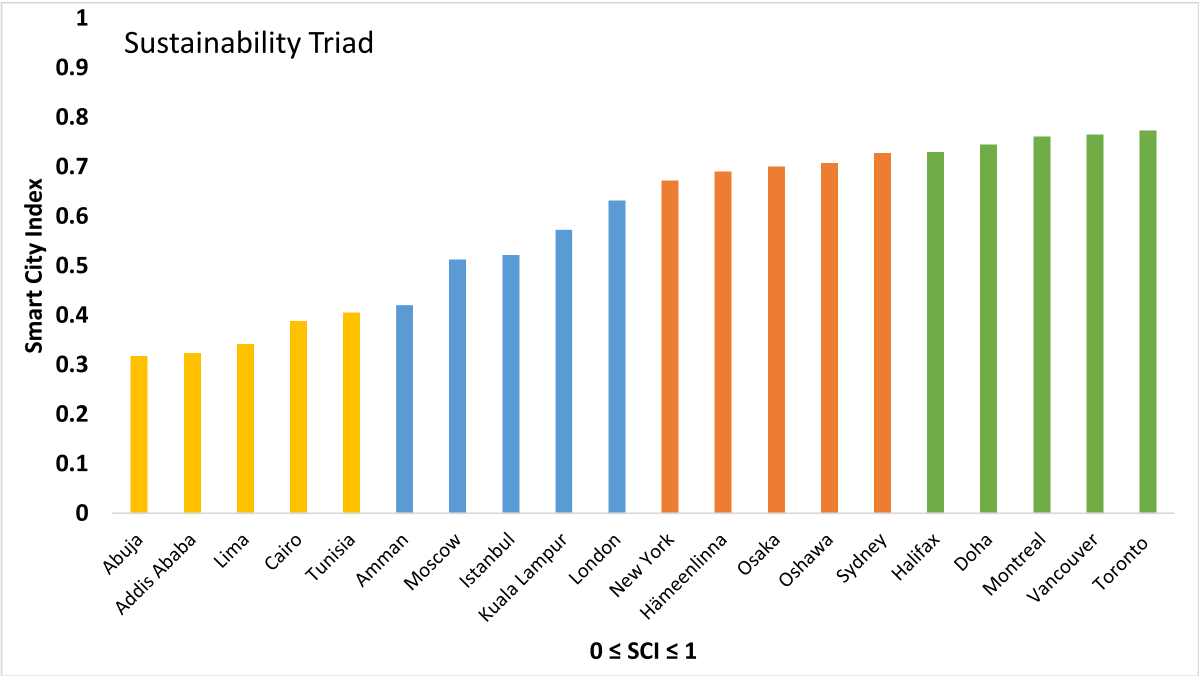


Figure 6.20 Smart City Index results based on the sustainability triad scheme

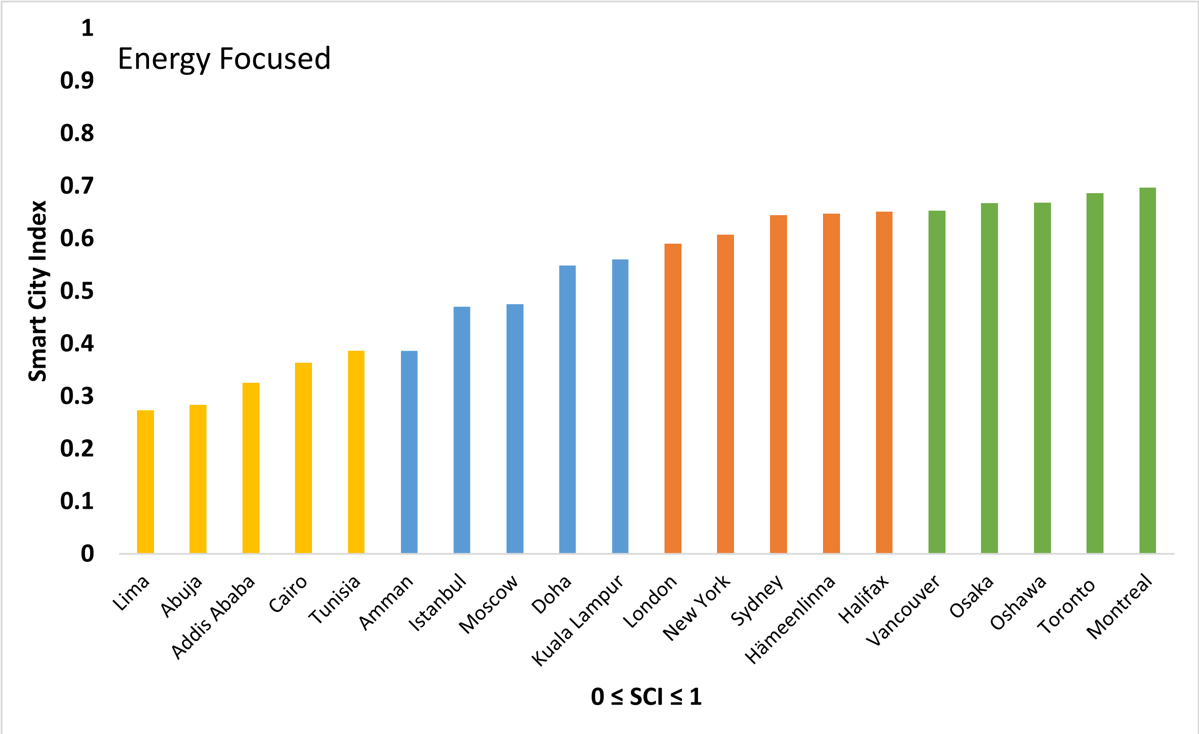


Figure 6.21 Smart City Index results based on the energy focused scheme

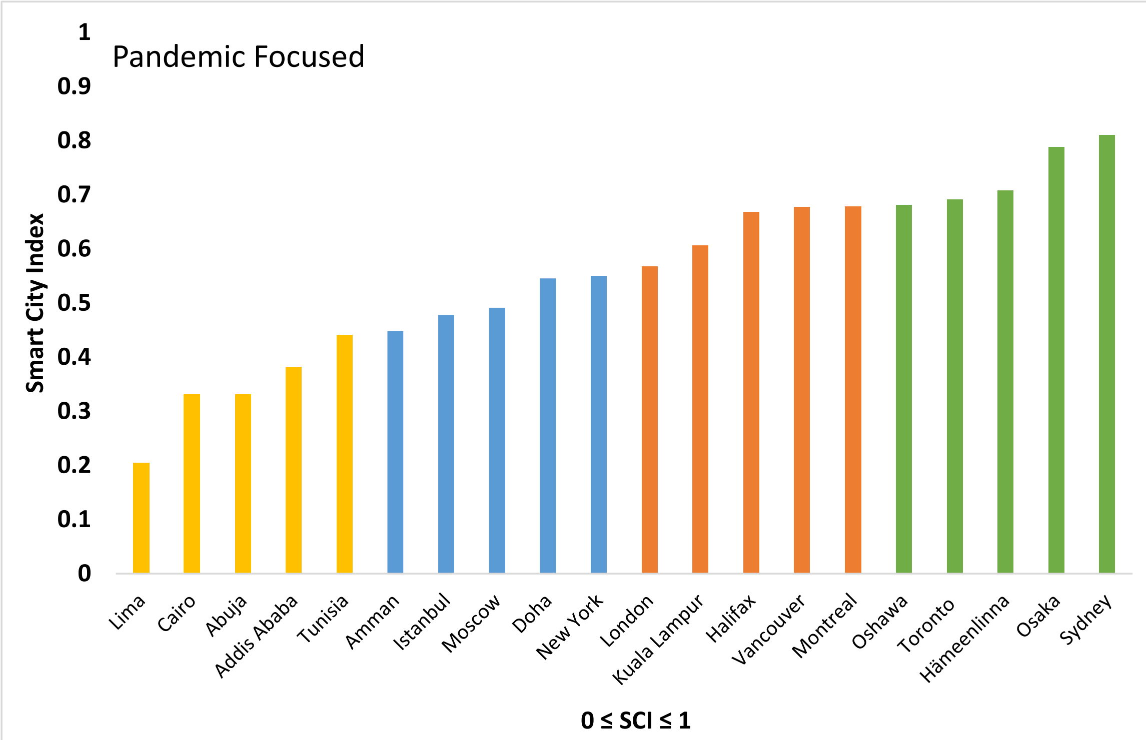


Figure 6.22 Smart City Index results based on the pandemic focused scheme

Table 6.5 Smart city index for all cities based on the four weighting schemes

City / Weighting Scheme	Pandemic Focused	Energy Focused	Sustainability Triad	Equal Weighting
Abuja	0.338	0.290	0.339	0.322
Addis Ababa	0.389	0.333	0.348	0.359
Amman	0.456	0.395	0.448	0.425
Cairo	0.331	0.363	0.389	0.355
Doha	0.556	0.559	0.778	0.638
Halifax	0.669	0.651	0.730	0.675
Hämeenlinna	0.721	0.660	0.735	0.695
Istanbul	0.478	0.470	0.522	0.490
Kuala Lampur	0.619	0.573	0.614	0.601
Lima	0.216	0.285	0.380	0.286
London	0.581	0.604	0.679	0.612
Montreal	0.679	0.697	0.762	0.706
Moscow	0.503	0.487	0.553	0.515
New York	0.563	0.620	0.717	0.626
Osaka	0.804	0.682	0.750	0.744
Oshawa	0.681	0.668	0.707	0.677
Sydney	0.825	0.659	0.778	0.751
Toronto	0.692	0.686	0.773	0.711
Tunisia	0.448	0.393	0.427	0.417
Vancouver	0.677	0.653	0.765	0.691

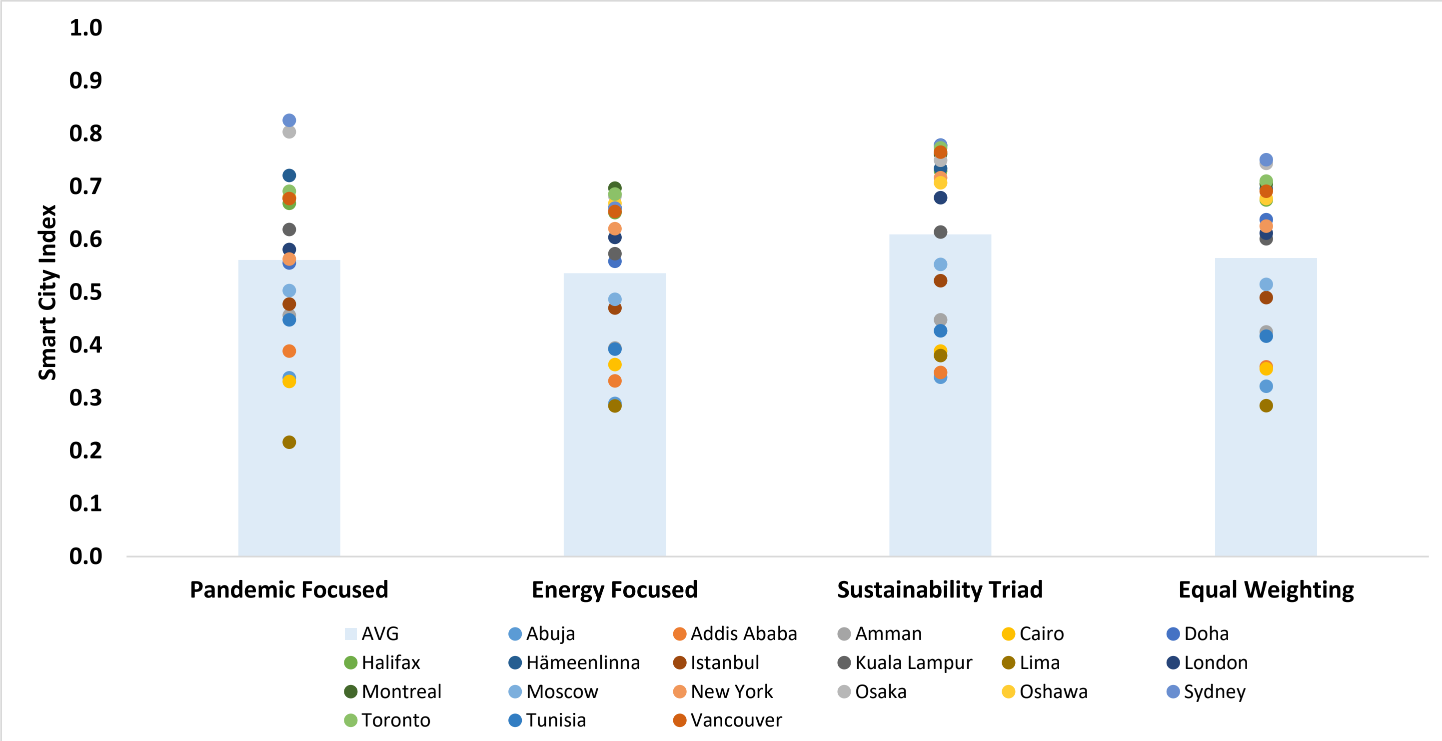


Figure 6.23 Smart city index results based on weighting scheme

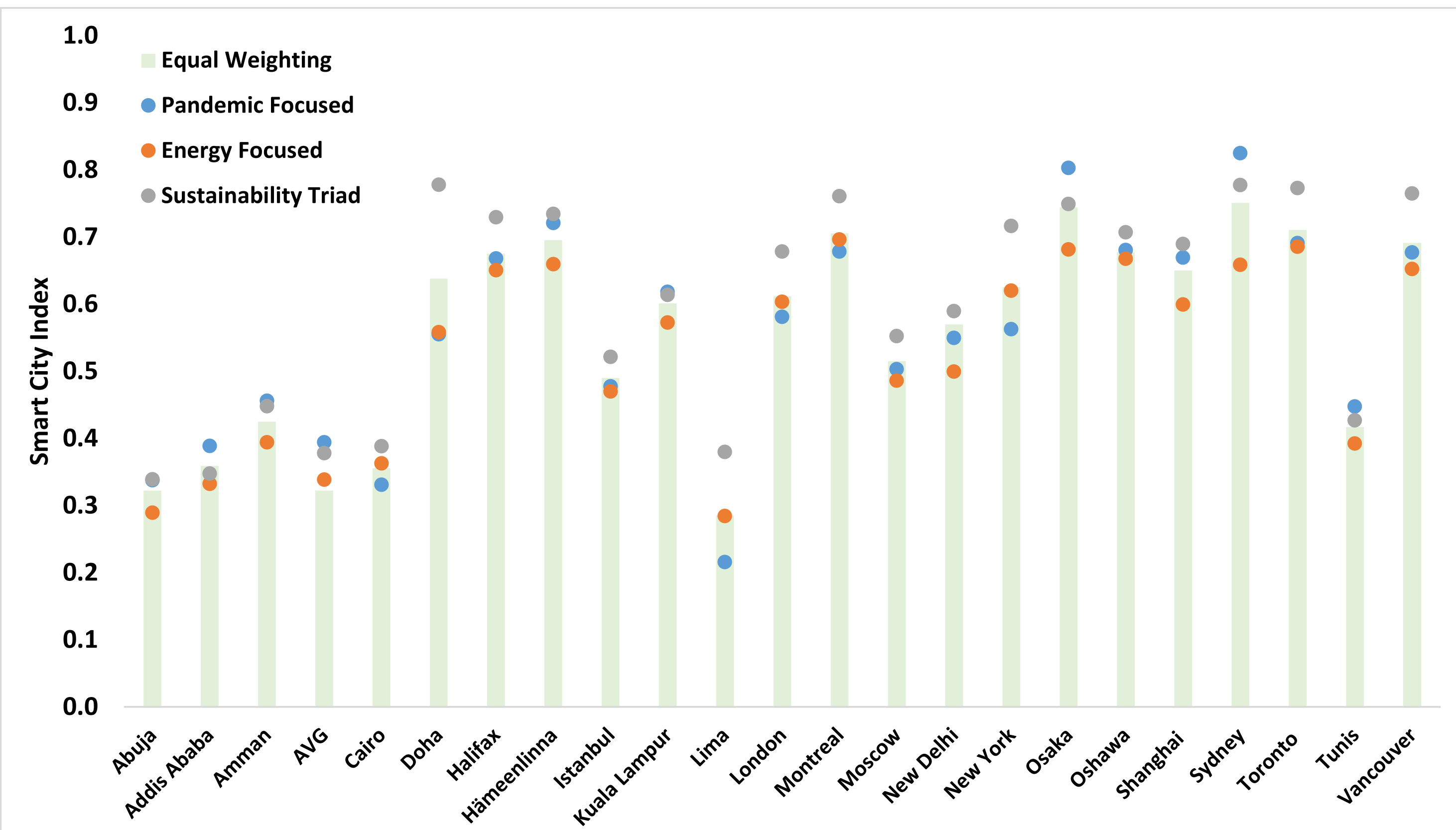


Figure 6.24 Variation of smart city index results based on weighting scheme

Table 6.6 Index performance for each city without scheme interference

City | Index	Environment	Society	Energy	Governance	Economy	Infrastructure	Pandemic R	Transportation
Abuja	32%	42%	6%	20%	33%	45%	41%	37%
Addis Ababa	30%	44%	22%	39%	26%	47%	41%	38%
Amman	57%	53%	7%	26%	33%	64%	57%	43%
Cairo	46%	47%	18%	17%	35%	60%	14%	48%
Doha	49%	60%	32%	29%	172%	63%	46%	58%
Halifax	82%	82%	32%	58%	74%	80%	60%	72%
Hämeenlinna	87%	73%	32%	55%	73%	74%	97%	66%
Istanbul	48%	62%	28%	49%	58%	76%	15%	58%
Kuala Lampur	60%	67%	35%	53%	61%	76%	62%	66%
Lima	44%	60%	4%	38%	43%	53%	-50%	37%
London	78%	73%	27%	54%	75%	90%	19%	73%
Montreal	82%	82%	45%	59%	83%	88%	47%	78%
Moscow	49%	72%	27%	27%	58%	75%	45%	59%
New York	77%	72%	35%	49%	97%	90%	8%	73%
Osaka	75%	78%	30%	46%	73%	77%	138%	78%
Oshawa	82%	81%	40%	57%	59%	88%	60%	75%
Sydney	80%	80%	20%	56%	83%	75%	141%	66%
Toronto	82%	82%	40%	59%	90%	88%	53%	75%
Tunisia	52%	44%	13%	36%	36%	59%	50%	45%
Vancouver	82%	81%	34%	59%	92%	80%	59%	66%

The bar graph is considered the reference, in this case, it is the Equal Weighting Scheme, against which the other schemes are benchmarked. For most cities, the differences in schemes result in marginal changes to the overall SCI. Compared to the Equal Weighting scheme, the Energy Focused scheme results in lower SCI scores for almost all cities. On the other hand, the Pandemic Focused scheme results in higher SCI for some cities such as Abuja, Addis Ababa and Amman, whereas it results in lower SCI in other cities such as Cairo, Lima and New York. Table 6.6 shows the index performance for each city despite any interference from any scheme. This means that no weighting scheme was taken into consideration to compute those results. The table shows the areas of improvements that each city needs to take. Where red indicates extremely poor performance, yellow denotes opportunities for improvements, and green reflects good performance. Energy and governance indexes are notably lower in values, suggesting that further investments and work need to be incorporated to achieve smarter cities across the world.

6.3 City Profiles

In this section, each city will be analyzed in detail to learn more about its specific performance using the SCI model. Granular data points will be analyzed along with SCI results and index performance presented in the previous section. Furthermore, cities with superior performance will be explored further to learn about the successful measures taken, leading those to higher SCI and index performance scores.

6.3.1 Abuja

Overall, Abuja is one of the lowest performing cities throughout all assessment indexes in this study. The environment index score is 32%, which is second lowest throughout all cities. This is due to very poor air quality score of 18% and waste management score of 6.7%. The economy index score is 33%, which is also the second lowest. This poor performance is attributed to very low GPD per capita, with a score of 17% and poor investment in research and development, scoring 0.2%. The society index of 42% is the lowest. This is because of the low educational level of 20.8%. The governance index of 20% is again the second lowest due to a very low government effectiveness of less than 1% and poor government digitalization of 9%. The energy index of 6% is due to low rates of energy efficiency and energy storage, both lower than 5%. Abuja’s infrastructure is its best index of 45%, yet it can be improved much further by investing in more sustainable infrastructure and smart device penetration. The transportation index score is 37% and can be enriched by allowing for more technology integration and accessibility.

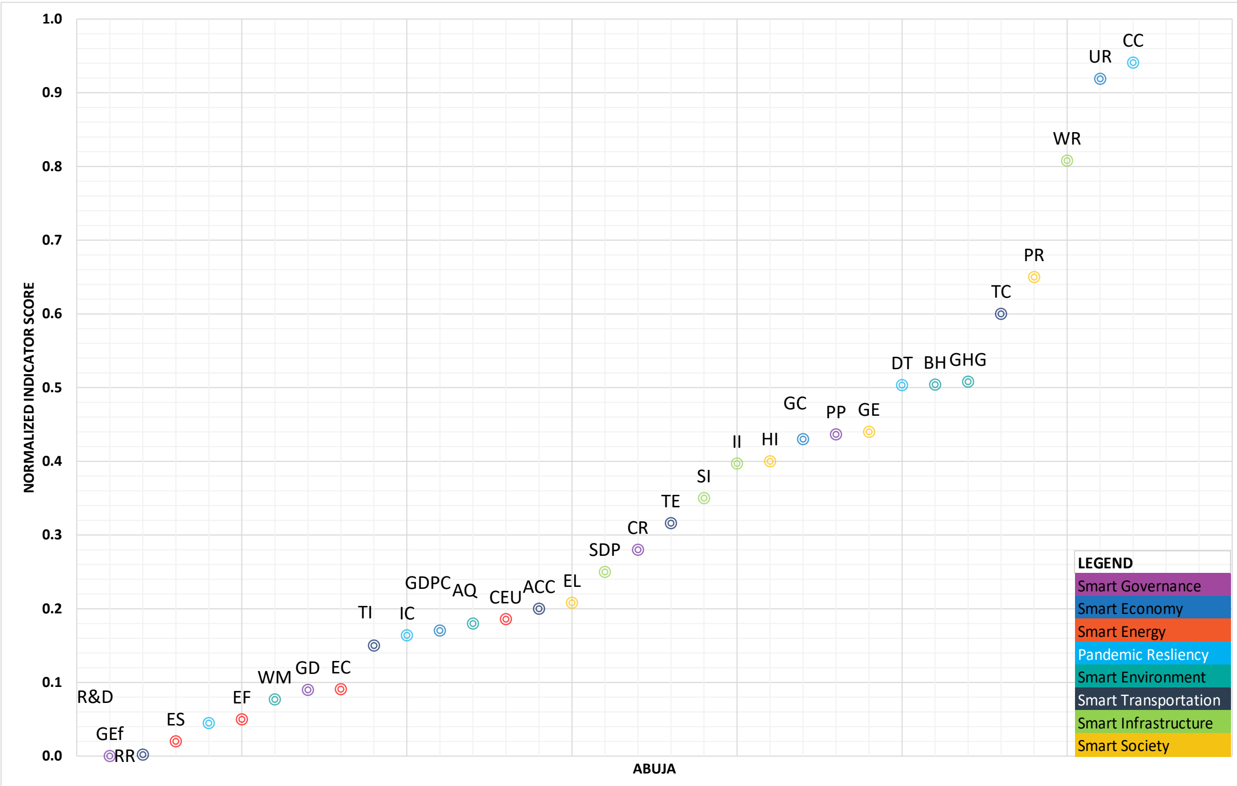


Figure 6.25 Normalized performance indicator scores for Abuja

Table 6.7 Highest and lowest performance indicators for Abuja

Lowest Performance Indicators	**Highest Performance Indicators**
R&D Expenditure in % of GDP	Pandemic Confirmed Cases
Government Effectiveness	Unemployment Rate
Pandemic Response Rate	Water Resources
Energy Efficiency	Poverty Rate
Energy Storage	Traffic Congestion

Lastly, the pandemic resiliency index score is 41%, which can be contributed to limited confirmed cases score of 94% (the higher this percentage, the better the performance), and a confined death toll score of 50%. Figure 6.25 shows the different performance indicators and their normalized scores for Abuja. The energy index is more skewed towards the lower values, whereas infrastructure and environment indexes are more inclined towards the higher and middle values. Some elements of the governance index are towards the lower end, while other elements are near the middle. In summary, Abuja's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.338, 0.290, 0.339, and 0.322, respectively.

6.3.2 Addis Ababa

Addis Ababa features a similar profile to that of Abuja's, as in its poor indexes' performance and significant room for improvements throughout all indexes. The environment index is the lowest at 30% due to its poor waste management and GHG emission scores of 0.5% and 26.1% respectively. The society index of 44% is also considered poor, resulting primarily from exceptionally low educational level of 5%. The energy index is slightly better than that of Abuja's and is considered mediocre, given its competitive energy cost of 6.7 cents per kWh, compared to the average of 11 cents per kWh. Addis Ababa is also a pioneer in clean energy utilization, scoring 93.6%. As for governance, government effectiveness and digitalization score less than 1%, mimicking a similar trend to that of Abuja's. The economy index is worse than that of Abuja's scoring 26% due to below average GDP per capita of $2,160 and an insignificant percentage towards research and development. The infrastructure index is slightly higher than that of Abuja's by 2% and opportunities to enhance smart device penetration and smart infrastructure is lucrative. The pandemic resiliency index of 41% can be misleading as the city has extremely limited cases and confined death toll. Lastly, the transportation index is 38% because of limited accessibility and basic technology integration. Figure 6.26 shows the different performance indicators and their normalized scores for Addis Ababa.

Table 6.8 Highest and lowest performance indicators for Addis Ababa

Lowest Performance Indicators	Highest Performance Indicators
Government Effectiveness	Water Resources
Waste Management	Unemployment Rate
R&D Expenditure in % of GDP	Clean Energy Utilization
Energy Storage	Public Participation
Pandemic Response Rate	Pandemic Confirmed Cases

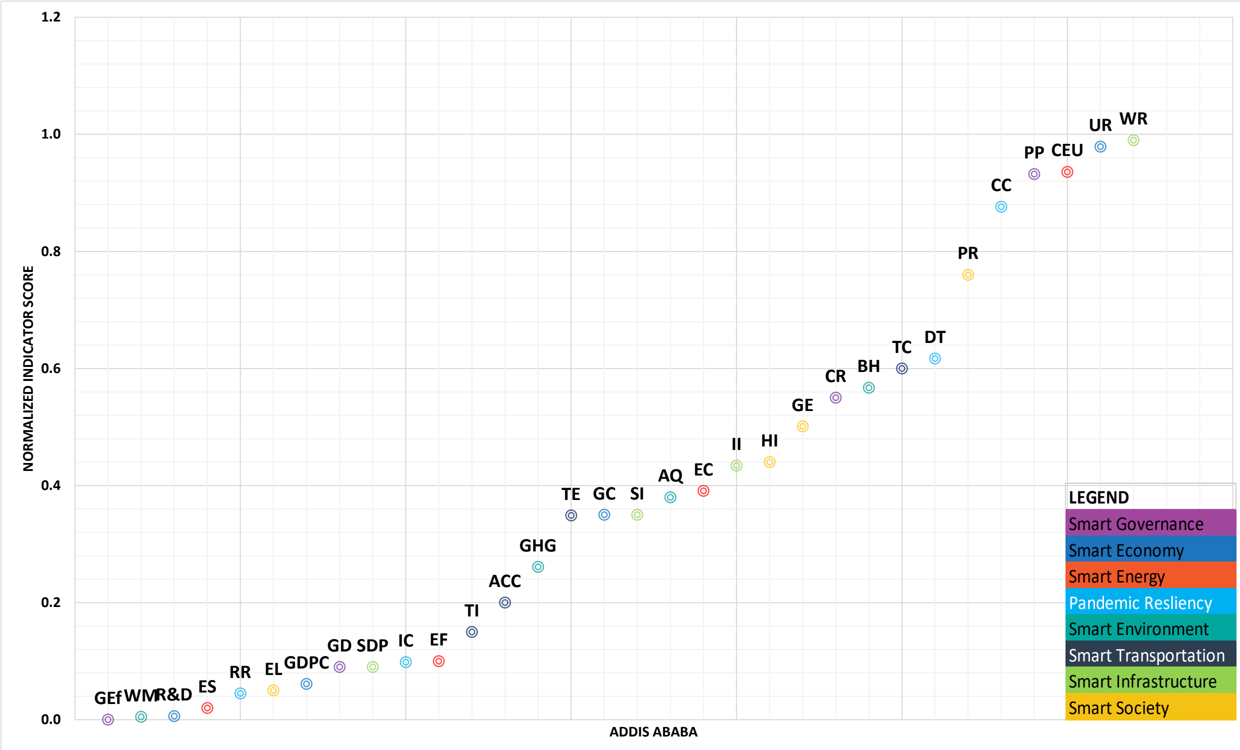


Figure 6.26 Normalized performance indicator scores for Addis Ababa

In summary, Addis Ababa's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.389, 0.333, 0.348, and 0.359 respectively.

6.3.3 Amman

Amman's strongest suit include the environment index, with score of 57%, resulting from decent air quality, GHG emissions, and biodiversity and habitat indicators performance. The society index is 53%, given a favorable score for poverty rate of 84%, coupled with a midpoint healthcare index indicator score of 50%. Amman's weakest suit and where room for significant improvement is needed for it to score a higher SCI is the energy index. The energy cost is slightly above the average value, making the normalized score to be -13.6%. Energy storage and clean energy utilization both are below the 5% mark. The governance index of 26% is low due to the low government effectiveness score of 2.6%, coupled with limited government digitalization and public participation of 15% and 36% respectively. Amman's economy index of 33% suffers because of the very low GDP per capita of $9,433, which is way below average, coupled with insignificant expenditures towards research and development of 0.4%. The infrastructure index is the highest index with 64% score, stemming from strong infrastructure investment score of

66.4%. While the pandemic response rate is very low at 6.7%, it is attributed to the insignificant number of confirmed cases in Amman of 373. Amman's transportation index can be improved by investing in all the assessment performance indicators, including technology integration, transport efficiency, traffic congestion and accessibility. Figure 6.27 shows the different performance indicators and their normalized scores for Amman.

Table 6.9 Highest and lowest performance indicators for Amman

Lowest Performance Indicators	Highest Performance Indicators
Energy Cost	Pandemic Confirmed Cases
R&D Expenditure in % of GDP	Water Resources
Government Effectiveness	Unemployment Rate
Energy Storage	Poverty Rate
Clean Energy Utilization	Pandemic Death Toll

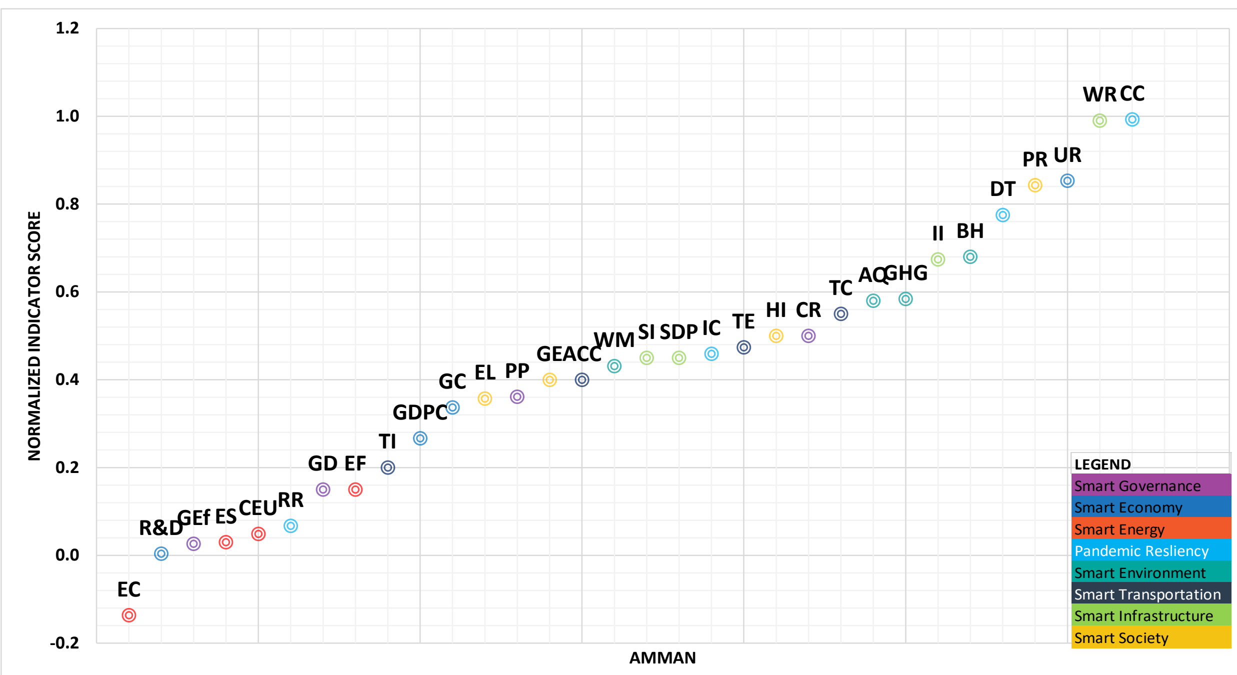


Figure 6.27 Normalized performance indicator scores for Amman

In summary, Amman's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.456, 0.395, 0.448, and 0.425 respectively.

6.3.4 Cairo

Cairo's strongest suit is in the infrastructure and society indexes. The environment index score for Cairo is 46% due to low waste management and air quality indicator scores of 16.3% and 35.3% respectively. The society index of 47%, while one of the highest indexes for Cairo, is considered poor performing, compared to other cities. This can be traced to poor several factors including poor educational level score of 12.7%, unfavorable poverty rate and gender equality scores of 72.2% and 43.5% respectively. The energy index score of 18% is much better than that of Amman's. This is due to an incredibly competitive and much below average energy cost of 4 cents per kWh. However, the other aspects of the energy index such as energy storage and clean energy utilization indicators are suffering, with scores of 4% and 8.2% respectively. Cairo's governance index score is the lowest among all cities in this study with 17%. This is because of deficient performance across all four smart governance indicators, primarily government effectiveness. The economy index of 35% reflects poor investment in research and development. The infrastructure index score of 60% is relatively mediocre, with significant infrastructure investment of 73%, yet limited smart device penetration and sustainable infrastructure scores of 28% and 40% respectively. The pandemic resiliency score, although 14% is concerning. This is because the confirmed cases of 45,206 is like the average confirmed cases throughout the cities in this study, however, Cairo's death toll is more than the average with score of -15%. The response rate score of 6.7% is also insignificant. Technology integration and accessibility are the two performance indicators that need improvement for the transportation index. Figure 6.28 shows the different performance indicators and their normalized scores for Cairo.

Table 6.10 Highest and lowest performance indicators for Cairo

Lowest Performance Indicators	**Highest Performance Indicators**
Pandemic Death Toll	Water Resources
Government Effectiveness	Unemployment Rate
R&D Expenditure in % of GDP	Biodiversity & Habitat
Energy Storage	Infrastructure Investment
Pandemic Response Rate	Poverty Rate
Clean Energy Utilization	

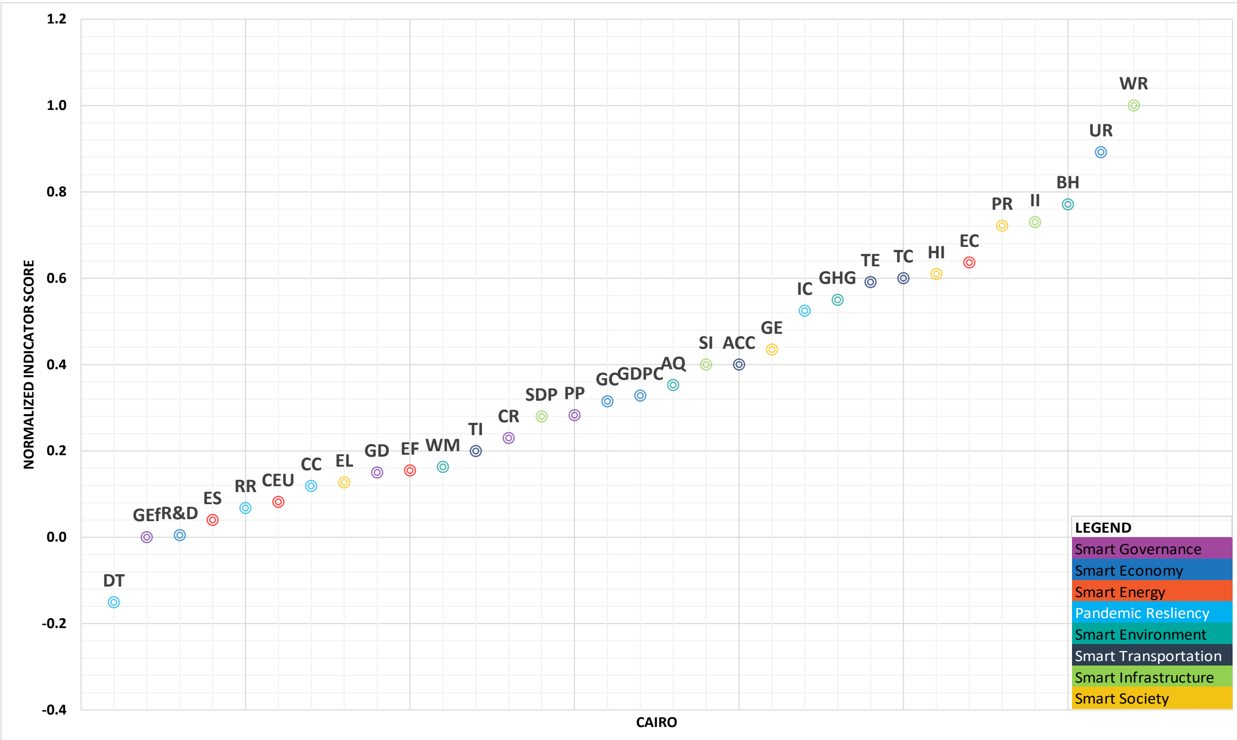


Figure 6.28 Normalized performance indicator scores for Cairo

In summary, Cairo's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.331, 0.363, 0.389, and 0.355 respectively.

6.3.5 Doha

Doha's economy index score of 172% is the highest among all cities in this study for reasons that will be explored shortly. Doha also scored the third highest SCI under the Sustainability Triad scheme. The environment index score of 49% is considered mediocre and improvements in air quality and GHG emission indicators would take it to good standing. The society index score of 60% is also considered decent, considering other similar cities in the cluster. Poverty rate is almost nonexistent with indicator score of 99%, however improvements can be made in the educational level and gender equality, both with scores of 40%. The energy index score is 32%, which is considered good standing in comparison to the results of the other cities in this study. This is attributed to lucrative energy cost of 3 cents per kWh, which is 8 cents lower than the average, coupled with competitive energy efficiency score of 45%. Nonetheless, grave concerns revolve around the clean energy utilization and energy storage indicators with scores of 0.3% and 3% respectively. The governance index score of 29% is suggestive of opportunity for improvements in the government effectiveness and public participation indicators, both with scores of 15% and 10% respectively. The economy index as mentioned earlier is the highest due to the very fact that the GDP per capita is $130,475, which is 3.7 times more than the average. While unemployment rate is also virtually nonexistent, the Gini coefficient score is only 36.8%. Furthermore, despite the substantial GDP per capita, the investments into research and development is very insignificant with score of only 0.5%. Amman, with a much lower GDP per capita scored 0.4% in the research and development expenditure. Therefore, considerable investments need to be channeled towards this aspect. The infrastructure index score is 63%, stemming from considerable infrastructure investment of 81.6%. However, this index score can be improved by enhancing the sustainable infrastructure and smart device penetration, both with scores of 25% and 45% respectively. The pandemic resiliency index is 14%, which is considered mediocre. While Doha has much larger than average confirmed cases, the response rate was also proportional to the demand and thus was also above average. Improvements in the infrastructure capacity can enhance the performance of this index. Lastly, the transportation index score of 48% is attributed to competent transport efficiency and accessibility. Further improvements in technology integration and traffic congestion can enhance the performance of this index. All these values take into consideration the citizens of Doha only and excludes foreign residents and resident workers. This could introduce skewedness or subjectivity to the data that may not be favorable. Figure 6.29 shows the different performance indicators and their normalized scores for Doha.

Table 6.11 Highest and lowest performance indicators for Doha

Lowest Performance Indicators	**Highest Performance Indicators**
Pandemic Confirmed Cases	Gross Domestic Product per Capita
Clean Energy Utilization	Pandemic Response Rate
R&D Expenditure in % of GDP	Water Resources
Energy Storage	Unemployment Rate
Public Participation	Poverty Rate

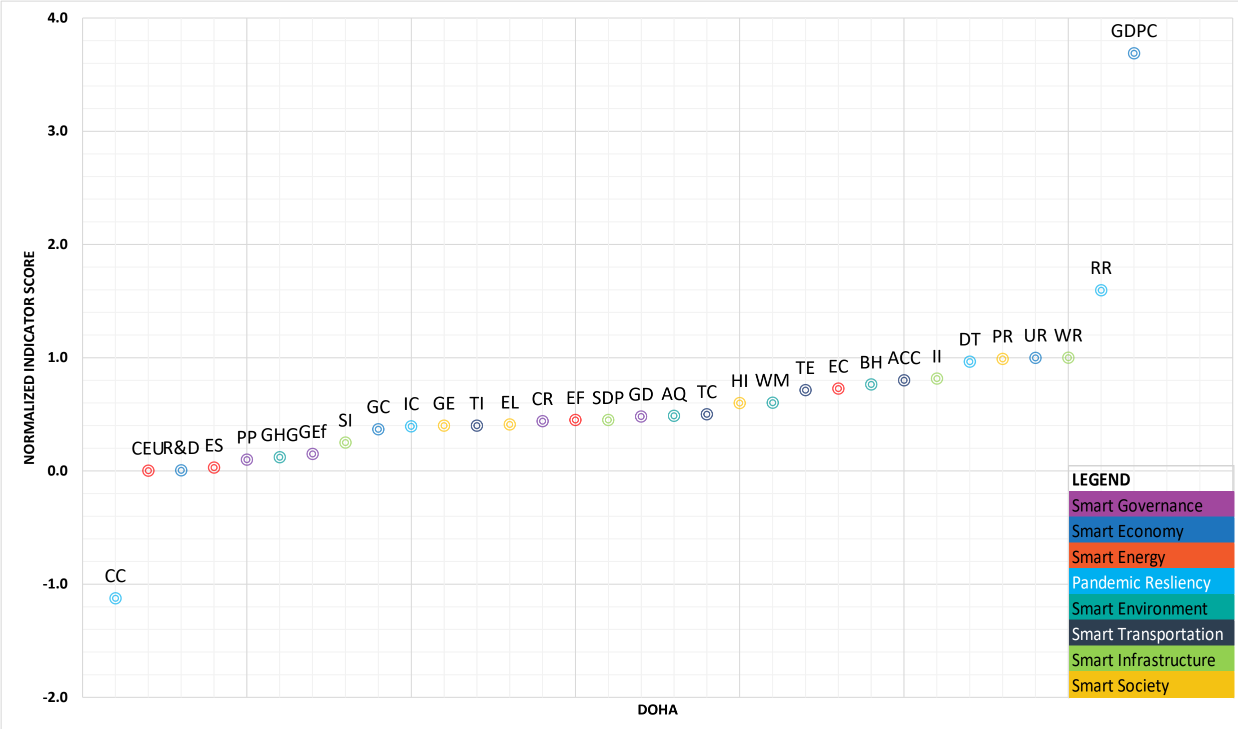


Figure 6.29 Normalized performance indicator scores for Doha

In summary, Doha's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.556, 0.559, 0.778, and 0.638 respectively.

6.3.6 Halifax

Halifax's environment index is one of the strongest in this model with score of 82%. This can be improved further if the GHG emissions indicator score of 65.7% is enhanced further. Similarly, the society index score of 82% is the highest in this model. The educational level of 60% can be improved to strive for better index performance. The energy index of 32% is also considered decent, however it is low considering the score of the other indexes. In fact, Halifax's energy cost is more than the average cost, making it score a negative score. The energy storage indicator score is also minimal at 2.7%. Therefore, better utility financial models along with more investments in energy storage will enhance the score of the energy index for Halifax. The governance index of 58% is the second highest among all cities in this model. This can be improved by enhancing government digitalization and public participation indicator scores. The economy index score of 74% is also considered decent, given its above average GDP per capita. However, improvements can be achieved by enhancing the Gini coefficient and the expenditures on research and development scores of 33.8% and 1.56% respectively. The infrastructure index of 80% is attributed to significant infrastructure investment and smart device penetration. Improvements to this index can be achieved by expanding sustainable infrastructure. The pandemic resiliency index score of 60% is due to an above average death toll, giving it a negative index score of -80%, despite its competitive response rate score of 133% and infrastructure capacity score of 89%. Lastly, the transportation index score of 72% is attributed to good accessibility and traffic congestion scores. Improvements to the transport efficiency and technology integration helps enhance the index score. Figure 6.30 shows the different performance indicators and their normalized scores for Halifax.

Table 6.12 Highest and lowest performance indicators for Halifax

Lowest Performance Indicators	Highest Performance Indicators
Pandemic Death Toll	Pandemic Response Rate
Energy Cost	Gross Domestic Product per Capita
R&D Expenditure in % of GDP	Water Resources
Energy Storage	Pandemic Confirmed Cases
Gini Coefficient	Air Quality

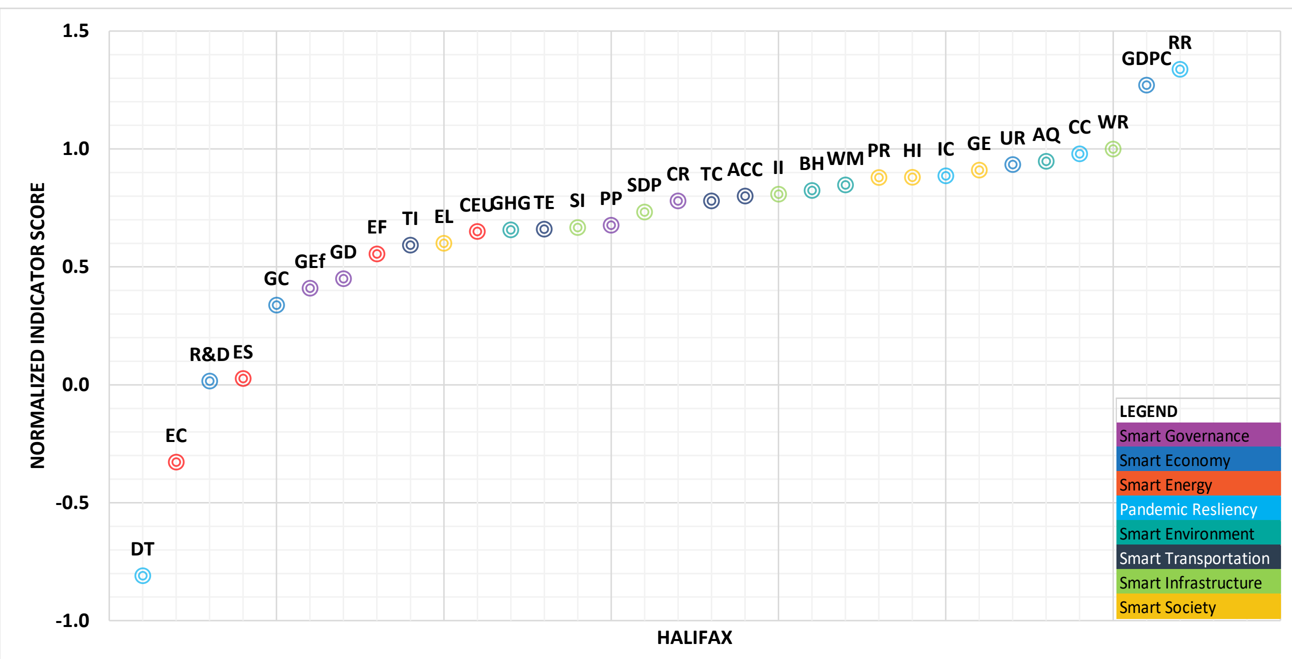


Figure 6.30 Normalized performance indicator scores for Halifax

In summary, Halifax's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.669, 0.651, 0.730, and 0.675 respectively.

6.3.7 Hämeenlinna

Hämeenlinna has the highest environment index score of 87% among all cities in this model, suggesting environmental leadership and stewardship embraced in this city. The society index of 73% is also considered good, given high indicator performance for the healthcare index and gender equality. The educational level of 45% can be improved to enhance this index. The energy index of 32% is considered good, given good utilization of clean energy and enhanced energy efficiency. However, the energy cost is above the average energy cost, giving this indicator a negative score of -24.8%. Therefore, a financially viable and competent model needs to be developed for the utility sector in this city. The governance index score of 55% is reinforced by a very strong government effectiveness score of 99%. However, improvements can be achieved by enhancing the government digitalization of 24% and public participation score of 69%. The economy index of 73% is due to the favorable GDP per capita, which is above average. The infrastructure index can be improved further be optimizing the score of the sustainable infrastructure indicator, currently at 22.6% only. The pandemic resiliency score is 97%, primarily because only one case has been confirmed. Technology integration and transportation efficiency can enhance the transportation index score of 66%. Figure 6.31 shows the different performance indicators and their normalized scores for Hämeenlinna.

Table 6.13 Highest and lowest performance indicators for Hämeenlinna

Lowest Performance Indicators	Highest Performance Indicators
Energy Cost	Gross Domestic Product per Capita
R&D Expenditure in % of GDP	Water Resources
Energy Storage	Air Quality
Technology Integration	Waste Management
Sustainable Infrastructure	Poverty Rate

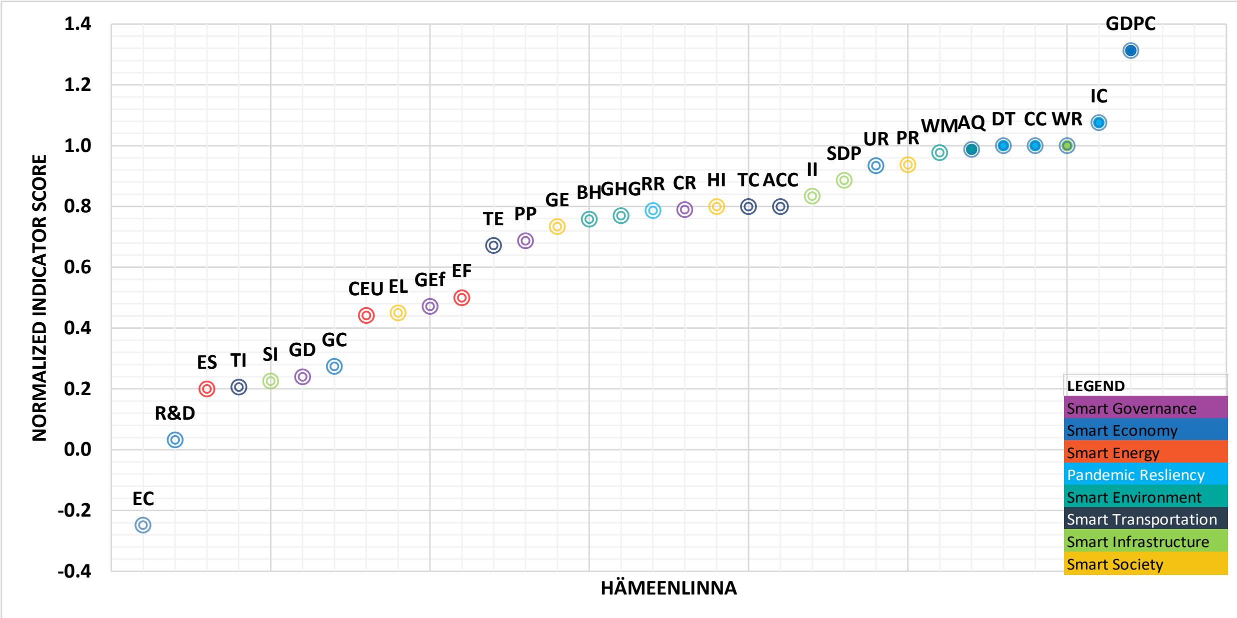


Figure 6.31 Normalized performance indicator scores for Hämeenlinna

In summary, Hämeenlinna's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.721, 0.660, 0.735, and 0.695, respectively.

6.3.8 Istanbul

Istanbul's SCI profile lies in the middle cluster along the spectrum. Therefore, values are generally revolving around the average or exceed it at times. In fact, Istanbul does not have any index score below average. The environment index score of 48% can be improved by investing in all four environmental indicators as they average indicator performance score is 48% as well. The society index is 62%, with competitive healthcare index score of 76% and gender equality score of 66.2%. The educational level score of 21% can certainly be improved further to achieve better index performance. The energy index score is 28%, due to slightly higher than average energy cost, and minimal adoption of energy storage. However, energy efficiency and clean energy utilization indicators are indicative of good progress in this direction. The governance index is 49%, due to a very high public participation score of 86%. However, the government effectiveness and corruption rate scores are both at 50%, indicating that there is much work to be done. Also, government digitalization can be improved significantly. The economy index of 58% can be improved by implementing programs throughout the four different indicator areas. The infrastructure is resilient with score of 76% and can be improved by enhancing smart device penetration, currently at 56.9%. The pandemic resiliency score is 15%, due to the high number of confirmed cases, exceeding the average. While infrastructure capacity score of 92% is lucrative, the death toll score of 42% can be improved. Lastly, the transportation index of 58% can be improved by optimization traffic congestion and enhancing technology integration. Figure 6.32 shows the different performance indicators and their normalized scores for Istanbul.

Table 6.14 Highest and lowest performance indicators for Istanbul

Lowest Performance Indicators	**Highest Performance Indicators**
Pandemic Confirmed Cases	Water Resources
Energy Cost	Pandemic Infrastructure Capacity
R&D Expenditure in % of GDP	Unemployment Rate
Energy Storage	Public Participation
Educational Level	Poverty Rate

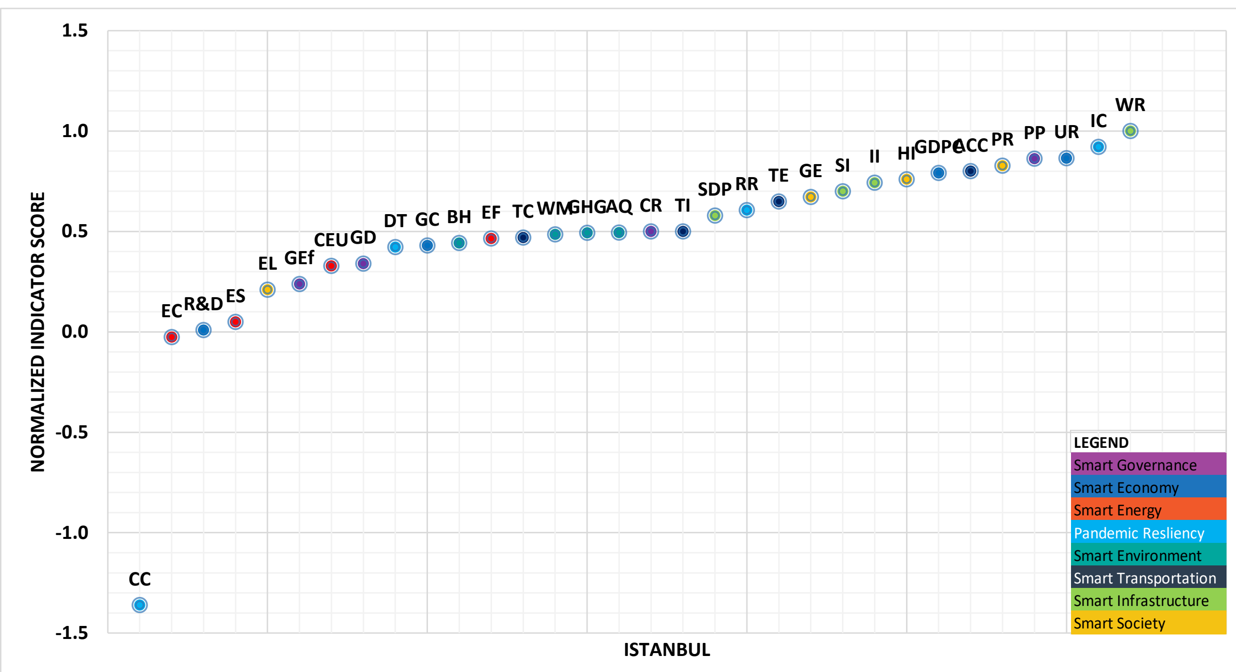


Figure 6.32 Normalized performance indicator scores for Istanbul

In summary, Istanbul's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.478, 0.470, 0.522, and 0.490, respectively.

6.3.9 Kuala Lampur

Kuala Lampur has a similar profile to that of Istanbul's. However, it exceeds Istanbul's performance in energy, governance, and pandemic resiliency. The environment index for Kuala Lampur is 60% due to effective waste management. Improvements to the three other indicators will enhance the value of this index. Competent healthcare index score of 75% resulted in a society index score of 67%. Improvement to this index can be achieved by enhancing the educational level score, currently at 21.7%. The energy index can also be improved significantly by incorporating energy storage and clean energy utilization, both indicators with scores of 7% and 13.7% respectively. The governance index is 53% is attributed to good progress on all four indicator scores, primarily public participation of 82%. The economy index of 61% is due to a nearly average GDP per capita and favorable unemployment rate score of 96.7%. On the other hand, expenditure to research and development is only 1.3%. The infrastructure index is also competitive with score of 76% and can be improved by increasing the smart device penetration score. The pandemic resiliency index 62%. Despite the limited number of cases, the response rate score is disproportionately low at 23.6%. The infrastructure capacity score is lower at 62%. Lastly, the transportation index is high due to accessible and efficient transportation. Further developments can be achieved in the technology integration and traffic congestion indicators. Figure 6.33 shows the different performance indicators and their normalized scores for Istanbul.

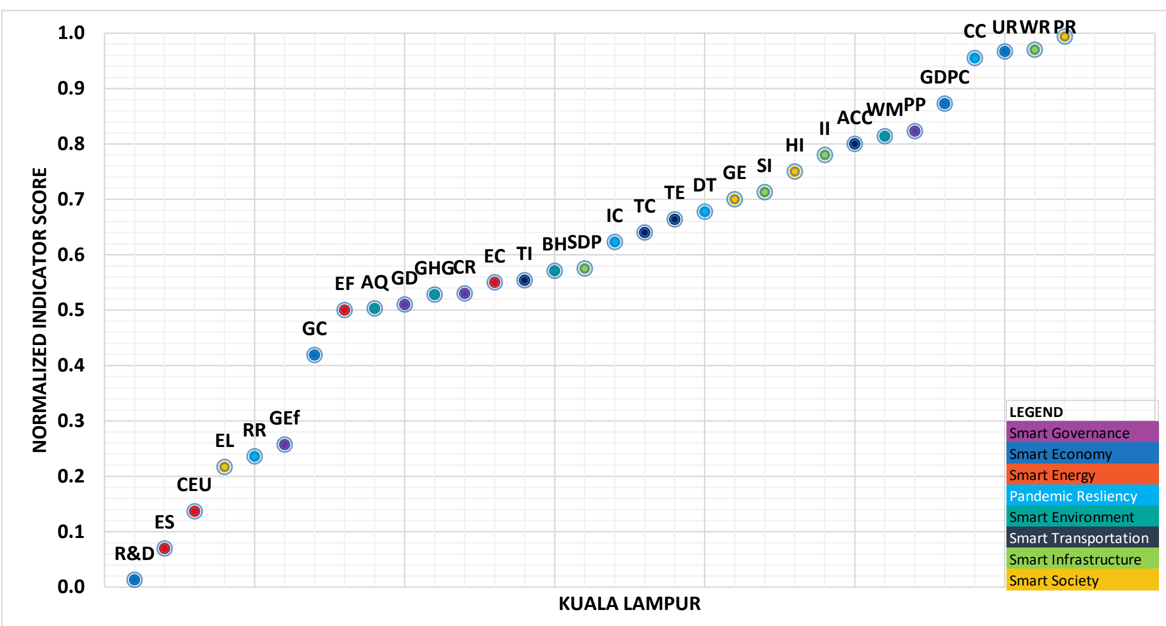


Figure 6.33 Normalized performance indicator scores for Kuala Lampur

Table 6.15 Highest and lowest performance indicators for Kuala Lampur

Lowest Performance Indicators	Highest Performance Indicators
R&D Expenditure in % of GDP	Poverty Rate
Energy Storage	Water Resources
Clean Energy Utilization	Unemployment Rate
Educational Level	Pandemic Confirmed Cases
Pandemic Response Rate	Gross Domestic Product per Capita

In summary, Kuala Lampur's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.619, 0.573, 0.614, and 0.601 respectively.

6.3.10 Lima

Lima's SCI performance is concerning and belongs to the third cluster, with lower performance. In specific, the pandemic resiliency index is the lowest score of -50%. It also has the lowest energy and transportation index scores throughout the cities in this study. The environment index of 44% can be improved by enhancing all four indicator areas, most notably waste management, currently at 30%. The society index of 60% can increase with a higher educational level score. The energy index score is 4% is the lowest, despite Lima's utilization of clean energy at score of 50%. This is because the energy cost is much above average at 16.7 cents per kWh, coupled with extremely limited energy storage at 1% and 10% energy efficiency. The governance index score is 38%, despite an active public participation with score at 74%. The government effectiveness is almost 0% along with a corruption rate score of 50% and 28% government digitalization. The economy index score of 43% is due to very favorable unemployment rate score of 96.7%. The GDP per capita is lower than average at $14,224 and very insignificant expenditure towards research and development of 0.1%. Relatively, water resources score of 87% is not a good sign and further work can be achieved in the infrastructure domain. The confirmed cases of the pandemic quadrupling the average, coupled with an above-average death toll and a response rate resulted in this negative score for pandemic resiliency index. Finally, the transportation index is also challenging with limited integration of technology. Figure 6.34 shows the different performance indicators and their normalized scores for Lima.

Table 6.16 Highest and lowest performance indicators for Lima

Lowest Performance Indicators	Highest Performance Indicators
Pandemic Confirmed Cases	Unemployment Rate
Energy Cost	Water Resources
Pandemic Death Toll	Poverty Rate
Government Effectiveness	Public Participation
R&D Expenditure in % of GDP	Healthcare Index

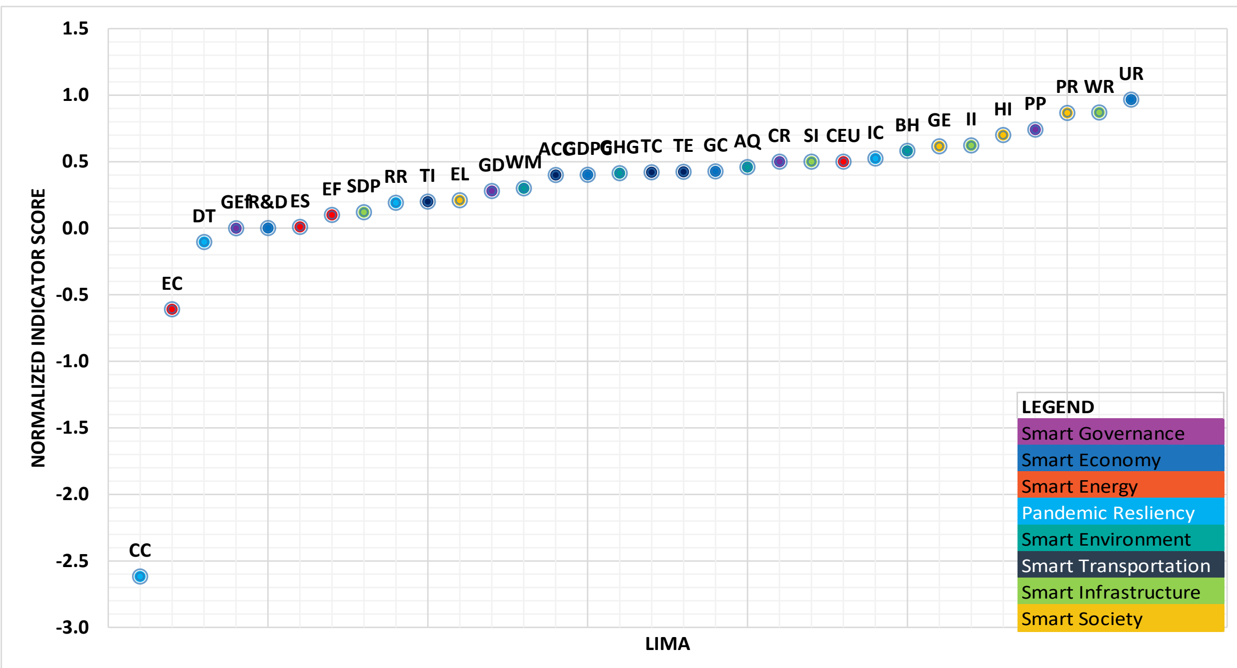


Figure 6.34 Normalized performance indicator scores for Lima

In summary, Lima's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.216, 0.285, 0.380, and 0.286, respectively.

6.3.11 London

London is most notably known for its best performance in the infrastructure index among all cities in this study. The environment index score of 78% is considered competitive, mainly due to effective waste management and GHG emissions control. Improvements can be achieved by optimizing the biodiversity and habitat indicator score of 44.7%. The society index of 73% however is only considered mediocre and can be improved by enhancing the educational level score of 46% and the poverty rate score of 88%, which is relatively disproportionate to the profile of this city. The energy index score is the second lowest within London's eight performance indexes. The energy cost is double the average cost, which brings its score to -100%. However, London is performing well in the clean energy utilization and energy storage scores, currently at 33% and 11% respectively. The governance index score of 54% is low due to low public participation score of only 67%, coupled with limited government digitalization score of 35%. The economy index, however, is 75%, with above average GDP per capita score of 129%. The infrastructure index score is 90%, which is indicative that all four indicator areas are progressing positively. The pandemic resiliency score is only 8%, due to the tripling of the death toll. However, the response rate was also more than double the average. Finally, the transportation sector can integrate more accessibility and resolve the issue of traffic congestion, which is currently at 60% and 63% respectively. Figure 6.35 shows the different performance indicators and their normalized scores for London.

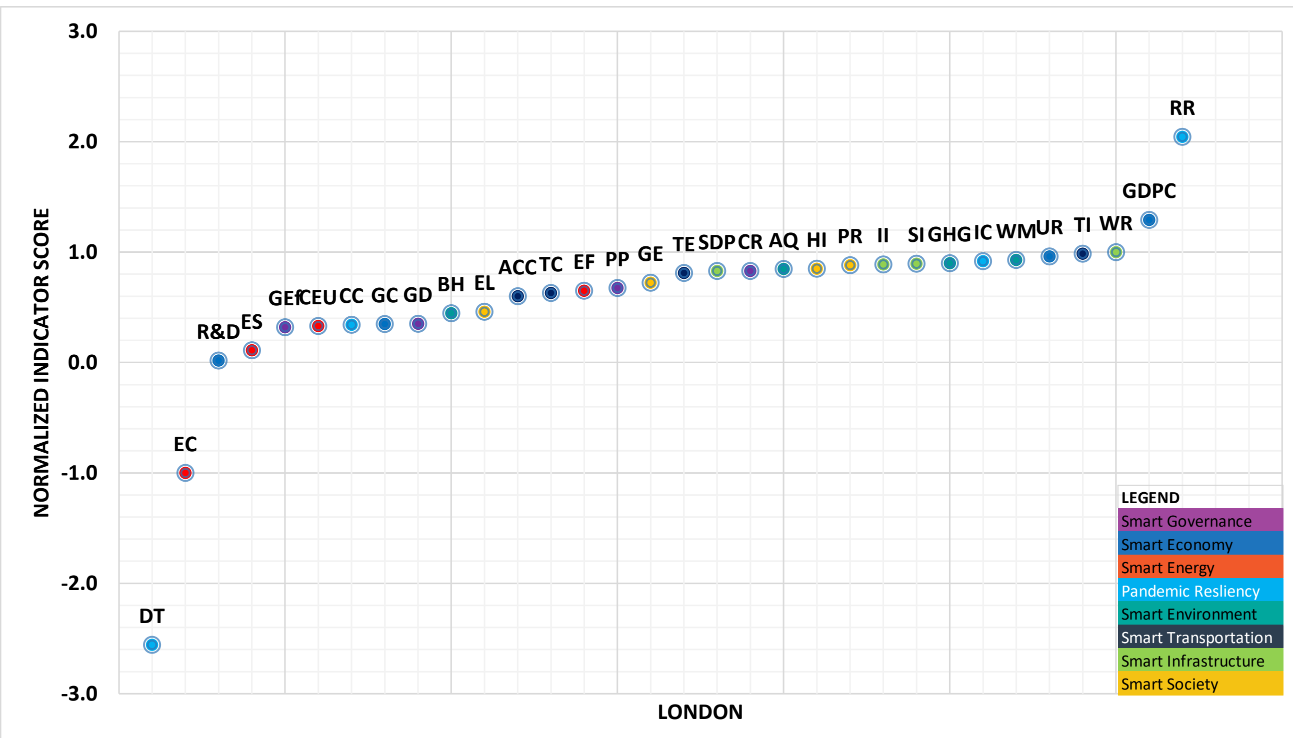


Figure 6.35 Normalized performance indicator scores for London

In summary, London's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.581, 0.604, 0.679, and 0.612, respectively.

Table 6.17 Highest and lowest performance indicators for London

Lowest Performance Indicators	Highest Performance Indicators
Pandemic Death Toll	Pandemic Response Rate
Energy Cost	Gross Domestic Product per Capita
R&D Expenditure in % of GDP	Water Resources
Energy Storage	Technology Integration
Government Effectiveness	Unemployment Rate

6.3.12 Montreal

Montreal scored the highest SCI among all cities under the Energy Focused scheme and the second highest under the Sustainability Triad Scheme. Furthermore, Montreal's strengths lie in its strong environment, society, economy, and infrastructure indexes scores. In fact, Montreal also features the highest energy index score among all cities in this study. The environment index score is 82%, which can be improved even further by attending to the GHG emission score of 65.7%, which is the only indicator score in this index that is less than 80%. Furthermore, the society index score is also 82%, illustrating relatively high educational levels, gender equality and healthcare index scores. The energy index score of 45% is attributed to the very conservative and affordable energy cost, clean energy utilization score of 65% and energy storage score of 9.1%, which are relatively high. The government effectiveness score of 86% is one of the highest. Furthermore, the GDP per capita is well above the average, with a favorable unemployment rate and a relatively generous expenditure on research and development of 2.2%. The infrastructure index score of 88% is attributed to considerable infrastructure investments and the adoption of sustainable infrastructure. While the pandemic death toll was above average, the response rate was also proportionate. Traffic efficiency and congestion scores can be improved to enhance the transportation index from its current score of 78%. Figure 6.36 shows the different performance indicators and their normalized scores for Montreal.

In summary, Montreal's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.216, 0.285, 0.380, and 0.286, respectively.

Table 6.18 Highest and lowest performance indicators for Montreal

Lowest Performance Indicators	Highest Performance Indicators
Pandemic Death Toll	Gross Domestic Product per Capita
R&D Expenditure in % of GDP	Pandemic Response Rate
Energy Storage	Water Resources
Government Effectiveness	Technology Integration
Gini Coefficient	Sustainable Infrastructure

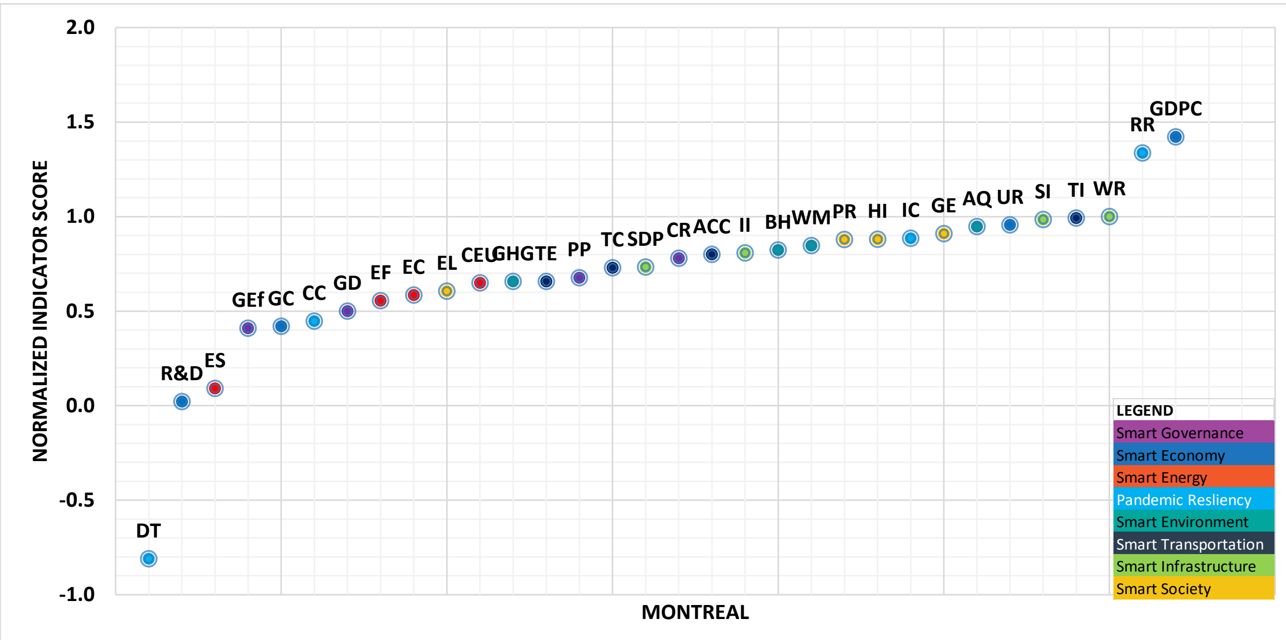


Figure 6.36 Normalized performance indicator scores for Montreal

6.3.13 Moscow

Moscow has a similar profile to that of Istanbul's. Its index performances are all around the average. The environment index score of 49% can be improved further by enhancing the exceptionally low waste management score of 3.2%. The society index score of 72% is like that of London's. The energy index score is 27%, with better than average energy cost of 7 cents per kWh and effective utilization of clean energy and energy storage solutions. The energy efficiency score of 38% reflective growth in this sector, and more is required to enhance the index performance. The governance index of 27% is disadvantageous and indicative of poorly performing indicators throughout the index. The economy index score is 58%, resulting from a near-average GDP per capita, yet low Gini coefficient. The infrastructure index is Moscow's strongest suit, with all indicators performing higher than 60%. However, its pandemic resiliency index is concerning with nearly five times more than the average confirmed cases. The infrastructure capacity, however, exceeds the average by more than double. The transport index features a remarkably high score for technology integration of 91%. However, further improvements can be achieved in the traffic congestion and efficiency domains. Figure 6.37 shows the different performance indicators and their normalized scores for Moscow.

Table 6.19 Highest and lowest performance indicators for Moscow

Lowest Performance Indicators	Highest Performance Indicators
Pandemic Confirmed Cases	Pandemic Infrastructure Capacity
Government Effectiveness	Pandemic Response Rate
R&D Expenditure in % of GDP	Water Resources
Waste Management	Unemployment Rate
Energy Storage	Technology Integration

In summary, Moscow's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.503, 0.487, 0.553, and 0.515, respectively.

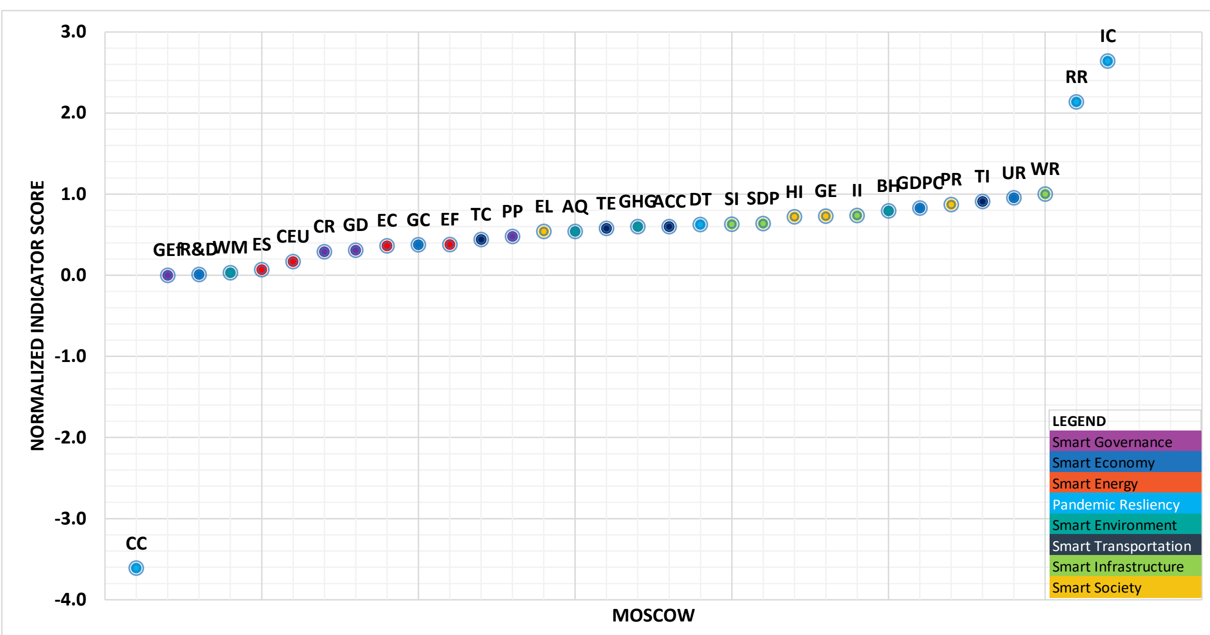


Figure 6.37 Normalized performance indicator scores for Moscow

6.3.14 New York

Excluding the outliers, New York has the highest economy and infrastructure index scores throughout all cities. The environment index score of 77% is attributed to effective waste management and controlled air quality. This score can be improved by enhancing the current score of biodiversity and habitat indicator of 58.2%. The society index score of 72% is considered mediocre for the profile of this city and can be improved by investing more in the educational level and healthcare index scores. New York's energy cost is above average, which brings it to a -13.6% indicator score. Energy storage score of 15% is one of the highest, however clean energy utilization score of 14.7% can be enhanced further. Public participation in New York is concerning and does not correlate with the city profile, with the score currently at 57%. Government digitalization score of 30% can be improved as well. The economy index is 97% and can be attributed directly to the GDP per capita, which is almost double the average. Similarly, the infrastructure index score of 90% is because of the highest infrastructure investment score of 96.7% and sustainable infrastructure score of 93.9%. The pandemic resiliency index is only 8% due to the significantly high number of confirmed cases, which is quadruple that of the average. The response rate is also proportional to the number of cases, and the death toll is less than that of the average. Finally, the transportation index can be enhanced by incorporating more accessibility and by resolving the traffic congestion issue. Technology integration score in this domain is 95.5%, which is reflective of the city's strong infrastructure. Figure 6.38 shows the different performance indicators and their normalized scores for New York.

Table 6.20 Highest and lowest performance indicators for New York

Lowest Performance Indicators	**Highest Performance Indicators**
Pandemic Confirmed Cases	Pandemic Response Rate
Energy Cost	Gross Domestic Product per Capita
R&D Expenditure in % of GDP	Water Resources
Clean Energy Utilization	Infrastructure Investment
Energy Storage	Unemployment Rate

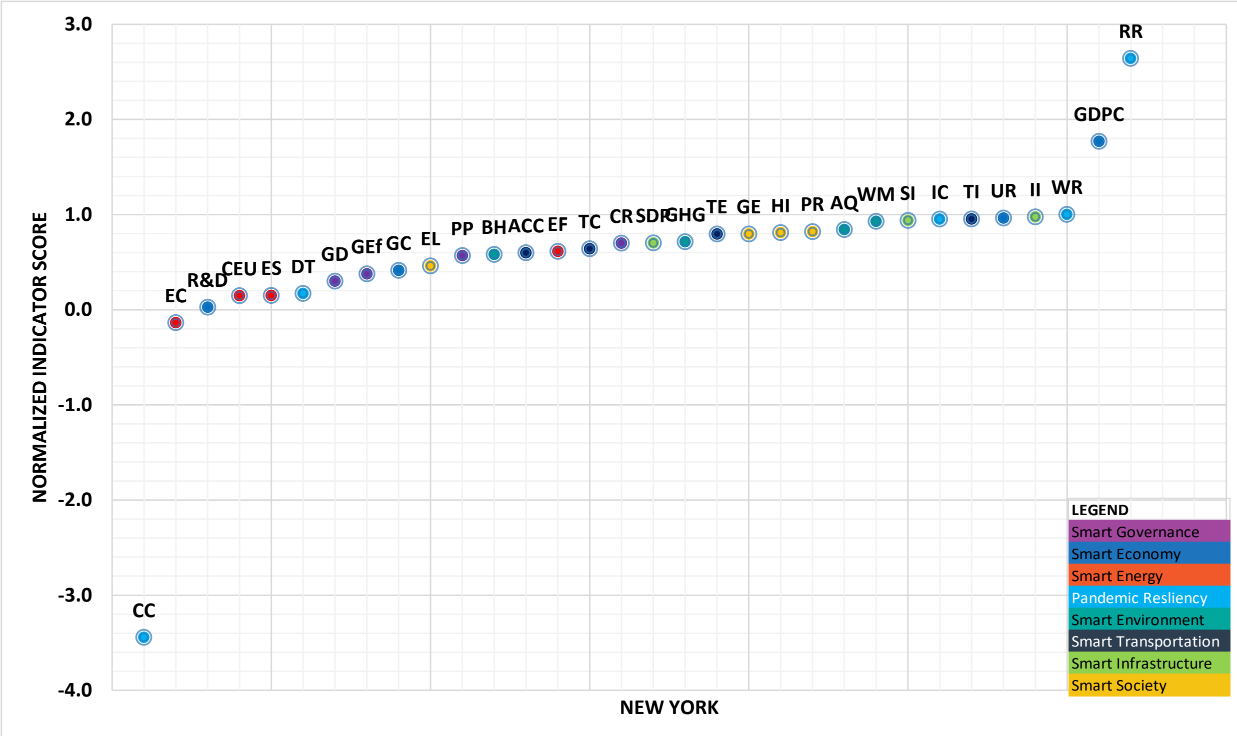


Figure 6.38 Normalized performance indicator scores for New York

In summary, New York's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.563, 0.620, 0.717, and 0.626, respectively.

6.3.15 Osaka

Osaka scored the highest SCI under the Equal Weighting scheme, second highest under the Pandemic Focused scheme, and fourth highest under the Energy Focused scheme. The only two indexes that are not over-performing are the governance and energy indexes. The environment index score is 75% and can be improved further by focusing on GHG emission control and nurturing of biodiversity and habitat indicators. The society index score is 78% results from most of the indicators scoring above 80%. While clean energy utilization and energy storage indicator scores are both 15%, which is competitive, the energy index score is depressed because of the expensive energy cost of 20 cents per kWh, which is almost double the average cost. Osaka's government effectiveness score is 84%, which is also incredibly competitive. However, public participation score of 53% and government digitalization score of 14% can be improved. The economy index is very well-established with above than average GDP per capita, coupled with a very favorable unemployment rate. The Gini coefficient score of 33% can be improved. Relatively generous expenditures towards research and development can also be observed. Infrastructure improvements through sustainable infrastructure and smart device penetration can increase the index score. Most notably, pandemic resiliency index score is 138%, which is the second highest among all cities in this model.

This is attributed to the resilient pandemic infrastructure capacity, which is quadruple that of the average. The response rate was low, along with the confirmed cases. Lastly, the transportation index score is the highest among all other cities, featuring advanced transport efficiency and technology integration. The score can be improved by enhancing the traffic congestion score of 59%. Figure 6.39 shows the different performance indicators and their normalized scores for Osaka.

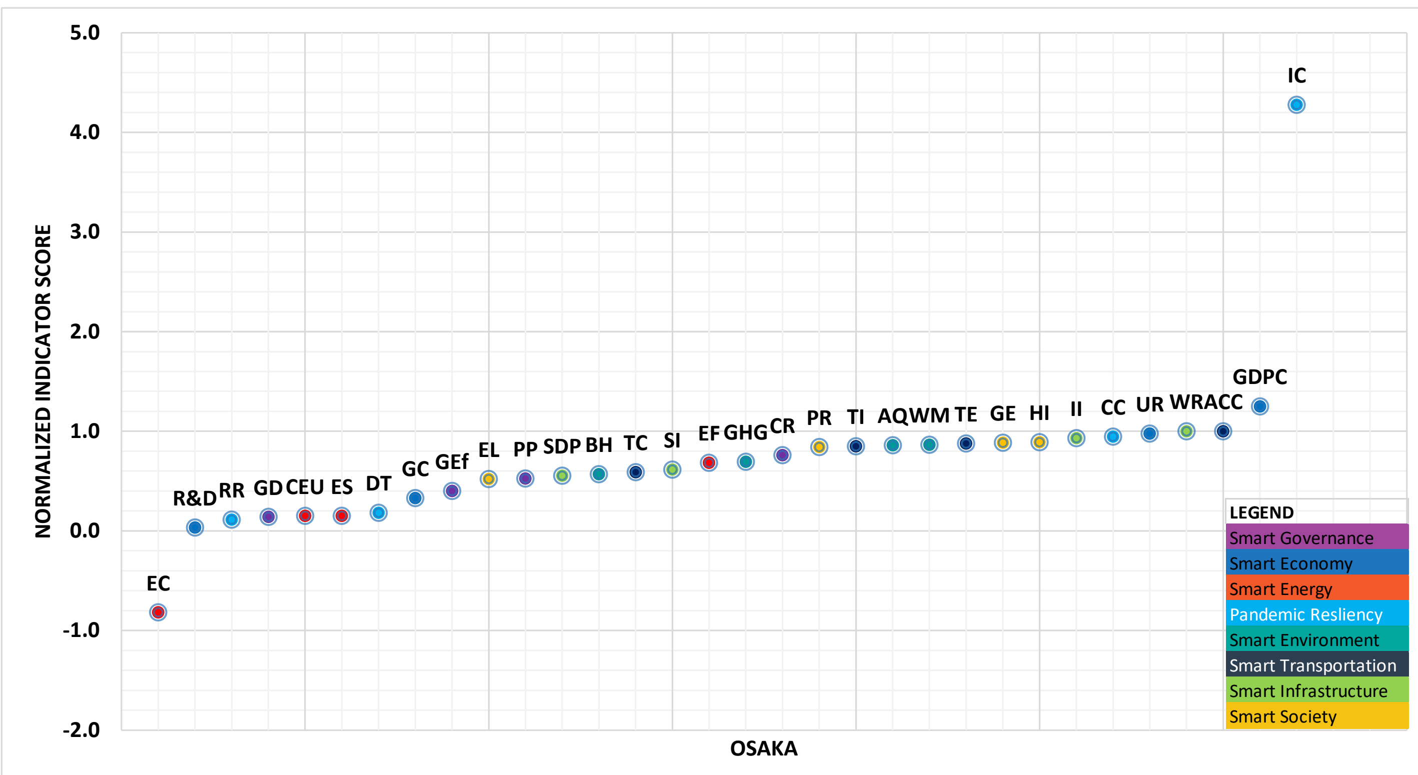


Figure 6.39 Normalized performance indicator scores for Osaka

In summary, Osaka's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.804, 0.682, 0.750, and 0.744, respectively.

Table 6.21 Highest and lowest performance indicators for Osaka

Lowest Performance Indicators	**Highest Performance Indicators**
Energy Cost	Pandemic Infrastructure Capacity
R&D Expenditure in % of GDP	Gross Domestic Product per Capita
Pandemic Response Rate	Transportation Accessibility
Government Digitalization	Water Resources
Clean Energy Utilization	Unemployment Rate

6.3.16 Oshawa

Oshawa's scored the third highest SCI under the Energy Focused scheme and the fourth highest under the Pandemic Focused scheme. All indexes are over performing, except for the economy index, which can be improved. The environment index score is 82%, which is the second highest among the cities in this model. The society index score of 81% is attributed to gender equality and strong healthcare index. However, improvements can be realized by enhancing the educational level score of 58%. The energy index score is favorable due to the intensive utilization of clean energy, scoring 65%, and having a lucrative energy cost of 9.1 cents per kWh, which is lower than the average. The government effectiveness score is 86%, yet opportunities to improve the governance index score lie in the public participation score of 68% and government digitalization score of 40%. The economy index suffers because of the GDP per capita score, which is lower than the average. The infrastructure score of 88% reflects the strong infrastructure investment and the adoption of sustainable infrastructure, scoring 98.5%. Limited number of confirmed cases exist in Oshawa; however, the death toll was above average, which made the score of this index lower. While transportation is accessible and technology is integrated well into the sector, transport efficiency can be improved along with traffic congestion. Figure 6.40 shows the different performance indicators and their normalized scores for Oshawa.

In summary, Oshawa's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.681, 0.668, 0.707, and 0.677, respectively.

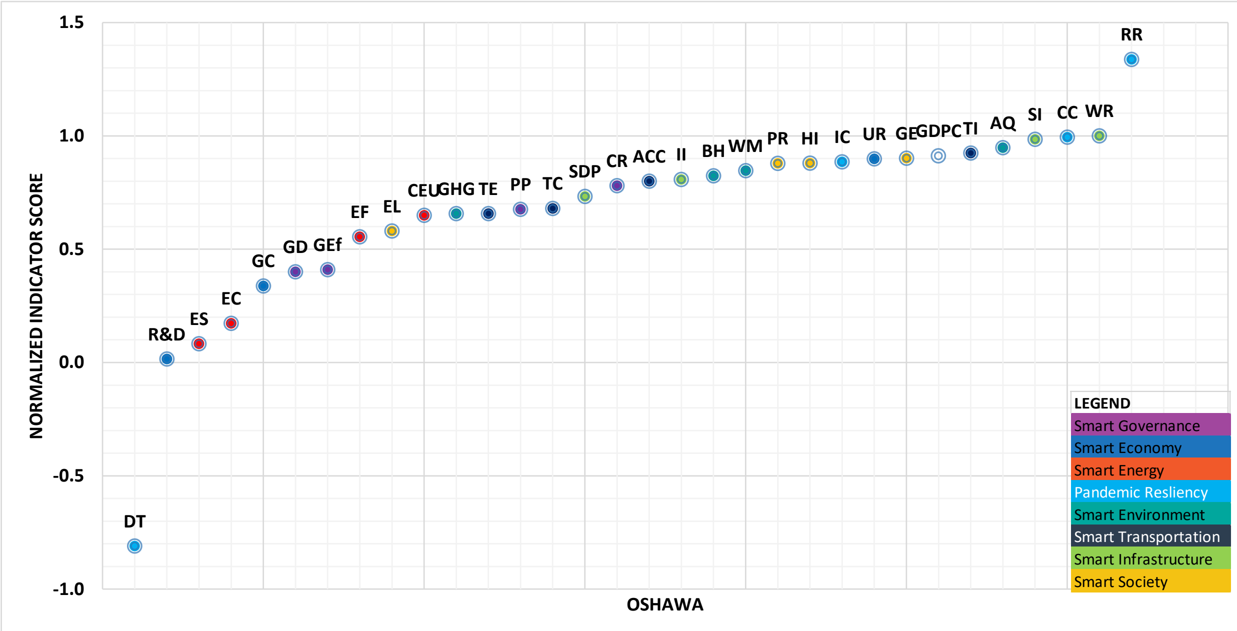


Figure 6.40 Normalized performance indicator scores for Oshawa

Table 6.22 Highest and lowest performance indicators for Oshawa

Lowest Performance Indicators	Highest Performance Indicators
Pandemic Death Toll	Pandemic Response Rate
R&D Expenditure in % of GDP	Water Resources
Energy Storage	Sustainable Infrastructure
Energy Cost	Air Quality
Gini Coefficient	Technology Integration

6.3.17 Sydney

Sydney scored the highest SCI under the Pandemic Focused scheme. Its performance is above average throughout all indexes, except for the energy, infrastructure, and transportation indexes. The environmental index score is 80% with all performance indicators scoring above 70%. The society index features a very high healthcare index and a decent gender equality score. However, the index score can be improved by enhancing the educational level score of 53%. The energy cost is above average, however, modest energy storage, clean energy utilization and energy efficiency is implemented. Therefore, better financial modeling for the utilities can enhance the index performance. Sydney features very active public participation, with a score of 92% and a government effectiveness score of 80%. However, the government digitalization score is only

19%. The GDP per capita is much above the average value. Special attention should be made to the smart device penetration as well as sustainable infrastructure investment in order to enhance the infrastructure index performance. The pandemic resiliency score is overwhelmingly high to 141% due to success at all fronts. Response rate was more than double that of the average, the death toll was limited, confirmed cases totaled 3,640, which is modest compared to the average, yet the infrastructure capacity was much higher than the average. The transportation index can be improved by incorporating more accessibility, addressing traffic congestion and efficiency. Figure 6.41 shows the different performance indicators and their normalized scores for Sydney.

Table 6.23 Highest and lowest performance indicators for Sydney

Lowest Performance Indicators	**Highest Performance Indicators**
Energy Cost	Pandemic Response Rate
R&D Expenditure in % of GDP	Gross Domestic Product per Capita
Energy Storage	Pandemic Infrastructure Capacity
Clean Energy Utilization	Water Resources
Government Digitalization	Air Quality

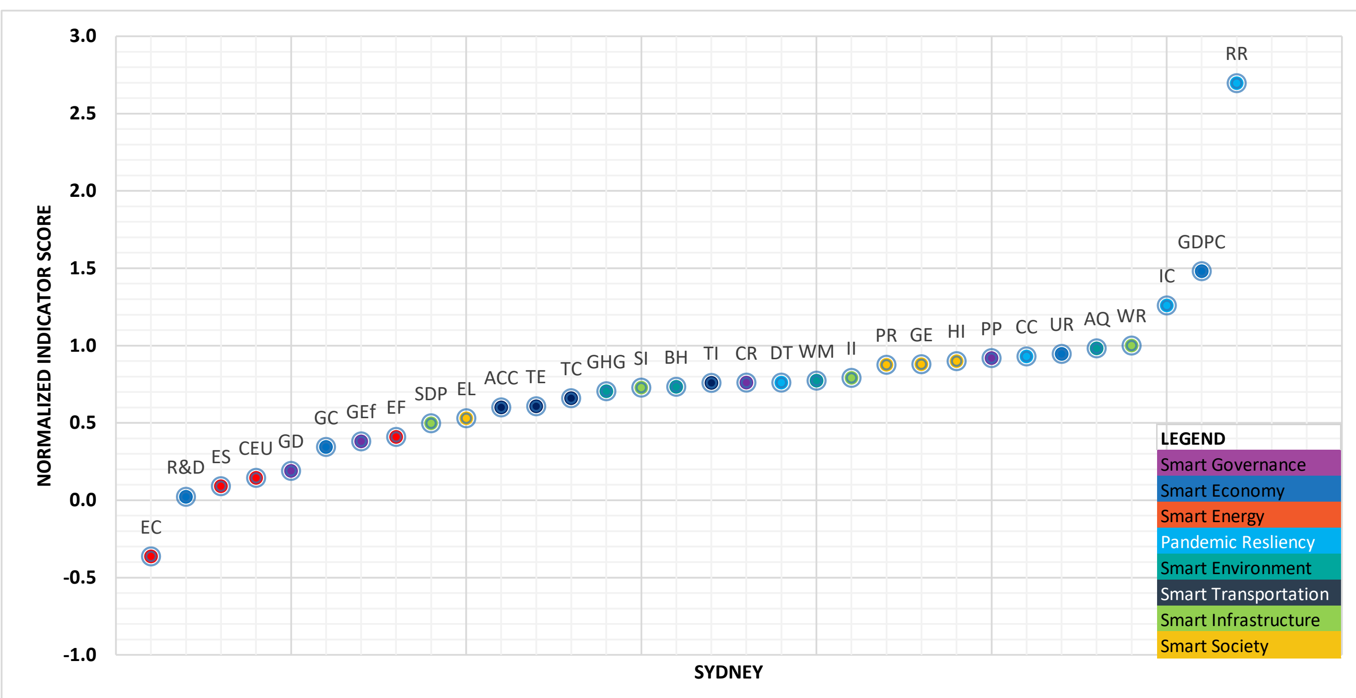


Figure 6.41 Normalized performance indicator scores for Sydney

In summary, Sydney's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.825, 0.659, 0.778, and 0.751, respectively.

6.3.18 Toronto

Toronto scored the highest SCI based on the Sustainability Triad scheme, second highest based on the Equal Weighting scheme as well as the Energy Focused scheme. It scored the fourth highest based on the Pandemic Focused scheme. Besides Montreal, Toronto is the only other city that has over-performed in all indexes, except for one index, which is the pandemic resiliency index. The environmental index score is high but can be enhanced more by improving the only indicator below the 80% mark, which is the GHG emissions. The Society index is also very high because of good indicator performance throughout all areas, including the educational level. Since the energy is managed provincially, the energy cost is the same as Oshawa's. Toronto's deployment of energy storage however is only 8.3%, which can be improved. While the government effectiveness is high, the government digitalization and public participation remain below expectation for a city of this profile. The economy index score is 90%, primarily due to a much above average GDP per capita. Infrastructure investment and sustainable infrastructure both boosted the infrastructure index score. While Toronto had a lower than average number of confirmed pandemic cases, its death toll was much higher than that of the average, bringing its index score to 53%. Finally, the transportation index score is 75% and special attention must be focused on traffic congestion and transport efficiency. Figure 6.42 shows the different performance indicators and their normalized scores for Toronto.

Table 6.24 Highest and lowest performance indicators for Toronto

Lowest Performance Indicators	**Highest Performance Indicators**
Pandemic Death Toll	Gross Domestic Product per Capita
R&D Expenditure in % of GDP	Pandemic Response Rate
Energy Storage	Water Resources
Energy Cost	Sustainable Infrastructure
Gini Coefficient	Unemployment Rate

In summary, Toronto's SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.692, 0.686, 0.773, and 0.711, respectively.

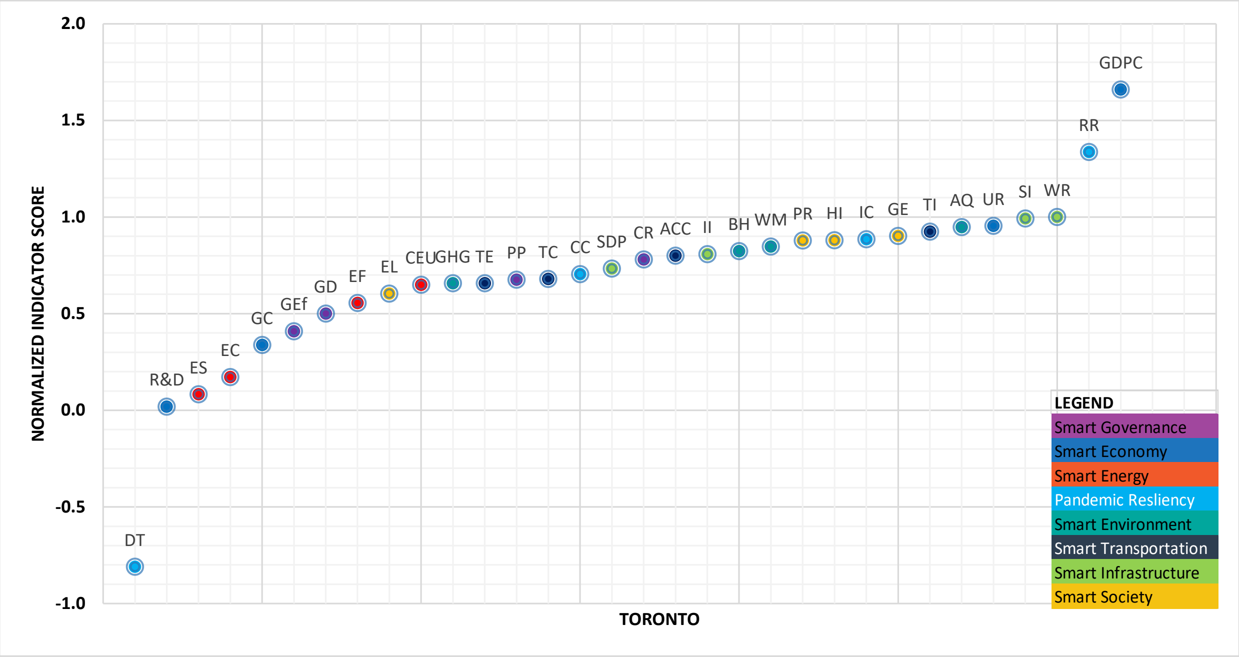


Figure 6.42 Normalized performance indicator scores for Toronto

6.3.19 Tunisia

Tunisia belongs to the third cluster of cities and follows a similar profile to that of Amman's. Numerous indexes need attention and improvements. The environment index specifically can be improved by enhancing the waste management and air quality scores of 39.6% and 48.7% respectively. The society index has the second lowest score due to deficient performance on the healthcare index as well as the gender equality score. The energy cost is lucrative, however the adoption of energy storage as well as clean energy is exceptionally low at scores of 3% each. Government effectiveness score is extremely low, less than 1%, while government digitalization is only 16%. The economy index score can also be improved by nurturing the GDP per capita to the average value. Infrastructure-wise, water resources score is 73%, which is considerably low, given the other cities in this study. Pandemic-wise, only 249 confirmed cases are reported in Tunisia. Lastly, accessibility, technology integration and efficiency can be enhanced to improve the transportation index score. Figure 6.43 shows the different performance indicators and their normalized scores for Tunisia.

Table 6.25 Highest and lowest performance indicators for Tunisia

Lowest Performance Indicators	Highest Performance Indicators
R&D Expenditure in % of GDP	Pandemic Confirmed Cases
Government Effectiveness	Poverty Rate
Clean Energy Utilization	Corruption Rate
Energy Storage	Unemployment Rate
Pandemic Response Rate	Pandemic Infrastructure Capacity

In summary, Tunisia SCI score based on the Pandemic Focused, Energy Focused, Sustainability Triad and Equal Weighting schemes are 0.448, 0.393, 0.427, and 0.417, respectively.

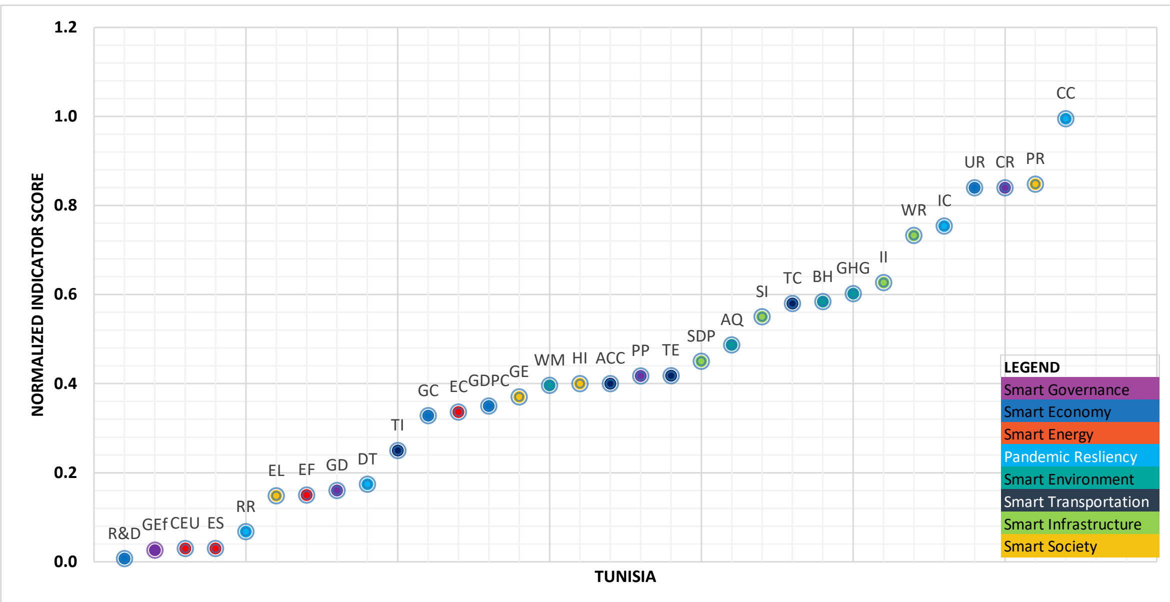


Figure 6.43 Normalized performance indicator scores for Tunisia

6.3.20 Vancouver

Vancouver scored the second highest based on the Sustainability Triad scheme, fourth highest based on the Equal Weighting scheme and fifth highest based on the Energy Focused scheme. Like other Canadian cities in this study, Vancouver over-performs throughout all indexes, with the exception to the pandemic resiliency and transportation indexes. The environment index can be improved by enhancing the GHG emission control. The society index of 81% is considered high, featuring high gender equality and effective healthcare index. Vancouver's energy cost is higher than the average, yet it is compensated by high clean energy utilization score of 65% and energy storage score of 10.5%. Government digitalization score of 50% is considered competitive but can be improved more. Public participations core of 68% is poor for a city of this profile. The economy index is flourishing with the GDP per capita higher than average, yet the Gini coefficient score of 43% can be improved further. Sustainable infrastructure and smart device penetration can be used for improving the infrastructure index score. While the confirmed number of pandemic cases is limited, the death toll was above the average. Furthermore, the infrastructure capacity was below the average. Lastly, the transportation index score is 66% and improvements can be achieved by enhancing all areas of the performance indicators. Figure 6.44 shows the different performance indicators and their normalized scores for Vancouver.

Table 6.26 Highest and lowest performance indicators for Vancouver

Lowest Performance Indicators	**Highest Performance Indicators**
Pandemic Death Toll	Gross Domestic Product per Capita
Energy Cost	Pandemic Response Rate
R&D Expenditure in % of GDP	Water Resources
Energy Storage	Unemployment Rate
Government Effectiveness	Air Quality

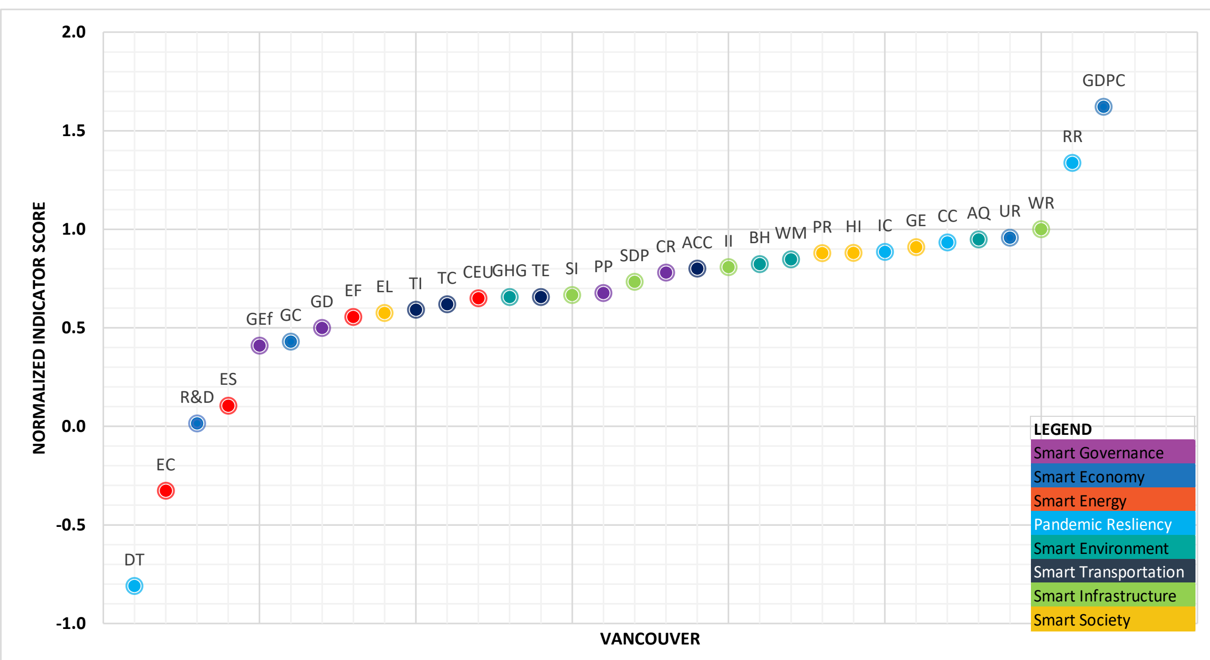


Figure 6.44 Normalized performance indicator scores for Vancouver

6.4 Indexes Results considering Schemes

The Energy Focused Scheme and the Sustainability Triad Scheme both result in the same environment index for all cities. In fact, these two schemes highlight higher values for the environment index than the Equal Weighting and Pandemic Focused Schemes. Hämeenlinna, followed by Oshawa and Toronto are the cities with the highest environment index as illustrated in Figure 6.45.

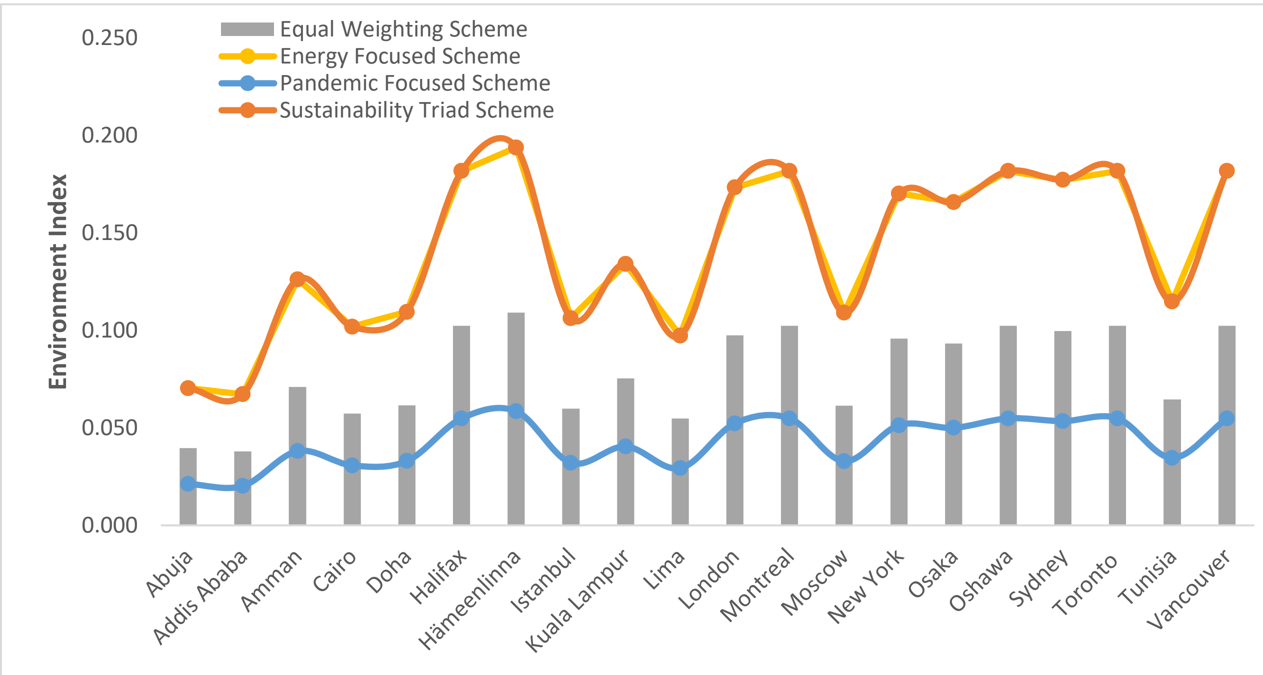


Figure 6.45 Results of the environment index based on the different weighting schemes

The Equal Weighting Scheme represent median values for this index for all cities, while the Pandemic Focused Scheme results in the lowest values. This is because the Pandemic Focused Scheme deprioritized the environment index by giving it a low and insignificant weight. Addis Ababa, followed by Abuja and Lima have the lowest environment index, despite the weighting schemes. The environment index results among all cities increase by 86.5% from the Pandemic Focused Scheme to the Equal Weighting Scheme, then increases by 76.6% to the Sustainability Triad Scheme. The economy index is only given significance in the Sustainability Triad Scheme as illustrated in Figure 6.46. The outlier peak represents Doha's economy index value, which is significantly higher due to the higher GDP per capita. New York, Vancouver, and Toronto follow to score the highest economy index. On the other hand, Addis Ababa, Amman, and Abuja have the lowest economy index results. The incremental increase between the schemes, from the schemes resulting in the lowest values to the Equal Weighting Scheme and then to the scheme that yields in the highest results is like that of the environment index. In specific, 86.5% and 77% increase in results are redundant in this index as well. Figure 6.47 shows the society index value distribution among the cities based on various schemes. While Montreal, Toronto and Halifax have the highest society index values, Abuja, Addis Ababa, and Tunisia have the lowest consecutively.

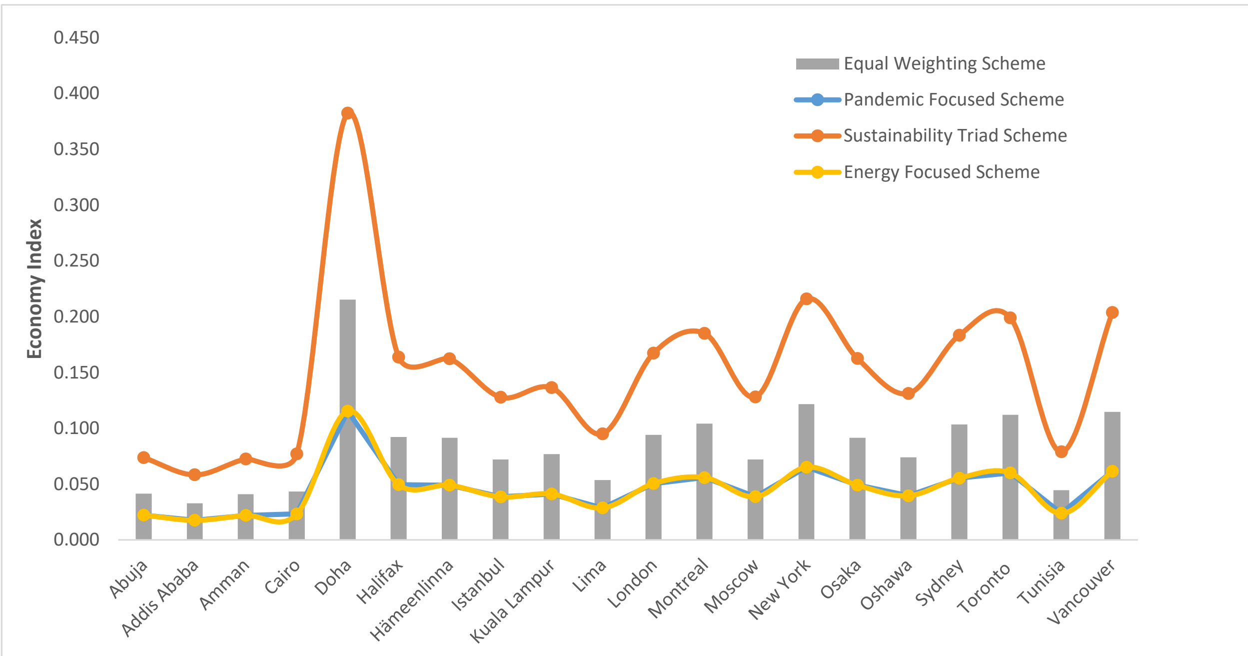


Figure 6.46 Results of the economy index based on the different weighting schemes

The governance index results vary among cities as Vancouver, Toronto and Montreal have the highest index results accordingly, while Cairo, Abuja and Amman have the lowest results. Istanbul and New York have the same index value, while Tunisia, Addis Ababa and Osaka have similar index profile. London, Kuala Lampur and Hämeenlinna have a similar index profile with better performance. Figure 4.48 shows the governance index results based on the four different schemes for all cities in the study. The energy index is the lowest performing index among all other indexes, reflecting the dire need in improving this sector in order to achieve smarter cities across the world. Montreal has the highest energy index value, followed by Toronto and Oshawa. On the other hand, Lima, Abuja and Amman have the lowest index values. As illustrated before, the Equal Weighting Scheme represents the median values with respect to the other schemes. Figure 6.49 shows the energy index results. London, New York and some Canadian cities such as Montreal and Oshawa have the highest infrastructure index values. On the other hand, Abuja, Addis Ababa, and Lima have the lowest index results for this sector.

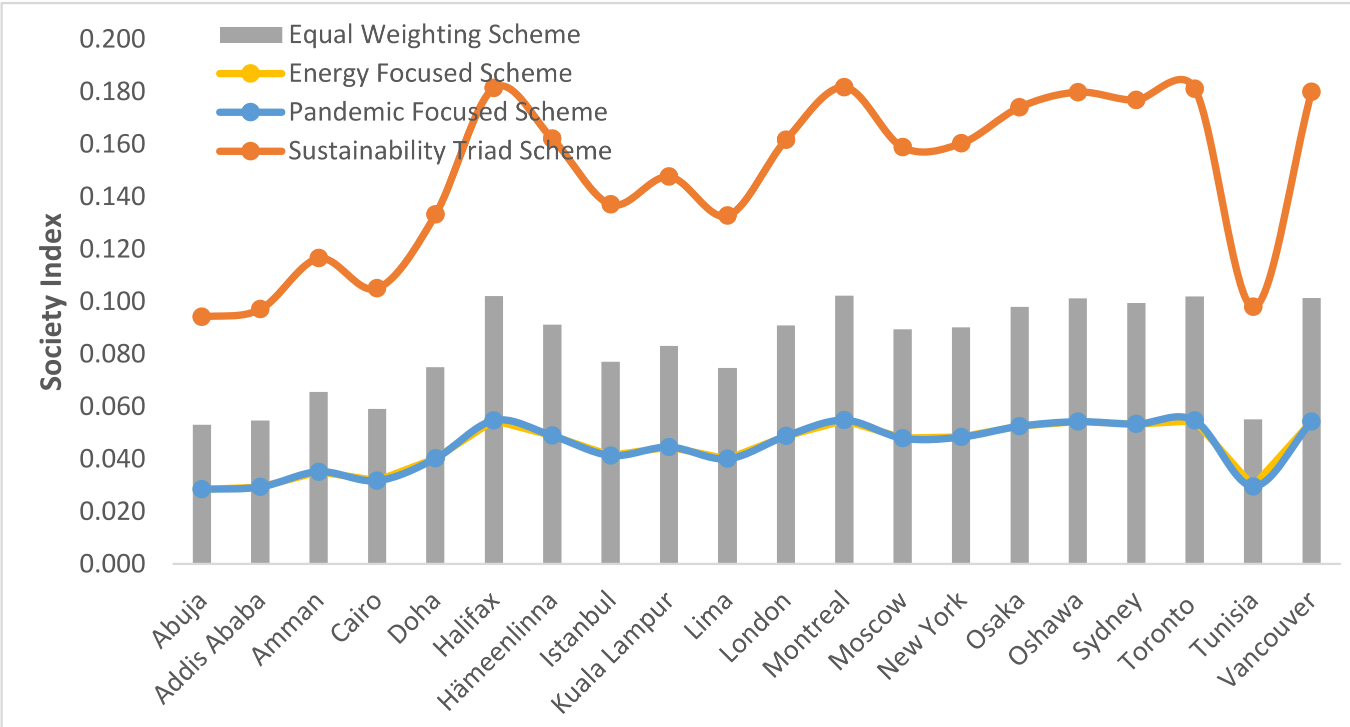


Figure 6.47 Results of the society index based on the different weighting schemes

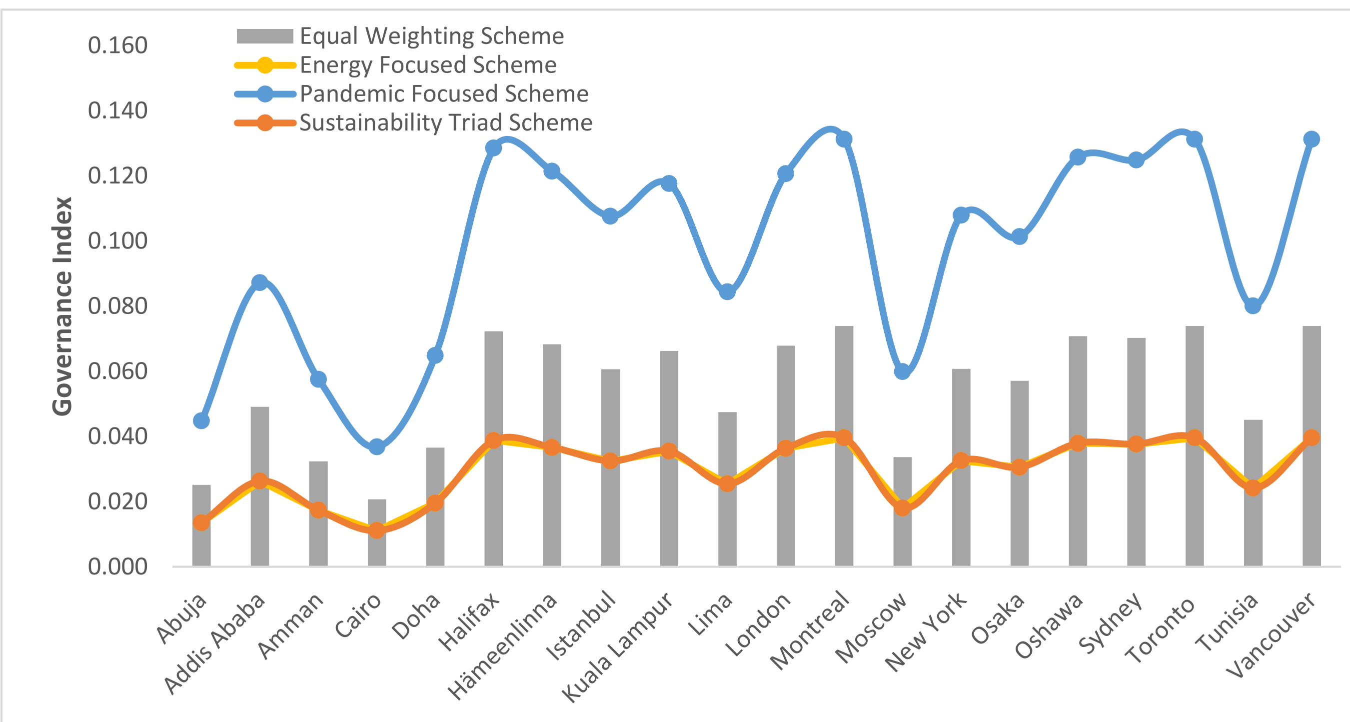


Figure 6.48 Results of the governance index based on the different weighting schemes

Hämeenlinna, Istanbul, Kuala Lampur, Sydney, and Moscow all have a similar index profile for infrastructure. Similarly, Amman, Cairo, Tunisia, and Doha have a similar profile. Vancouver and Halifax both have the same result of 0.1 as opposed to Montreal, Toronto, and Oshawa, which have a result of 0.11.

The Energy Focused Scheme and the Sustainability Triad Scheme both result in identical infrastructure index for the cities, while the Pandemic Focused Scheme results in the highest results for this index among all other schemes. Figure 6.50 shows the results of the infrastructure index while Figure 6.51 shows the results of the transportation index.

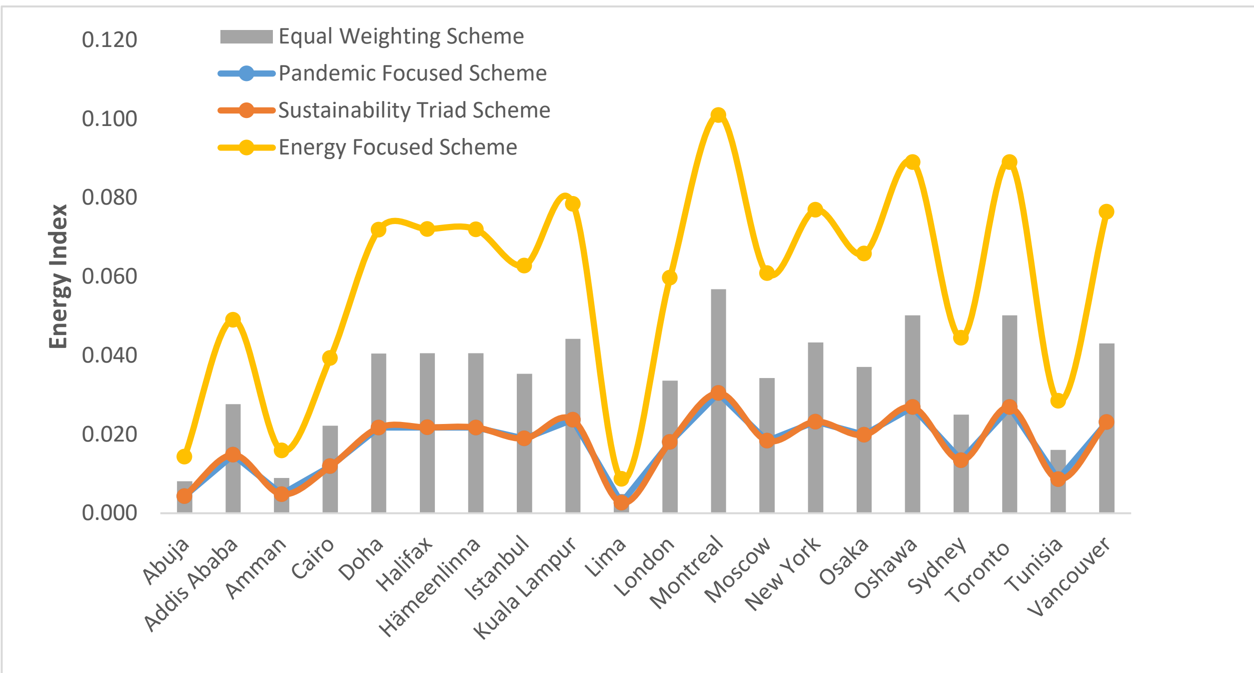


Figure 6.49 Results of the energy index based on the different weighting schemes

Montreal, Osaka and Toronto have the highest transportation index results. On the other hand, Lima, Abuja and Addis Ababa have the lowest results of 0.046. Hämeenlinna, Vancouver, Sydney, and Kuala Lampur all have the same index value of 0.082. Figure 6.52 shows the pandemic resiliency index results.

As illustrated, some cities have performed tremendously in this index scoring, while some performed negatively. In specific, Sydney, Osaka and Hämeenlinna have the highest pandemic resiliency index results, whereas Lima has a negative index value, followed by low performing Abuja and Addis Ababa.

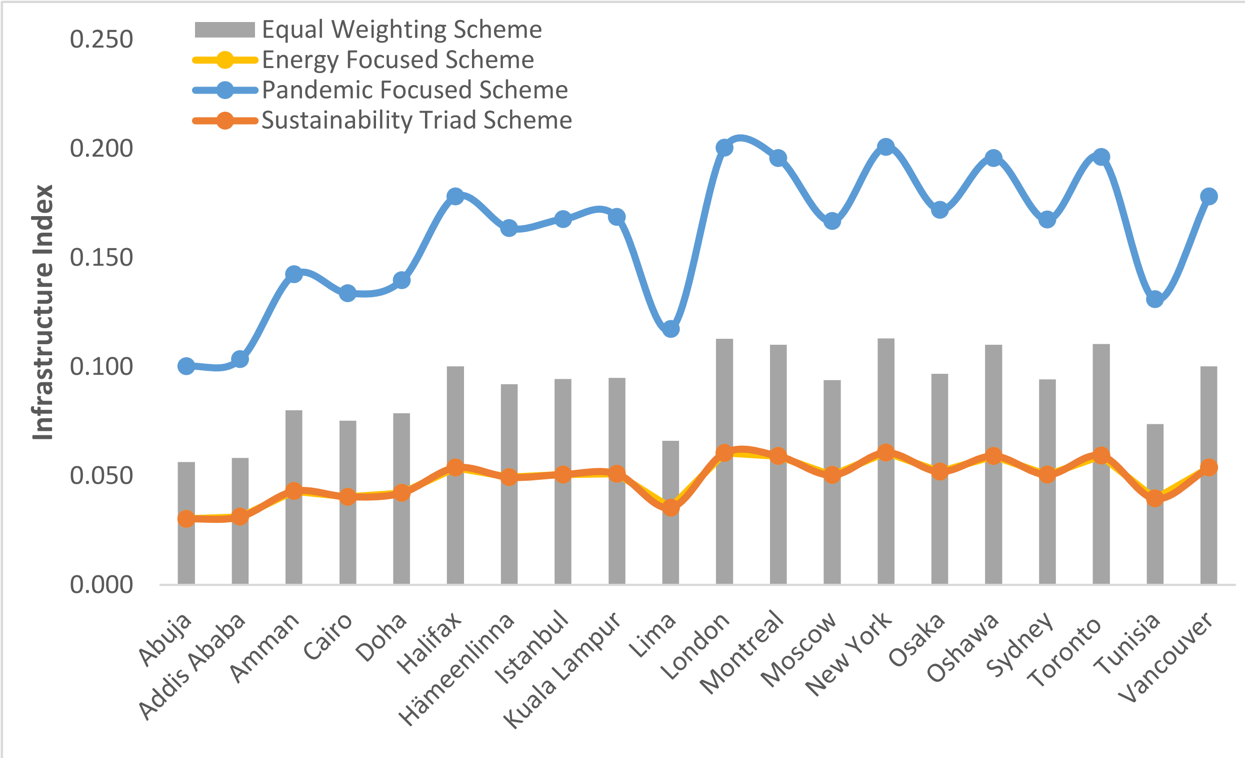


Figure 6.50 Results of the infrastructure index based on the different weighting schemes

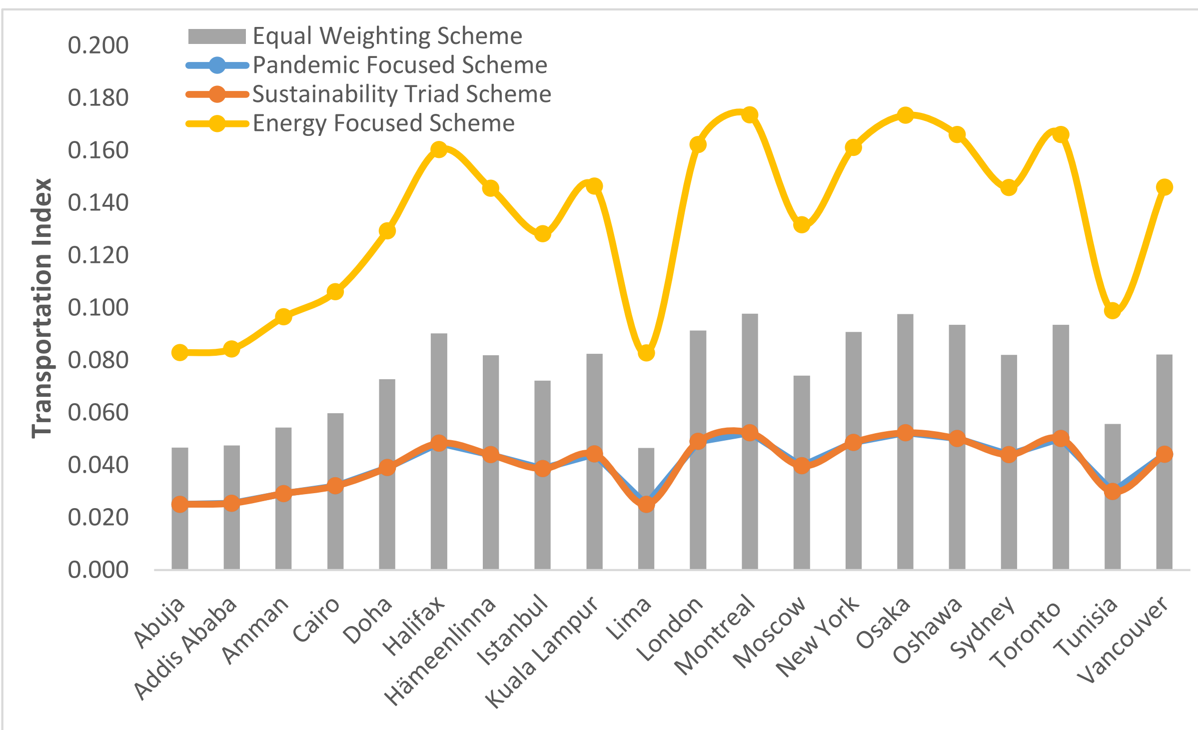


Figure 6.51 Results of the transportation index based on the different weighting schemes

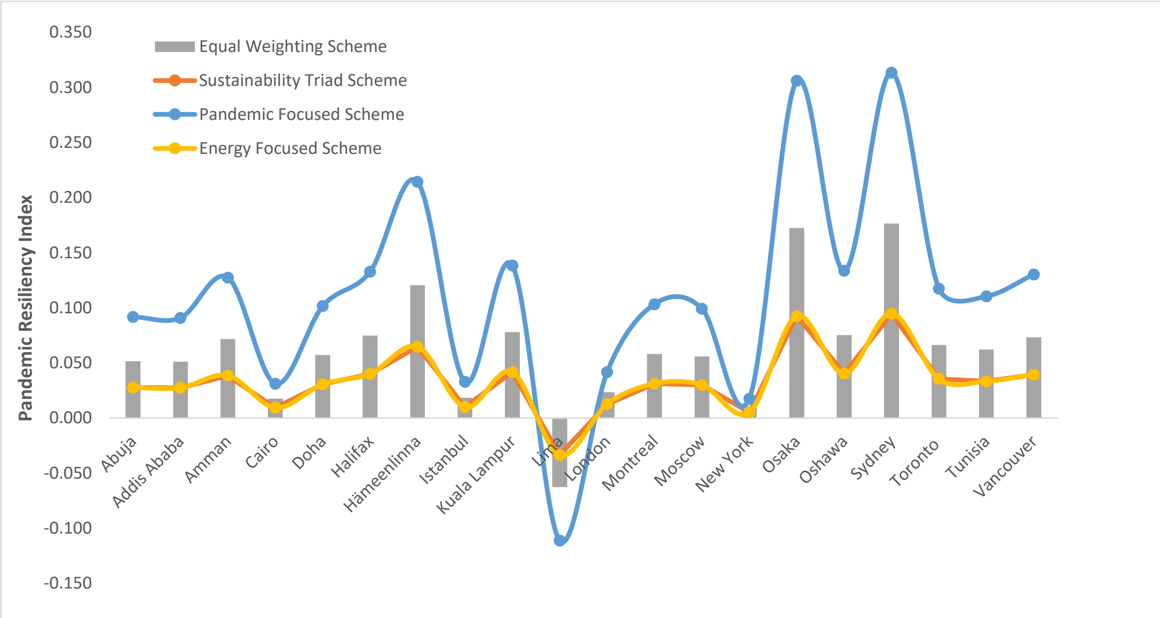


Figure 6.52 Results of the pandemic resiliency index based on different weighting schemes

6.5 Parametric Study Results

The relationship between the government effectiveness ratio and the GDP per capita has been previously studied in the literature. Based on the model in this thesis, a clear exponential relationship is observed between the two indicators with a p value of less than 0.05, suggesting a strong causative correlation between the two indicators. Furthermore, Figure 6.53 shows that cities with higher government effectiveness ratios tend to have higher GDP per capita. These findings are in line with (Emara & Chiu, 2016), who developed a composite governance index and concluded that increases by one unit of the governance index results in 2% increase to the GDP per capita. Furthermore, (Alam, Erick Kitenge, & Bizuayehu Bedane, 2017) also reported significant positive effect of the government effectiveness on economic growth, after analyzing 81 countries using the System Generalized Method of Moments. Lastly and most recently, (Lee & Whitford, 2020) also show a linear positive relationship between perceived government effectiveness and the GDP. In light of COVID-19, digitalization and online services are booming, including government services. The impact of government digitalization on the smart governance index ratio show another exponential and a strong positive trend. This suggests that cities with higher percentages of digital services result in smarter governance. Figure 6.54 illustrates this relationship in detail.

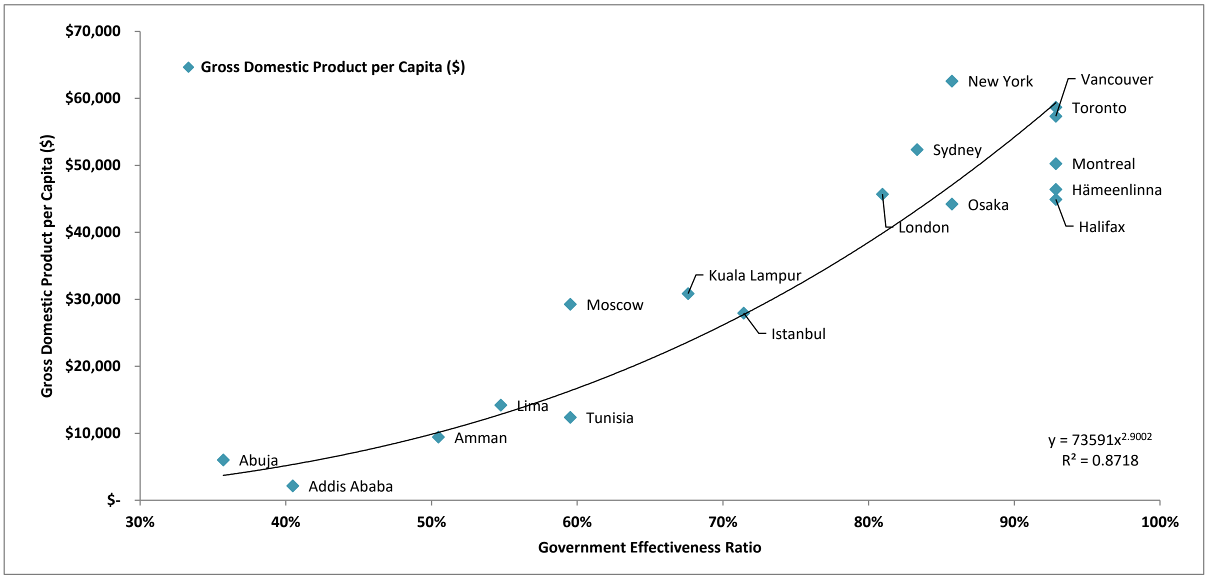


Figure 6.53 Impact of governance on the GDP per capita

Public participation is another positively correlated indicator to smart governance. Figure 6.55 shows a linear trend among the cities in this model between the rate of public participation (% voting) and the score of the smart governance index. What is unique with this indicator is namely Lima and Addis Ababa, which belong to lower-tier smart cities, based on the overall results, yet their public participation rates are extremely higher than their average. This suggests that these cities yearn for smarter governance, despite their local challenges and conditions.

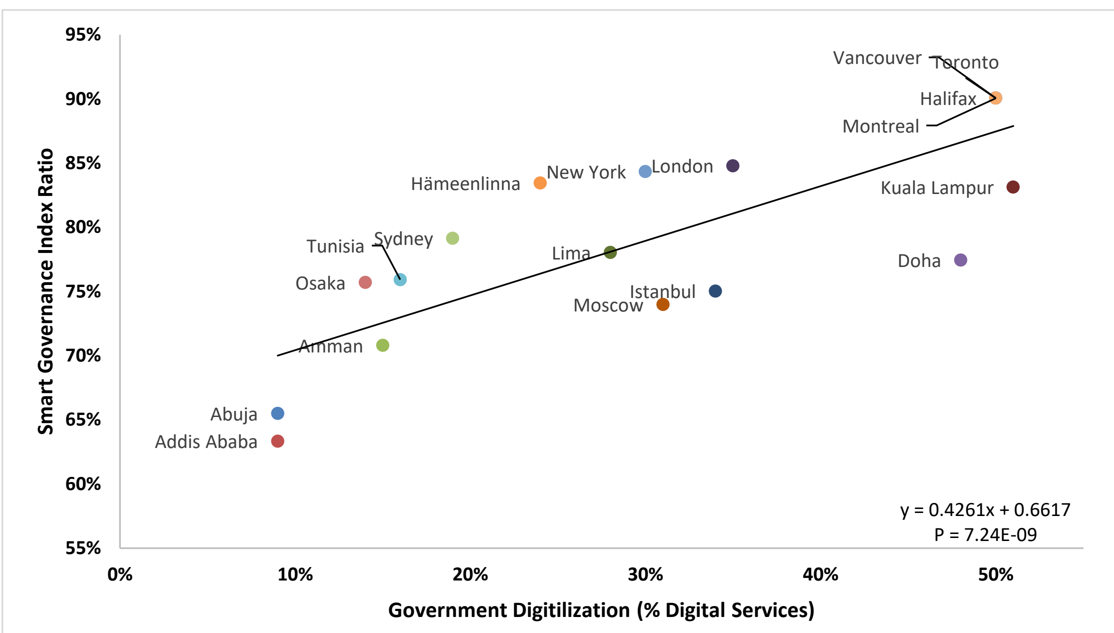


Figure 6.54 Relationship between government digitalization and smart governance index

Does smart governance, lead to smart societies? This is an interesting phenomenon, because managing the affairs of societies in an organized and honest manner, should yield in growing societies, yet they are distinct in their own scope. Based on Figure 6.56, there is a mild positive relationship between smart governance and smart society indexes. In fact, the R value of 0.7 highlights that smart governance does positively correlate and lead to smarter societies. This is understandable as smart governance would ensure higher educational levels among citizens, better healthcare index, lower poverty rates and more competitive and fair gender equality.

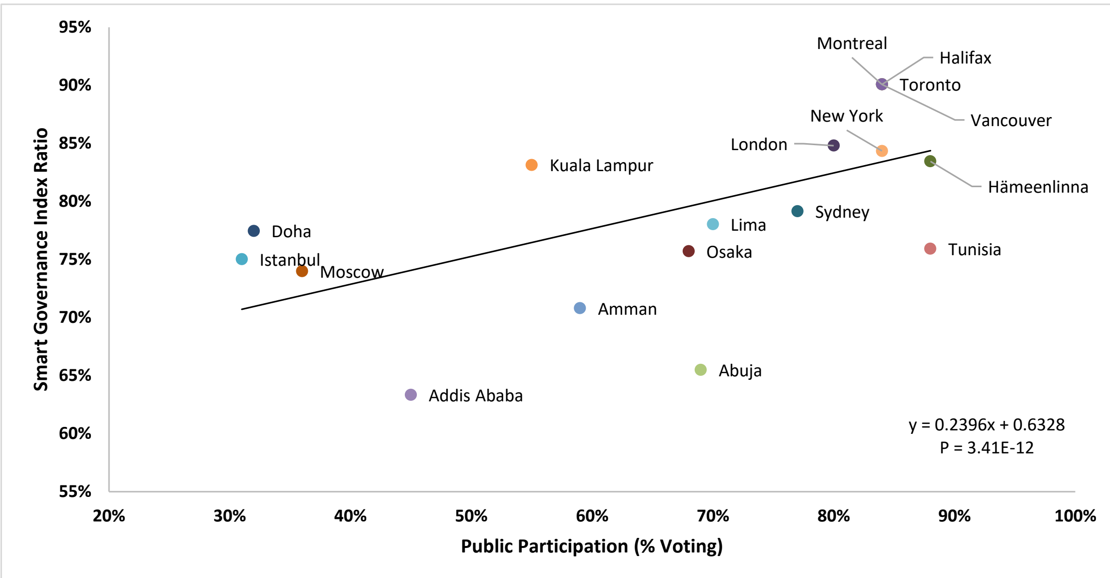


Figure 6.55 Impact of public participation on the smart governance index ratio

Similarly, does smart governance result in smarter economy? In theory, smarter governance ensures economic growth and prosperity. Lower corruption rates and higher government effectiveness ratios both contribute to enhancing the economic index by lowering unemployment rates and growing the GDP per capita as illustrated earlier. Figure 6.57 highlights the relationship between both indexes. Since the GDP per capita is considered one of the main and important indicators that enhance the smart economy index, a parametric assessment is conducted to show how enhancements to the GDP per capita impact the overall smart economy index. Figure 6.57 shows the predicted smart economy indexes after 25% and 50% enhancement to the GDP per capita from the current values. It is important to note that for this model, considerable enhancements to the GDP per capita results in very modest increases in the overall smart economy index. This could be due to the impact of the other economic indicators such as percentage of expenditure on research and development.

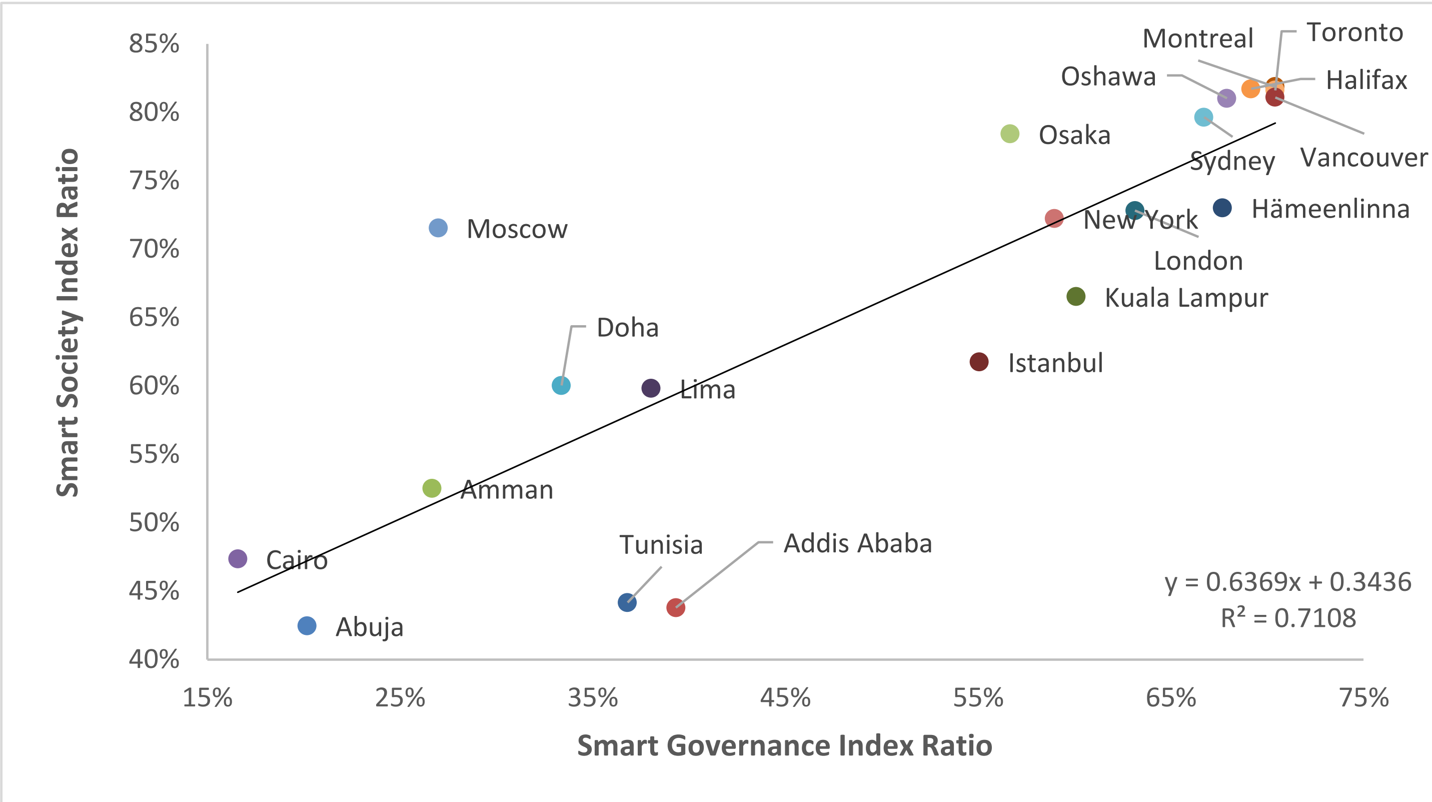


Figure 6.56 Relationship between governance and society indexes

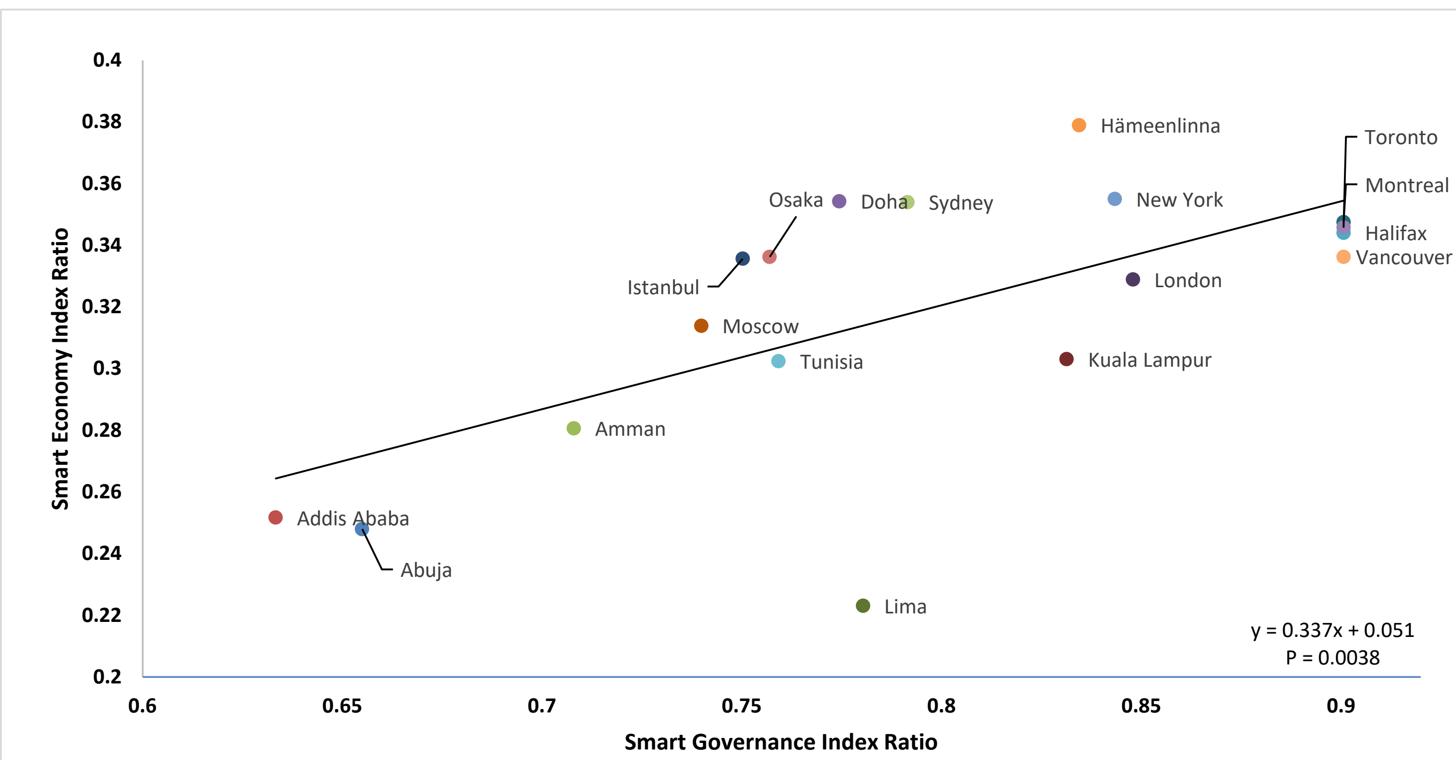


Figure 6.57 Relationship between governance and economy indexes

Sustainability traditionally revolves around the social, economic, and environmental perspectives. Does a smart environment result in a smart economy? This is a critical question for both governments and societies alike. After all, economic growth is most sensible and has direct impacts on those stakeholders, whereas the environmental aspects are more long term and not physically experienced. Based on this model, environment has an exponential positive relationship with economy. In other words, increases in the smart environment index ratio, results in exponential increases to the smart economy index with p value lower than 0.05, indicating significance between the two indexes as highlighted in Figure 6.58. This is in line with (Hans Bruyninckx, 2019) of the European Environment Agency who reported that our consumption and production systems are unsustainable. Similarly, (Tejvan Pettinger, 2019) suggested that while environmental impacts of economic growth may include pollution, global warming and disruption of environmental habitats, some forms of economic growth can mitigate that such as clean energy technology and renewables. Similarly, the energy index is another important indicator to the economy index. The impact of investing in enhancing the energy index can have lucrative economic returns as illustrated in Figure 6.59.

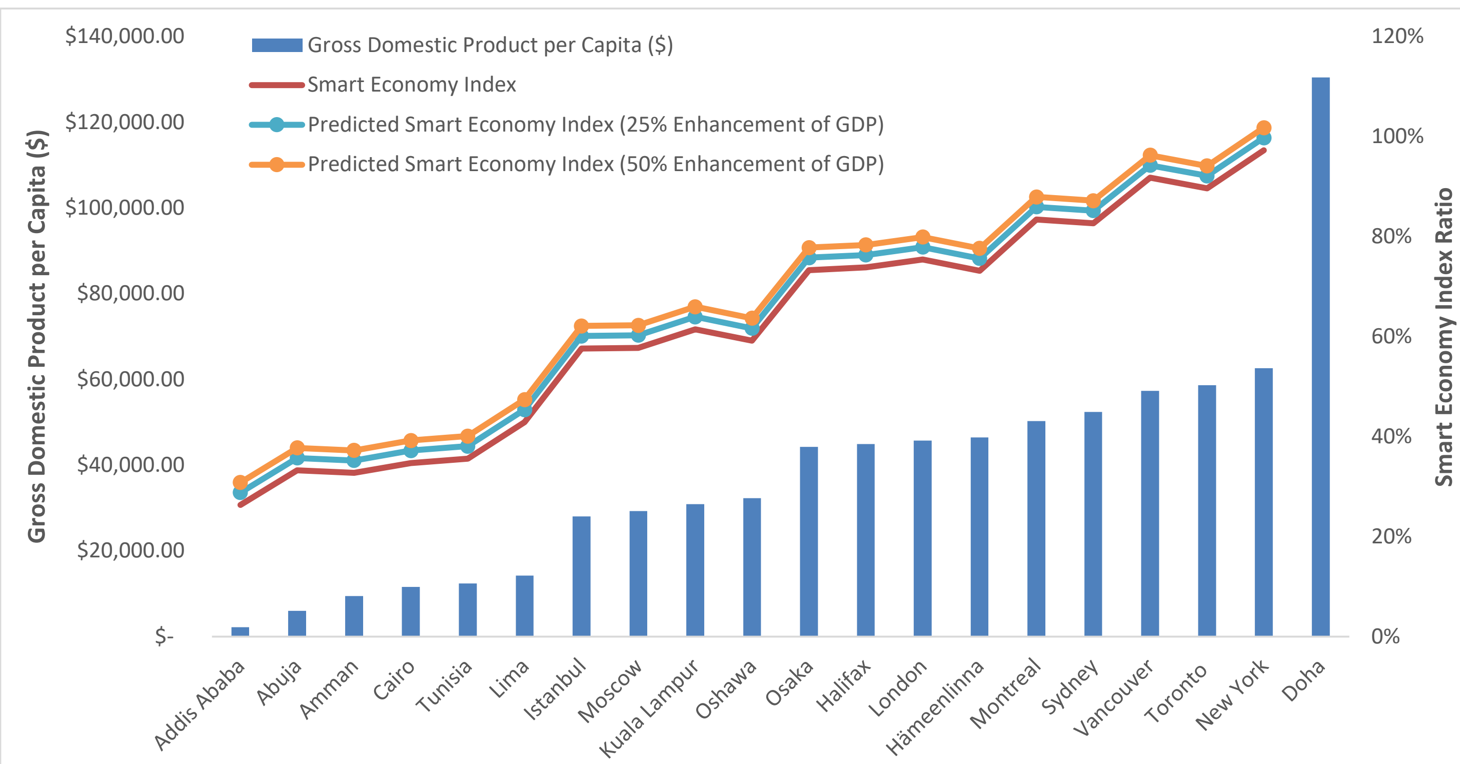


Figure 6.58 Impact of GDP per capita on the overall economic index

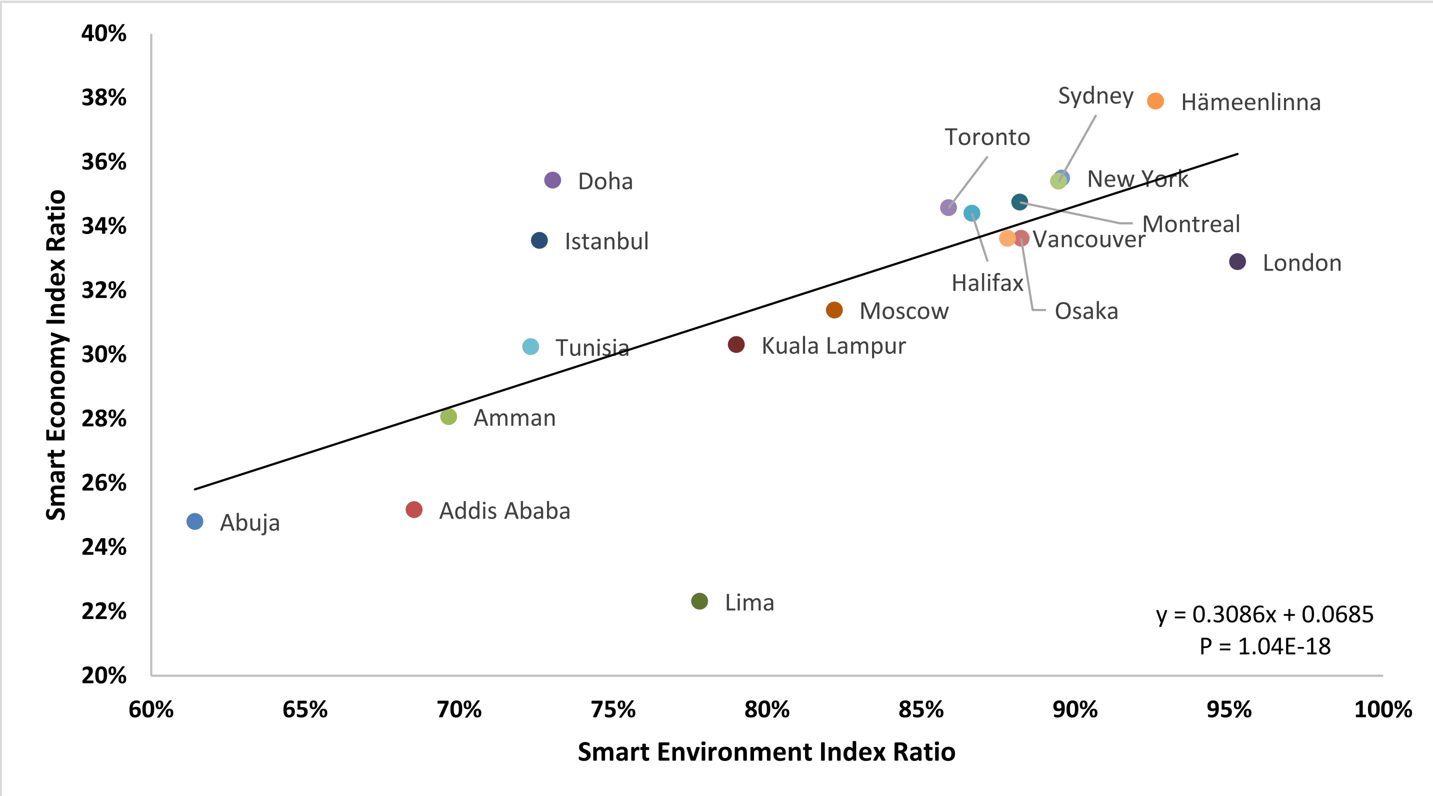


Figure 6.59 Relationship between environment and economy indexes

The relationship between the two indexes as enhancement takes place is extraordinarily strong, illustrated by a significant R value of 0.96. The figure illustrates the impact of enhancing the score of the smart energy index for each respective city by 25%, 50% and 75% and the resulting economy index increase from that. Similarly, the correlation between the society index and economy index shows significant positive exponential relationship. This means that enhancing the society index will result in exponential economic growth for the cities. The trend is supported with a relatively strong R value of 0.8. This trend excluded Doha from taking part in this relationship due to its outlier smart economy index ratio of 172%. However, the phenomenon is applicable to the remainder of the cities across the world, with higher populations and relatively corresponding economic growth. Figure 6.60 illustrates this relationship in detail. An exponential relationship exists between the energy environment indexes. This is also proven as smarter energy index performance by utilizing more clean energy, enhancing energy storage and improving energy efficiency all contribute to lower GHG emissions, better air quality and waste management, consequently preserving of habitat. Figure 6.61 illustrates the relationship between these two indexes.

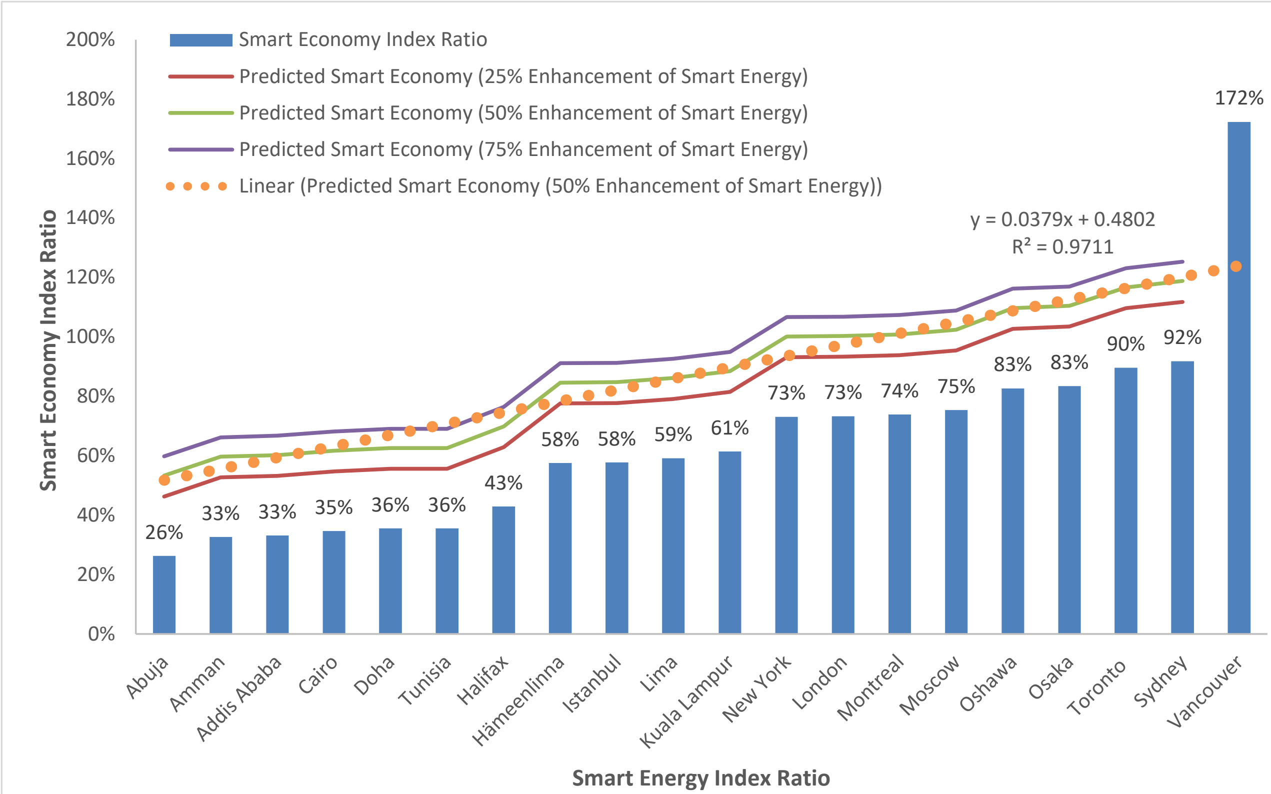


Figure 6.60 Impact of the energy index on the overall economic index

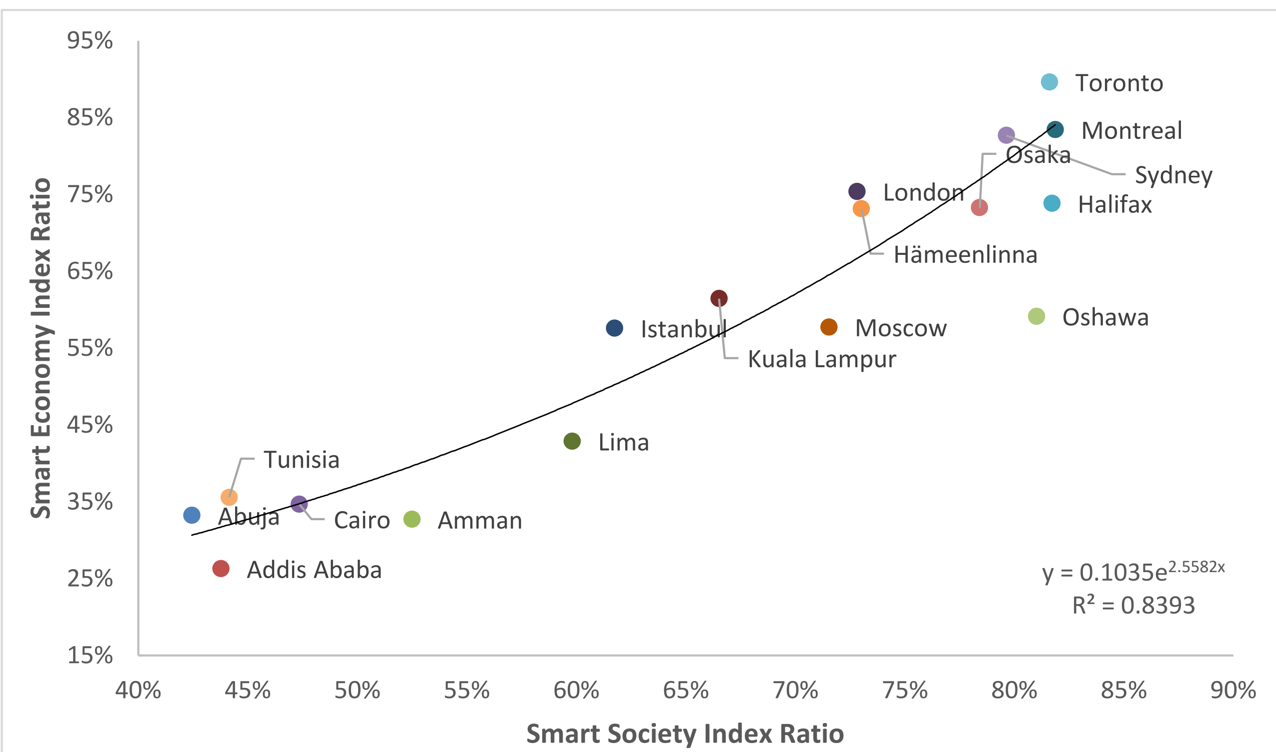


Figure 6.61 Relationship between society and economy indexes

Another important domain is the infrastructure index. Does investment and enhancement in the energy index result in better and more resilient infrastructure? According to the results in this model, there is a significant positive linear relationship between the energy and infrastructure indexes, suggesting that higher energy index ratio is associated with higher infrastructure index ratio. This is clear as the p value is much less than 0.05, as illustrated in Figure 6.62.

Clean energy utilization and energy efficiency both correlate with the infrastructure's indicators of sustainable infrastructure and smart device penetration. Similarly, lower energy cost, allows for infrastructure investment to be enhanced. In fact, Figure 6.62 shows the energy cost and respective energy index for the different cities.

Lastly, the relationship between the transportation domain and infrastructure domain is explored in Figure 6.63. A positive linear relationship between the two indexes is evident with a p value lower than 0.05. Investing in transport efficiency and technology integration, reinforces sustainable infrastructure and smart device penetration.

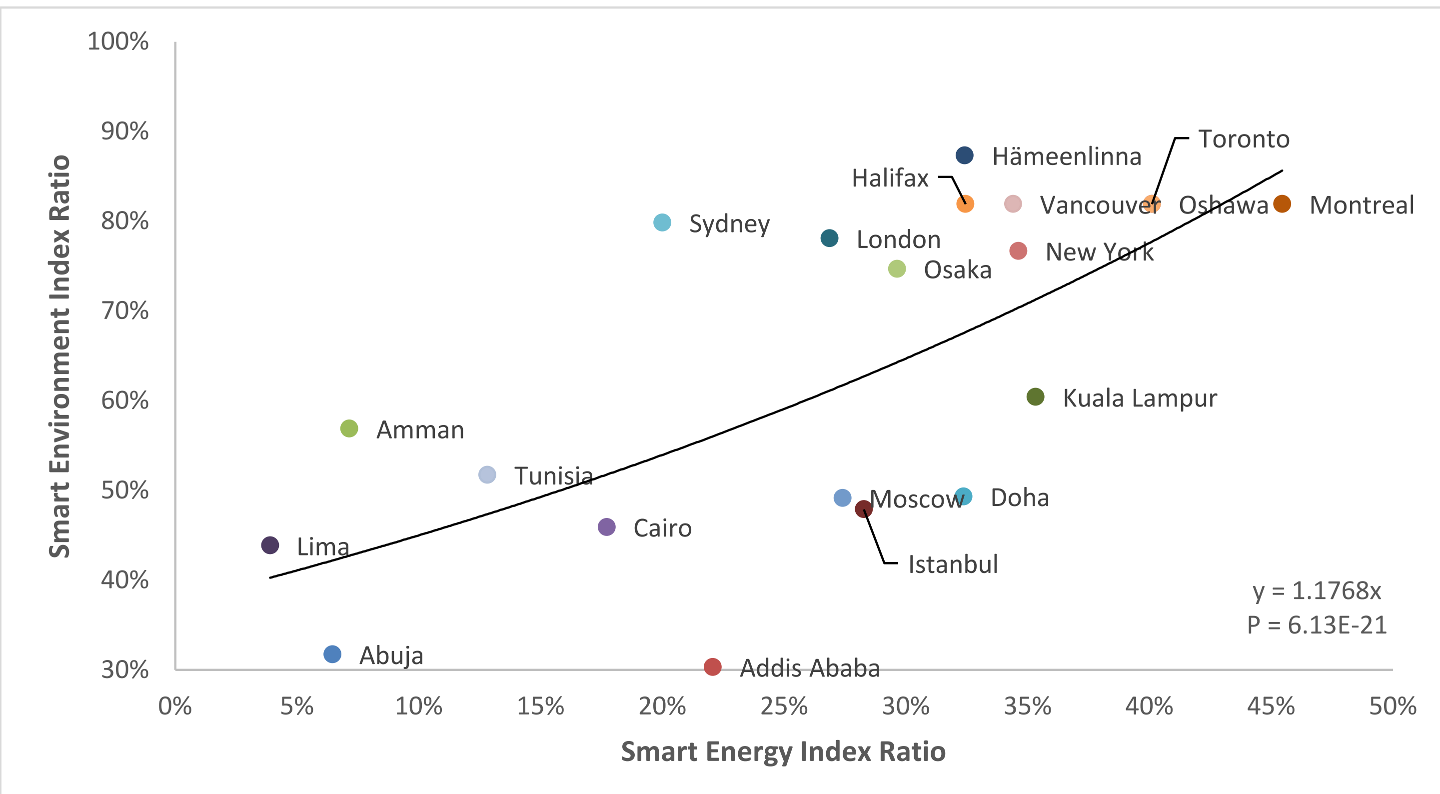


Figure 6.62 Relationship between energy and environment indexes

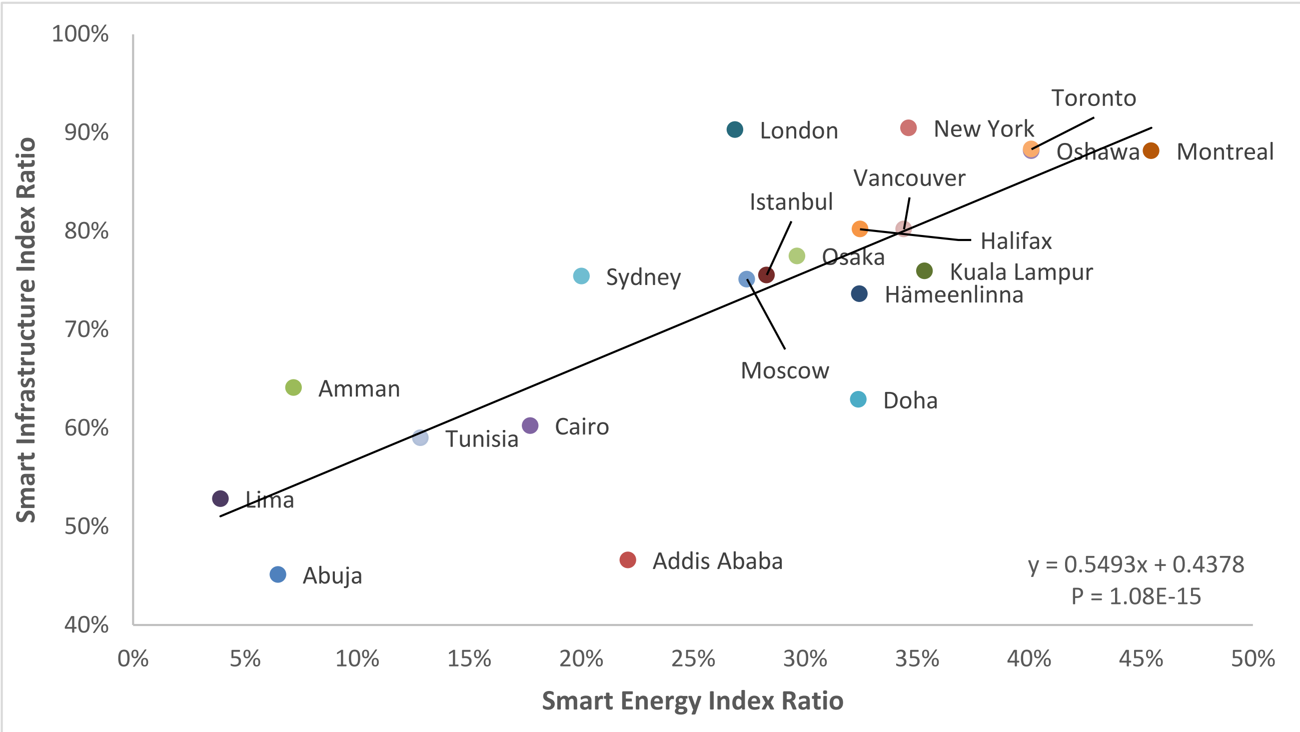


Figure 6.63 Relationship between energy and infrastructure indexes

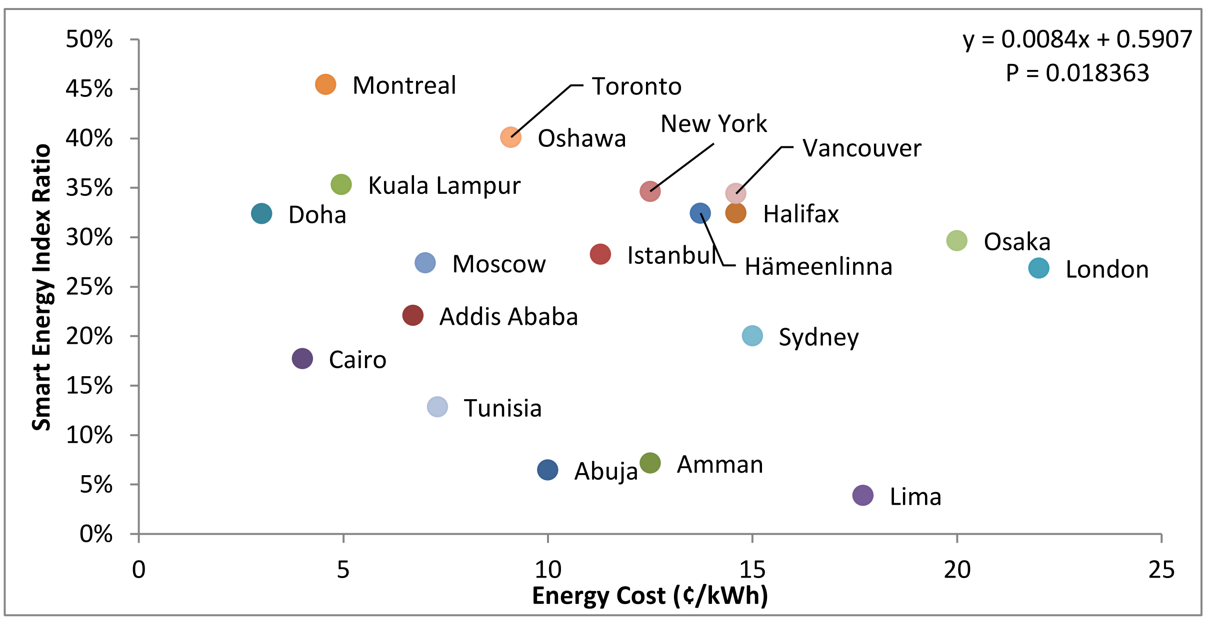


Figure 6.64 Energy cost and corresponding smart energy index for all cities

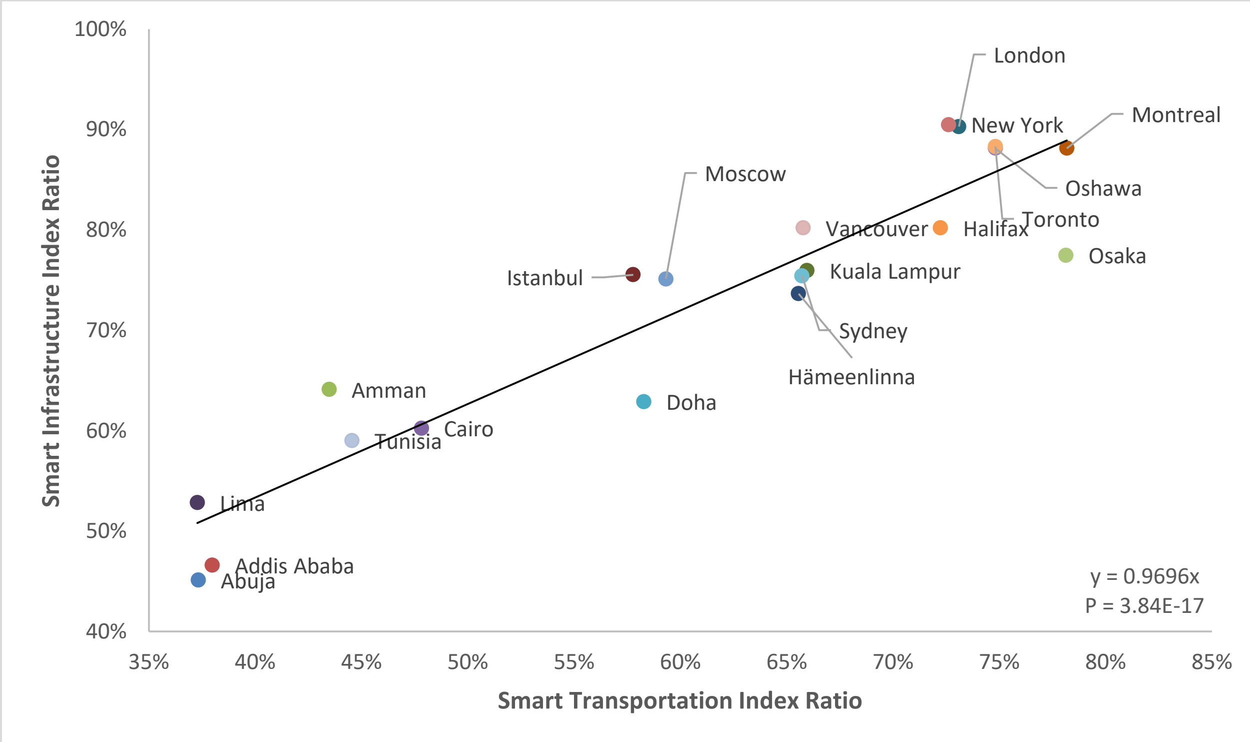


Figure 6.65 Relationship between transportation and infrastructure indexes

6.6 Lifecycle Assessment Results

The five different energy systems, designed to meet the demand of 5000 homes in a given city, are analyzed from a lifecycle perspective. The components within each system are further investigated to better understand the environmental impact assessment of these proposed systems. Figure 6.66 shows the LCA results of all five systems using the North American TRACI assessment methodology. System 1, which is the current business as usual (BAU) base case scenario for Ontario, Canada, is very environmentally friendly. This is because the electricity and cooling demands are fulfilled through nuclear and hydropower evenly. In fact, Ontario's electric grid is one of the cleanest worldwide, with emission factor of 0.000031 tCO_2eq/kWh (Toronto Atmospheric Fund, 2019). System 5 is also incredibly competitive environmentally, with lower ozone lower depletion than that of System 1. The similarity between both systems stem from the fact that both are nuclear based, which is considered a clean energy fuel source that does not contribute any GHGs. On the other hand, System 2 is based on a CSP, coupled with a PVT farm for electricity and heat generation. The system also employs an Organic Rankine cycle as well as an absorption refrigeration cycle. System 4 is less environmentally intrusive than System 3. In fact, apart from Ozone Layer Depletion, all other environmental indicators are reduced by half in system 4 than in system 3. Figure 6.67 shows the various environmental indicators as highlighted in the TRACI methodology and the contribution by percentage of each system to the respective environmental impact category.

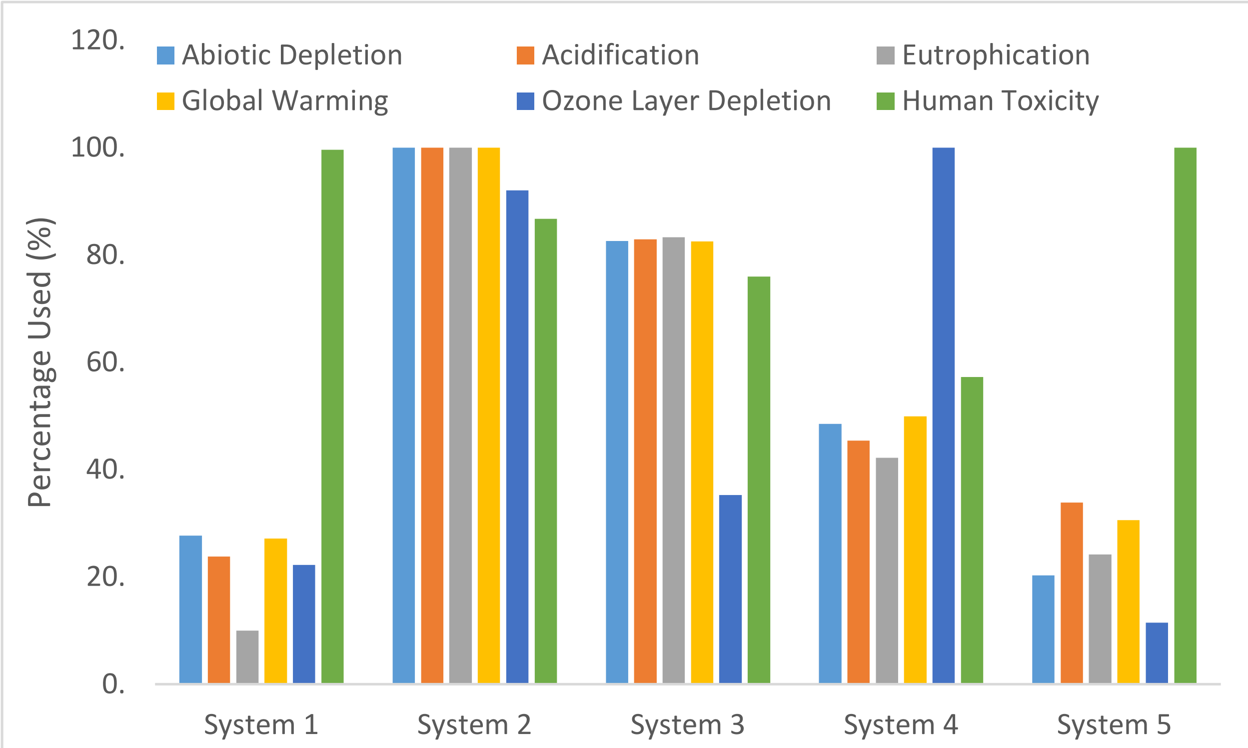


Figure 6.66 Summary of LCA results among all systems using TRACI methodology

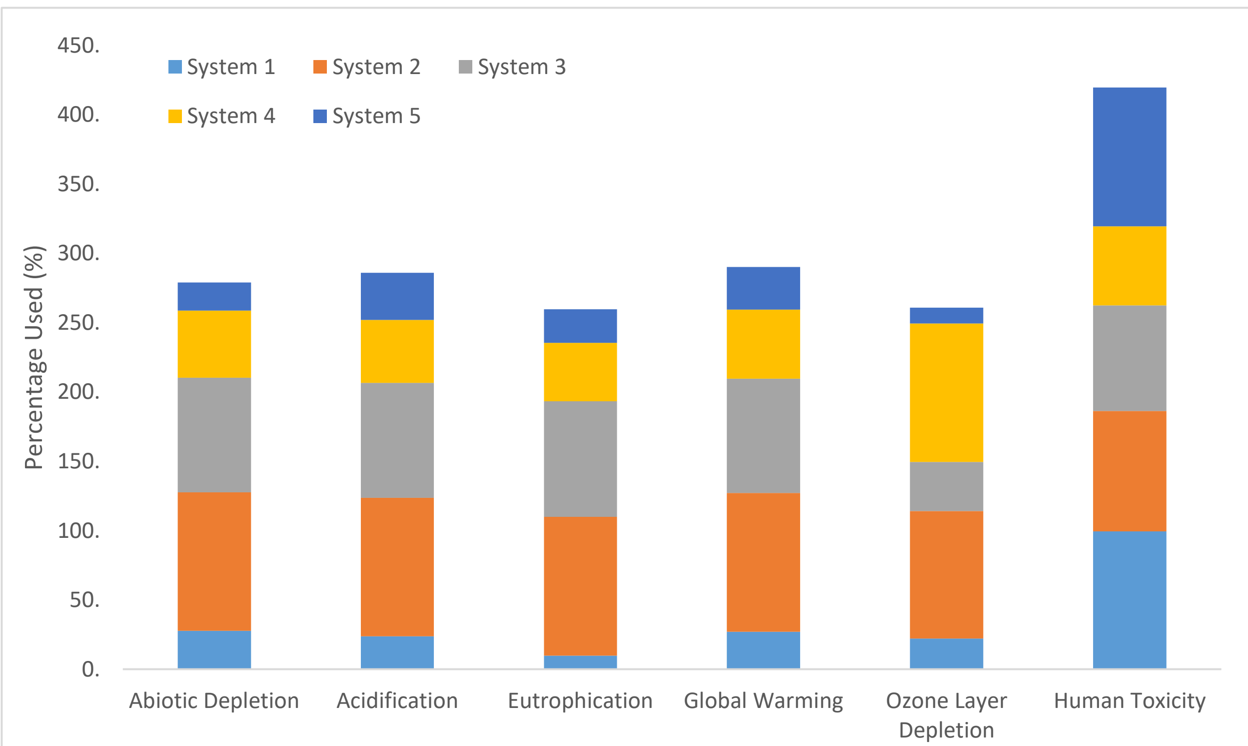


Figure 6.67 Summary of the environmental impact categories by system contribution

Human toxicity is one the main concerns among all systems, followed by global warming and acidification potential. Systems 2 and 3 accounts for most of the abiotic depletion, acidification, eutrophication, and global warming. From that perspective, systems 4 and 5 are more environmentally benign. However, system 4 has considerable ozone layer depletion impacts, compared to the other systems. Table 6.27 shows the actual values for each system and their associated environmental impact based on TRACI.

Table 6.27 Summary of the environmental impact results by system

Impact Category	Unit	System 1	System 2	System 3	System 4	System 5
Abiotic Depletion	*kgCFC-11eq*	26.725	100	82.6614	48.5223	20.2428
Acidification	*$kgSO_2eq$*	23.7519	100	82.9614	45.4026	33.8384
Eutrophication	*kgNeq*	9.971	100	83.3354	42.1947	24.1729
Global Warming	*$kgCO_2eq$*	26.1505	100	82.5438	49.9055	30.577
Ozone Layer Depletion	*kgCFC-11eq*	22.2057	92.0718	35.2638	100	11.4655
Human Toxicity	*CTUh*	99.6376	86.797	75.9947	56.2461	100

The main components of system 1 include the conventional gas heating, refrigeration system, nuclear electricity, and hydro power. Each of these components have different impacts environmentally as illustrated in Figure 6.68. Nuclear electricity and the refrigeration system account for most of the environmental impacts.

Table 6.28 Summary of the environmental impact results for system 1

Impact Category	Unit	System 1: Hydro Power	System 1: Nuclear Electricity	System 1: Refrigeration System	System 1: Conventional Gas Heating
Ozone depletion	*kgCFC-11eq*	1.52E-11	2.59E-09	3.88E-09	1.28E-10
Global warming	*$kgCO_2eq$*	0.000185	0.000439	0.000659	0.000757
Smog	kgO_3eq	1.67E-05	3.72E-05	5.58E-05	1.17E-05
Acidification	*$kgSO_2eq$*	4.17E-05	0.000163	0.000244	3.38E-05
Eutrophication	*kgNeq*	4.44E-07	1.70E-06	2.55E-06	1.10E-07
Carcinogenics	*CTUh*	5.43E-11	1.38E-10	2.07E-10	4.75E-12
Non carcinogenics	*CTUh*	4.95E-11	1.53E-09	2.30E-09	5.81E-12
Respiratory effects	$kgPM_{10}eq$	1.03E-06	2.82E-06	4.23E-06	8.52E-08
Ecotoxicity	*CTUe*	0.000587	0.00402	0.00603	5.55E-05

In fact, hydropower is almost benign, while the conventional gas heating has the largest impact on the global warming category due to high emissions of CO_2. Table 6.28 shows the actual results of this assessment. As for system 2, the electricity generation through the Organic Rankine Cycle, followed by the PV power generation are responsible for the biggest environmental impacts as illustrated in Figure 6.69. The refrigeration system has modest contribution throughout all categories, however CSP farm had the lowest impact environmentally. Figure 6.70 shows the processes in systems 1 and 2 that result in these environmental impacts.

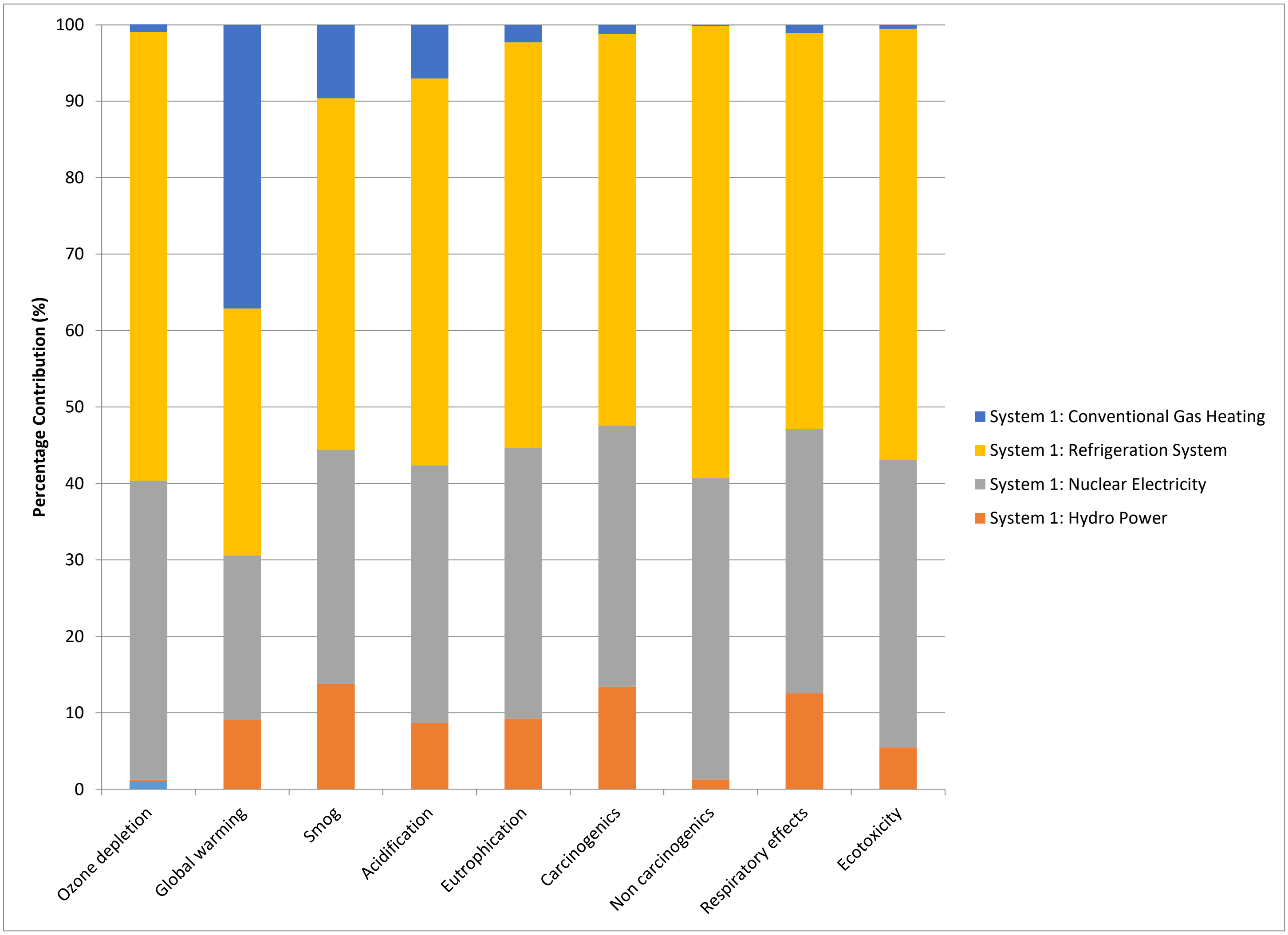


Figure 6.68 Environmental impact assessment of system 1 components

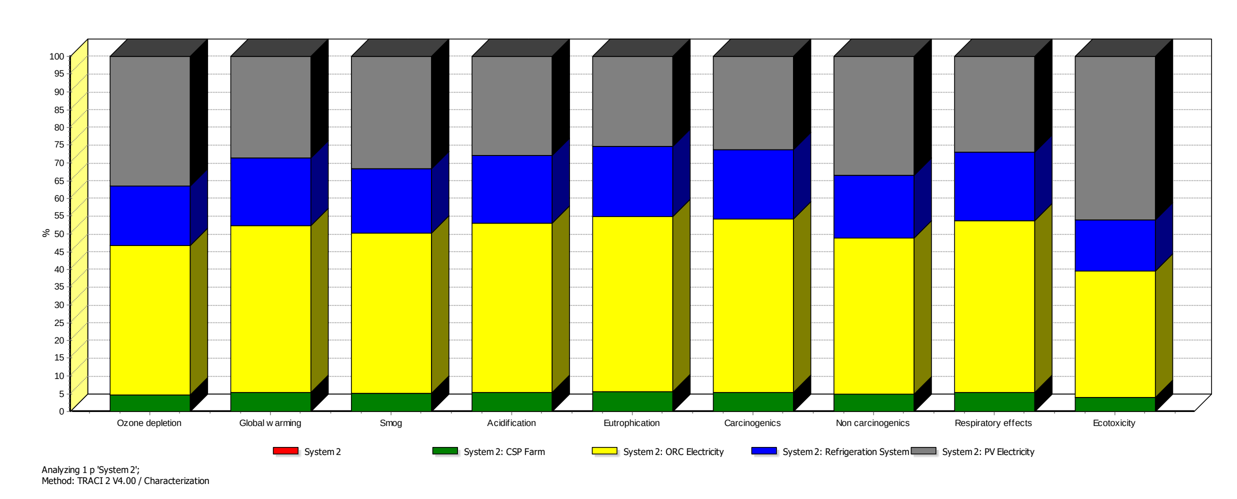


Figure 6.69 Environmental impact assessment of system 2 components

Similarly, Table 6.29 shows the actual value contribution to each impact category for system 2. Ecotoxicity is the most impacted category with total value of 0.03 CTUe.

Table 6.29 Summary of the environmental impact results for system 2

Impact Category	**Unit**	**System 2: CSP Farm**	**System 2: ORC Electricity**	**System 2: Refrigeration System**	**System 2: PV Electricity**
Ozone depletion	*kgCFC-11eq*	5.91E-11	5.32E-10	2.13E-10	4.62E-10
Global warming	*$kgCO_2eq$*	0.000393194	0.003538746	0.001415498	0.002150395
Smog	kgO_3eq	1.78E-05	0.000160633	6.43E-05	0.000112268
Acidification	*$kgSO_2eq$*	0.00010111	0.000909994	0.000363998	0.000533173
Eutrophication	*kgNeq*	3.18E-06	2.86E-05	1.14E-05	1.46E-05
Carcinogenics	*CTUh*	6.31E-11	5.68E-10	2.27E-10	3.07E-10
Non carcinogenics	*CTUh*	1.95E-10	1.75E-09	6.01E-10	1.33E-09
Respiratory effects	$kgPM_{10}eq$	5.81E-07	5.23E-06	2.09E-06	2.93E-06
Ecotoxicity	*CTUe*	0.001192957	0.01073661	0.004294644	0.013869438

System 3 components vary more in their contribution to the different impact categories. The ORC electricity generation seems to have the most impact on all categories, followed by the refrigeration system. The wind and solar farms have limited impacts on all categories as illustrated in Figure 6.71. The processes contributing to the environmental impacts for systems 3 and 4 are further detailed in Figure 6.72 Electricity generation from ORC is the main contributor for system 3, while electricity generation from PV is the main contributor for system 4.

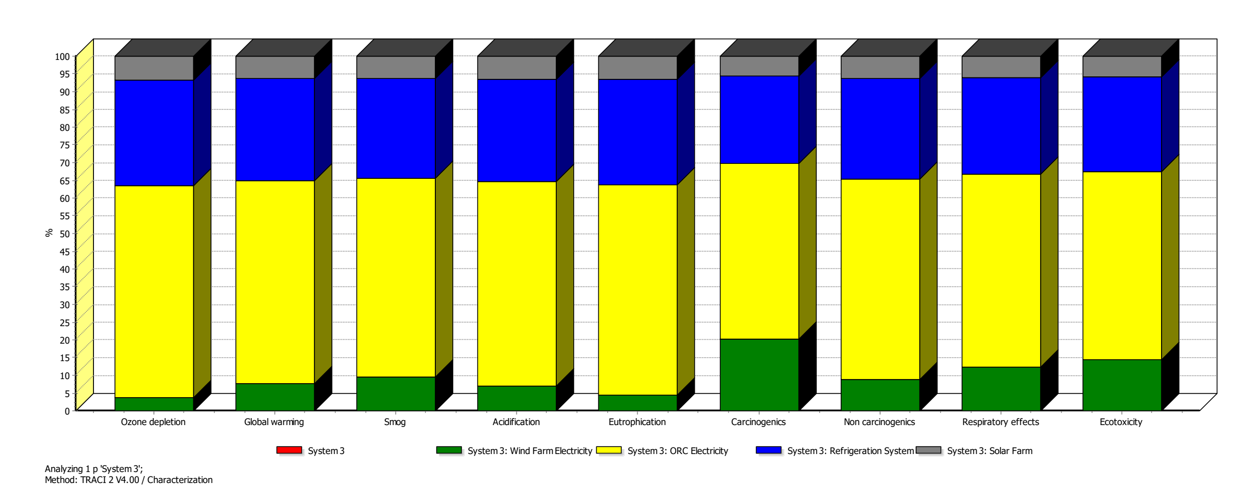


Figure 6.71 Environmental impact assessment of system 3 components

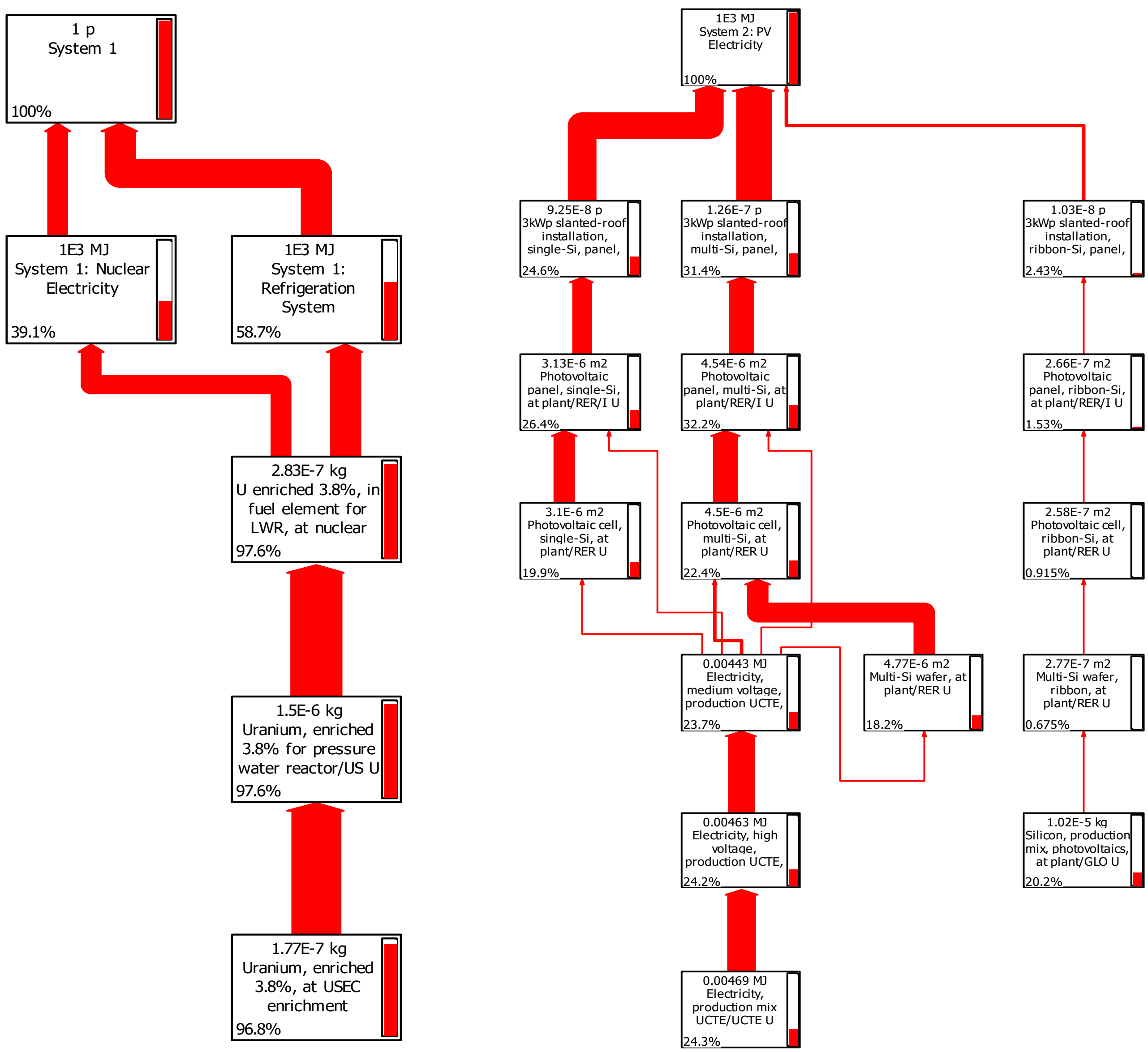
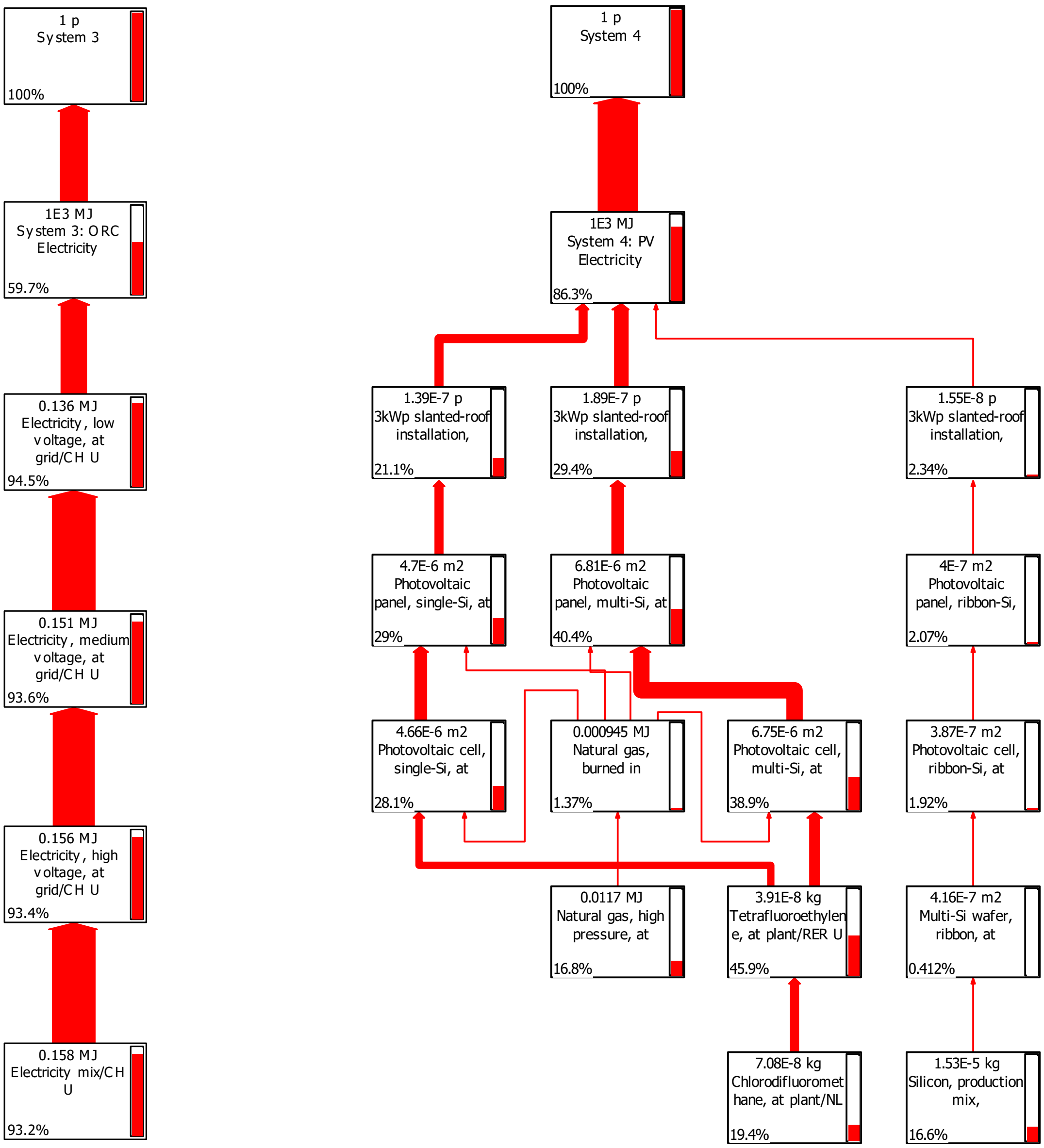


Figure 6.70 Processes causing environmental impacts in systems 1 and 2



(a) (b)

Figure 6.72 Processes causing environmental impacts in systems 3 and 4

Furthermore, ecotoxicity, followed by acidification, smog and global warming are the main impacts affected by system 3 components as detailed in Table 6.30, which shows the various system components and their associated impacts on each impact category.

Table 6.30 Summary of the environmental impact results for system 3

Impact Category	Unit	System 3: Wind Farm Electricity	System 3: ORC Electricity	System 3: Refrigeration System	System 3: Solar Farm
Ozone depletion	*kgCFC-11eq*	3.35E-11	5.32E-10	2.66E-10	5.91E-11
Global warming	*kgCO₂eq*	0.000474931	0.003538746	0.001769373	0.000393194
Smog	kgO3eq	2.69E-05	0.000160633	8.03E-05	1.78E-05
Acidification	*kgSO2eq*	0.000109519	0.000909994	0.000454997	0.00010111
Eutrophication	*kgNeq*	2.14E-06	2.86E-05	1.43E-05	3.18E-06
Carcinogenics	*CTUh*	2.30E-10	5.68E-10	2.84E-10	6.31E-11
Non carcinogenics	*CTUh*	2.76E-10	1.75E-09	8.76E-10	1.95E-10
Respiratory effects	kgPM10eq	1.19E-06	5.23E-06	2.61E-06	5.81E-07
Ecotoxicity	*CTUe*	0.002901883	0.01073661	0.005368305	0.001192957

System 4 is unique because most of the impacts stem from the power generation from the PV farm. The absorption refrigeration system, geothermal heating and power generation from hydro all have minimal impacts, relatively. This is shows in Figure 6.73 in detail.

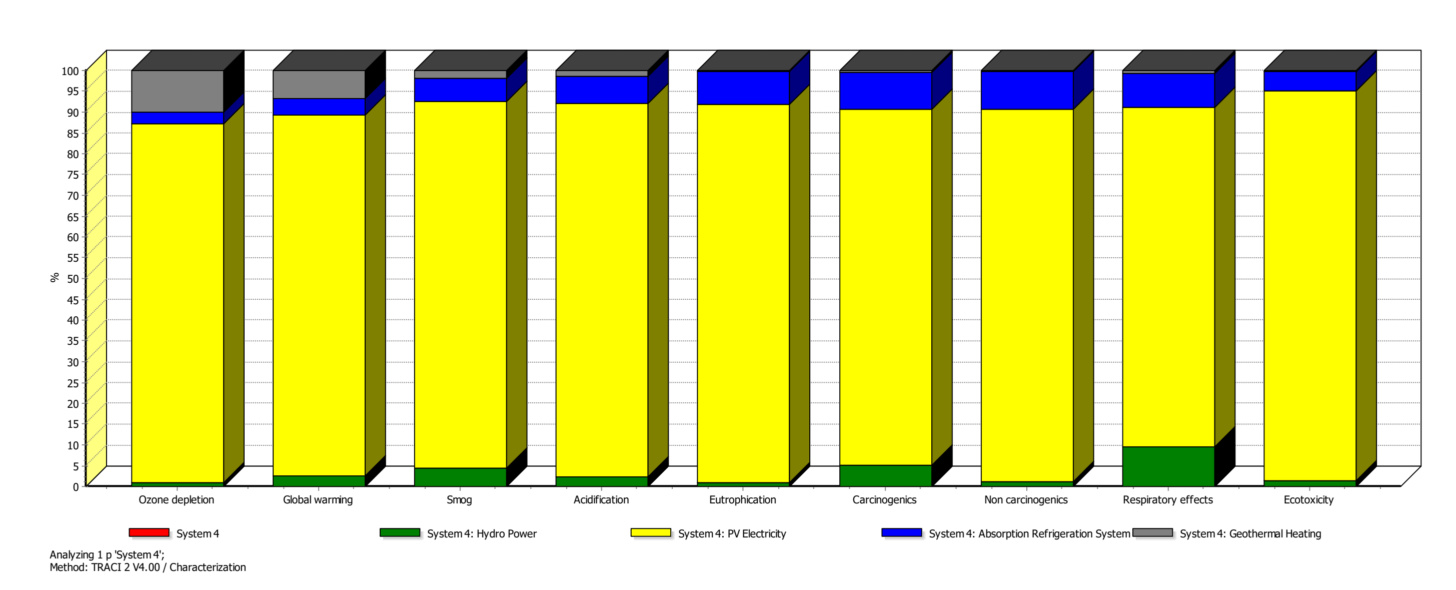


Figure 6.73 Environmental impact assessment of system 4 components

The actual values for the impact assessment for system 4 and its components is highlighted in Table 6.31. Finally, the processes contributing to system 5 environmental impacts are shows in Figure 6.74. Uranium enrichment to supply energy to the refrigeration system and nuclear power generation is the process that results in most of the impacts.

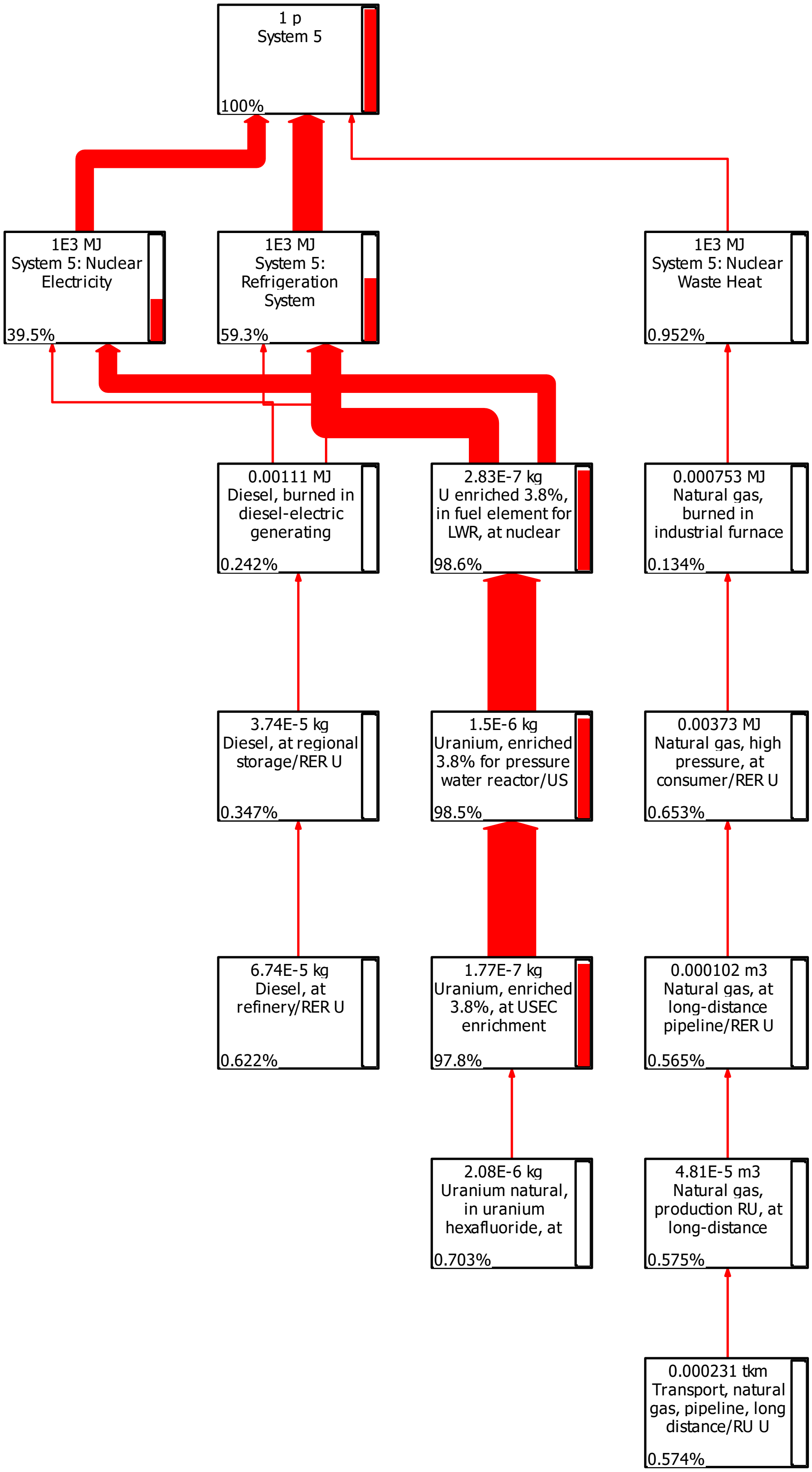


Figure 6.74 Processes causing environmental impacts in system 5

Table 6.31 Summary of the environmental impact results for system 4

Impact Category	Unit	System 4: Hydro Power	System 4: PV Electricity	System 4: Absorption Refrigeration System	System 4: Geothermal Heating
Ozone depletion	*kgCFC-11eq*	6.59E-12	6.93E-10	2.11E-11	8.09E-11
Global warming	*kgCO$_2$eq*	9.25E-05	0.003225592	0.000145145	0.000249106
Smog	kgO$_3$eq	8.37E-06	0.000168402	1.07E-05	3.39E-06
Acidification	*kgSO$_2$eq*	2.09E-05	0.00079976	5.78E-05	1.19E-05
Eutrophication	*kgNeq*	2.22E-07	2.19E-05	1.93E-06	4.38E-08
Carcinogenics	*CTUh*	2.71E-11	4.60E-10	4.79E-11	2.20E-12
Non carcinogenics	*CTUh*	2.47E-11	2.00E-09	2.04E-10	4.34E-12
Respiratory effects	kgPM$_{10}$eq	5.13E-07	4.40E-06	4.36E-07	3.41E-08
Ecotoxicity	*CTUe*	0.000293293	0.020804158	0.001051317	3.16E-05

As for system 5, nuclear waste heat contributes greatly to the smog, eutrophication, acidification and global warming impact categories. The refrigeration system and nuclear power generation are also equal contributors to various categories as shown in Figure 6.75.

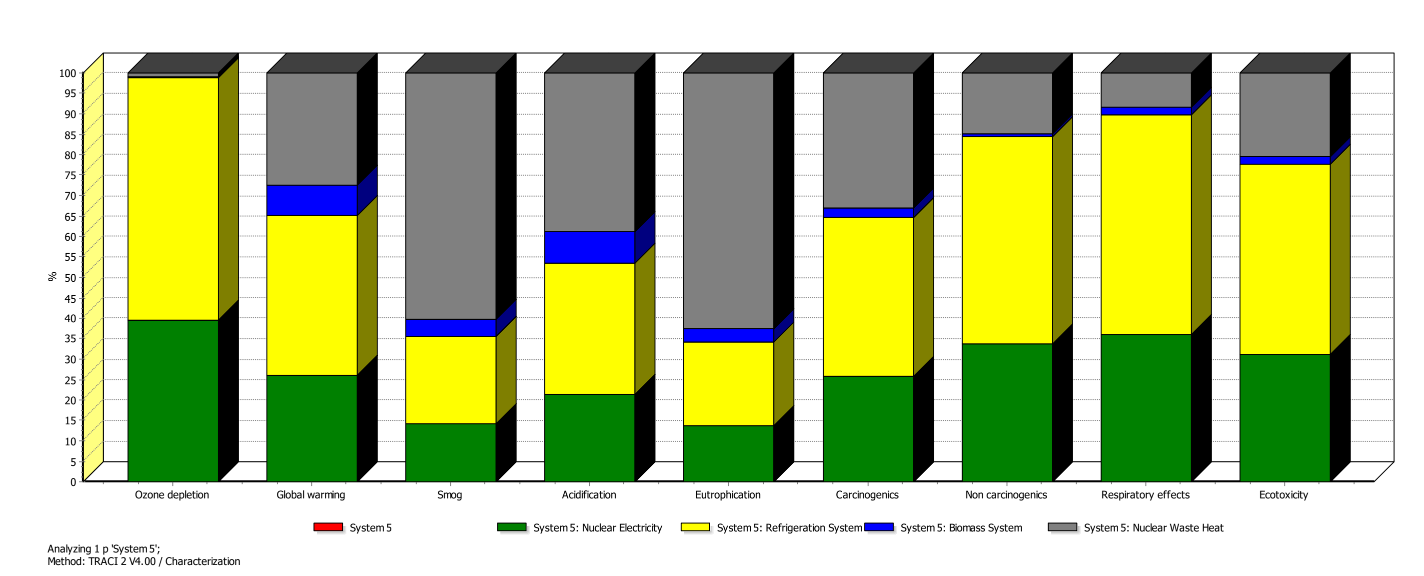


Figure 6.75 Environmental impact assessment of system 5 components

Lastly, this is the system that has the greatest variety in system components and their attribution to different impact categories. The actual values are listed below in Table 6.32 for further analysis.

Table 6.32 Summary of the environmental impact results for system 5

Impact Category	Unit	System 5: Nuclear Electricity	System 5: Refrigeration System	System 5: Biomass System	System 5: Nuclear Waste Heat
Ozone depletion	*kgCFC-11eq*	2.59E-09	3.88E-09	1.52E-11	6.23E-11
Global warming	*kgCO$_2$eq*	0.000439378	0.000659068	0.000122519	0.000463033
Smog	kgO$_3$eq	3.72E-05	5.58E-05	1.05E-05	0.000157172
Acidification	*kgSO$_2$eq*	0.00016264	0.00024396	5.73E-05	0.000295481
Eutrophication	*kgNeq*	1.70E-06	2.55E-06	3.85E-07	6.78E-06
Carcinogenics	*CTUh*	1.38E-10	2.07E-10	1.27E-11	1.77E-10
Non carcinogenics	*CTUh*	1.53E-09	2.30E-09	2.98E-11	6.78E-10
Respiratory effects	kgPM$_{10}$eq	2.82E-06	4.23E-06	1.33E-07	6.64E-07
Ecotoxicity	*CTUe*	0.00401973	0.006029595	0.000226956	0.002654114

6.7 System Analysis Results

While individual energy systems from various sources can have standard efficiencies that are well established in literature, integrated energy systems tend to have an amplified effect on the overall system performance. Figure 6.76 shows the overall system energy and exergy efficiencies for the proposed systems. System 1 has the lowest energy and exergy efficiencies due to the non-integrated nature of the current business as usual energy infrastructure. In this system, nuclear and hydropower are the main sources of electricity, while conventional boilers and chillers are used for heating and cooling. Furthermore, heating is solely supplied by natural gas, which is a fossil-based fuel.

The energy and exergy efficiencies of system 1 are 31.7% and 22.4% respectively. On the other hand, system 2 solely relies on solar energy for all three commodities. Since this system constitutes an enlarged thermal energy infrastructure, heat loss leads to more exergy destruction due to the temperature variance between ambient and output temperatures. This explains the energy and exergy efficiencies of system 2 of 53.4% and 34.6% respectively. System 3 is the second least efficient system among the five systems with energy and exergy efficiencies of 46.3% and 44.1% respectively. This is due to lower efficiencies stemming from the wind farm and the organic Rankine cycle, which causes significant exergy destruction.

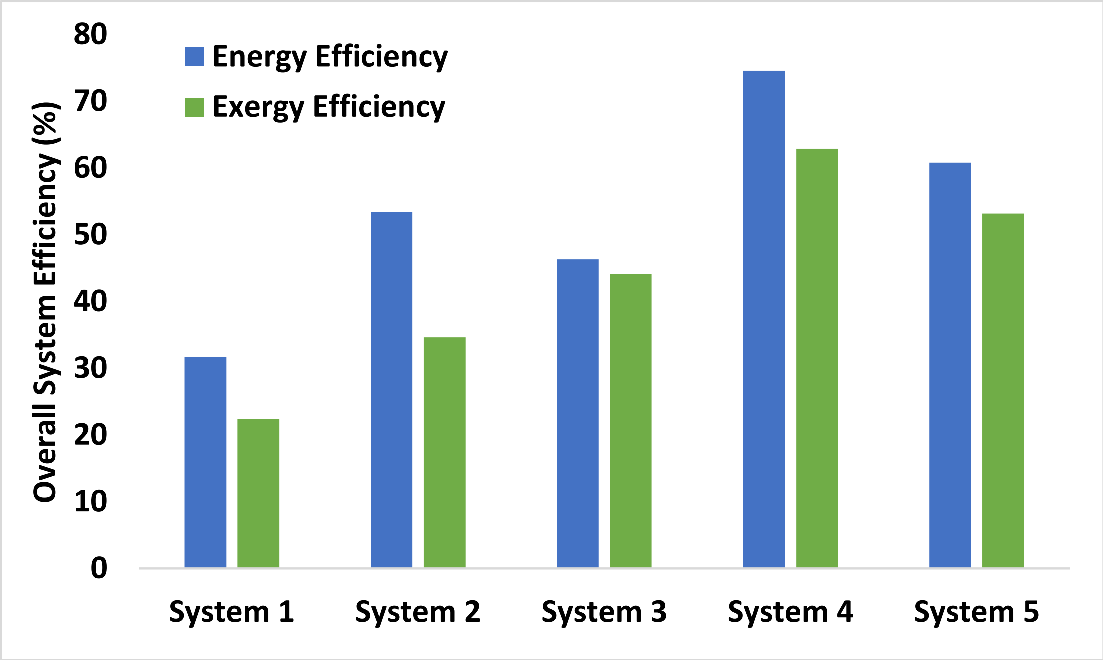


Figure 6.76 Overall system energy and exergy efficiencies of the proposed systems

The energy and exergy efficiencies of system 4 on the other hand is the highest due to the utilization of quintuple flash geothermal cycle instead of the organic Rankine cycle, in addition to the absorption refrigeration cycle, both which enhance the efficiencies of the system considerably. The overall energy and exergy efficiencies of system 4 are evaluated at 74.6% and 62.9% respectively. Lastly, system 5 integrates biomass and nuclear energy, achieving the second highest energy and exergy efficiencies of 60.8% and 53.2% respectively. This is largely due to the utilization of waste heat from the nuclear plants for space heating and domestic hot water use, in addition to the integration of the gasification process into the biomass system.

Exergy destruction is another indicator of resource degradation, pinpointing the specific subcomponents that account for the highest destruction within a given system. For the purpose of this thesis, the overall exergy destruction of these systems are evaluated and analyzed. Figure 6.77 shows the percentage that each system accounts for from an exergy destruction perspective had all the systems been 100%. These results are consistent with the efficiencies results earlier. Generally, systems with higher exergy efficiencies result in lower exergy destruction ratios. Similarly, systems with lower efficiencies, result in significant exergy destruction ratios within their subcomponents. Systems 3 and 2 account for approximately half of the exergy destructions of all systems. On the other hand, system 4 yields in the lowest exergy destruction rates at only 12% of the total systems' destruction. On the other hand, system 1, which is the least efficient system results in the highest exergy destruction of 28%, one third of the total exergy destruction across all systems. The second most efficient system, which is system 5 also yields in a conservative exergy destruction rate, accounting for only 17% of the total destruction rates.

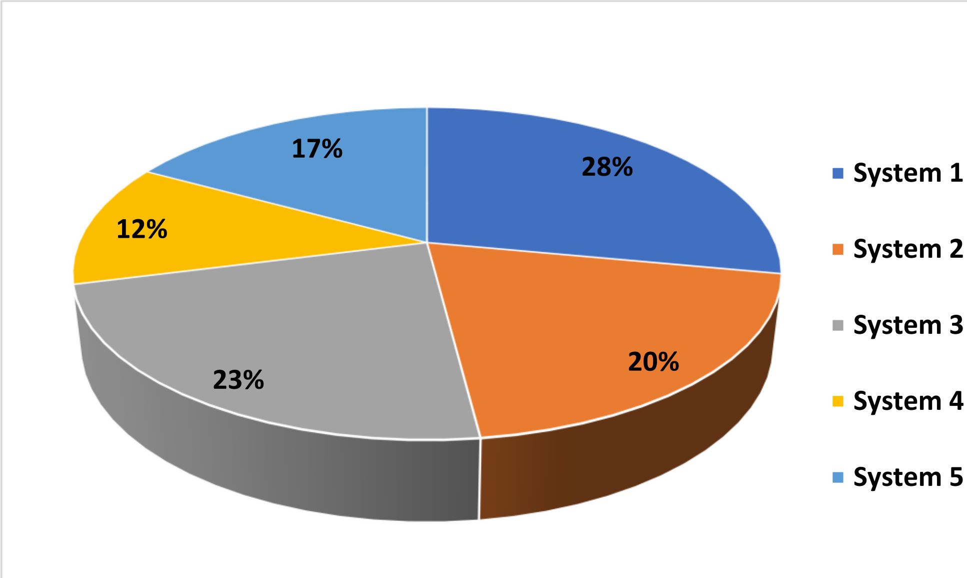


Figure 6.77 Exergy destruction ratios for each proposed system

While the reliability of this energy may be questionable, due to the intermittent nature of solar energy, battery and thermal storage offset this variable by providing a more resilient energy infrastructure that is sustainable and efficient for smart city applications. The overall energetic and exergetic efficiencies of the system are evaluated at 53.4% and 49.2%, respectively, which is consistent with the published ratings of similar integrated systems in the literature. Table 6.33 shows the various state points and their respective exergetic and enthalpy performance. The mass flowrate is rated as constant throughout the system at 10.305 kg/s. the changes in temperature and pressure throughout the system are evident. Input temperatures from the solar collectors through the solar tower are close to 400 °C. Similarly, the inlet pressure is designed at 17 MPa, while the outlet pressure is 4 MPa. The temperature and pressure variant explains the exergy rate decline throughout the system as outlined below. It is crucial to understand the exergy destruction dynamics within this complex system. Figure 6.78 shows the exergy destruction rates in (MW) for the various components in this integrated system. The highest exergy destruction rate is observed at the CSP farm, with rating of 42.5 MW. The PVT farm is similar to the high-grade thermal energy storage and the absorption refrigeration system with exergy destruction rates that range between 10-14 MW.

Table 6.33 Thermodynamic properties at each state point in the system

State Point	$\dot{m}$ (kg/s)	Temperature (°C)	Pressure (MPa)	Exergy Rate (kJ/kg)	Specific Enthalpy (kJ/kg)	x (–)
0	---	25	0.1001	0	-0.8764	---
1	10.305	396	17	410.3	348.9	1
2	10.305	352	10	385.6	290.4	1
3	10.305	396	10	359.1	354.2	1
4	10.305	310	4	300.5	265.8	1
5	10.305	28	4	209.3	-56.2	1
6	10.305	5	4	236.3	-320.4	0
7	10.305	16	17	247.2	-301.8	1
8	10.305	140	17	312.7	23.5	---

The lowest exergy destructions occur in the medium grade thermal energy storage and the ORC, with exergy rates lower than 8 MW. The reason behind the high exergy destruction at the CSP farm can be attributed to the significant grade of heat transfer, temperature and pressure disparity between the solar tower and thermal energy storage, including the heat losses.

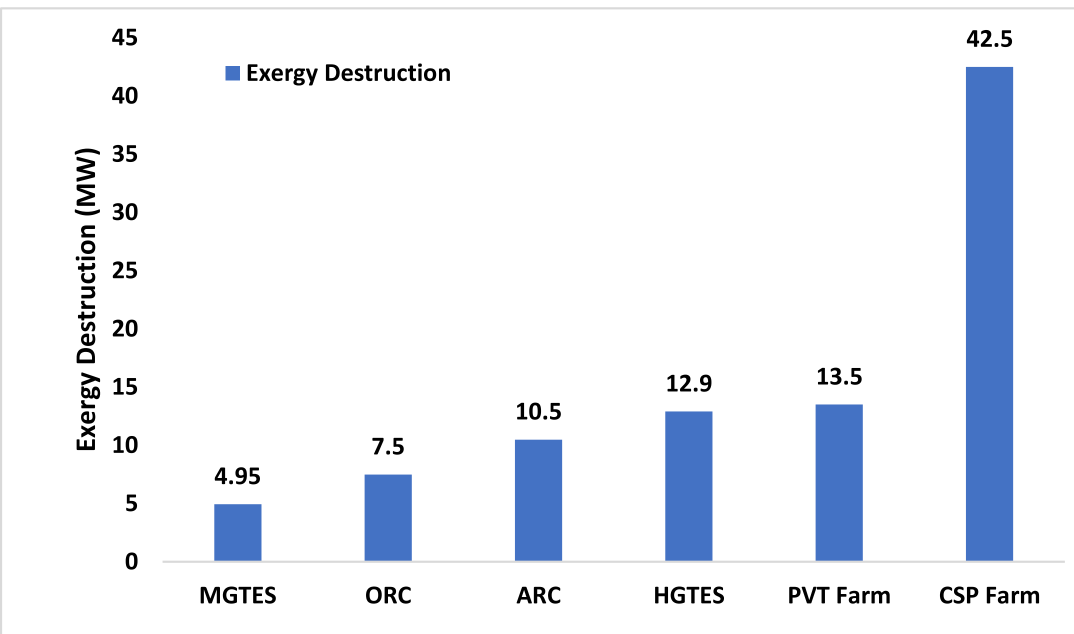


Figure 6.78 Various components and their exergy destruction rates

Further parametric studies were performed to observe the effect of changing parameters, especially solar receiver temperature and heater outlet pressure to the overall efficiencies of the system. The system's highest performance is at receiver temperature of 650 K, which is reasonable as the temperature has an inverse relationship with the inlet and ambient temperature variance. The highest energy efficiency is 56% and the lowest energy efficiency is at 50.5%. Similarly, the highest exergy efficiency is 50.5, while the lowest is 46.5% as illustrated in Figure 6.79. Another varying parameter is the outlet pressure from the heating system. the maximum pressure is evaluated and its impact on the overall energy and exergy efficiencies are presented in Figure 6.80. The receiver temperature with is a key parameter used when evaluating solar heliostats in CSP farms. The increase in the receiver temperature from 650 K to 800 K reduces the energy efficiency by approximately 5% and increases receiver heat loss by 500 kW. The best efficiencies are achieved with the higher pressure. The energy efficiency ranges between 35-46.6%, while the exergy efficiency ranges between 48-56.7%.

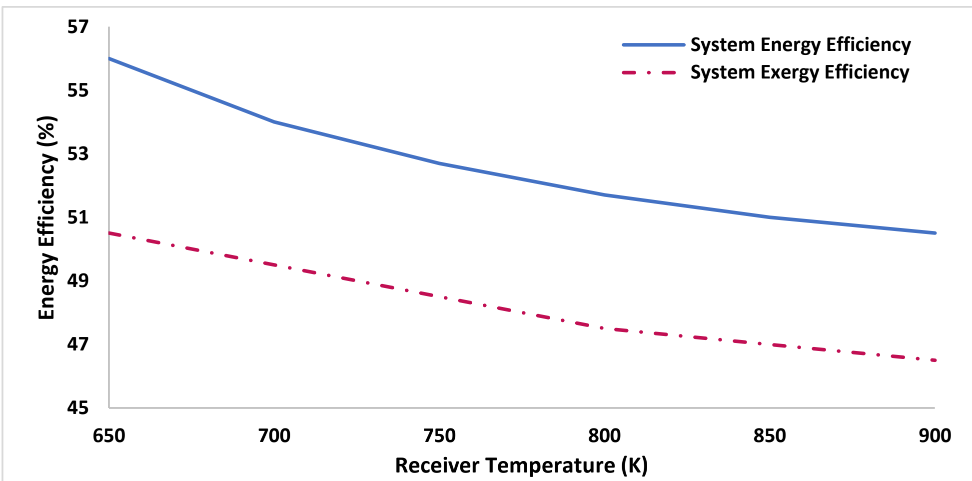


Figure 6.79 Overall energy and exergy efficiencies in relation to the receiver temperature for system II

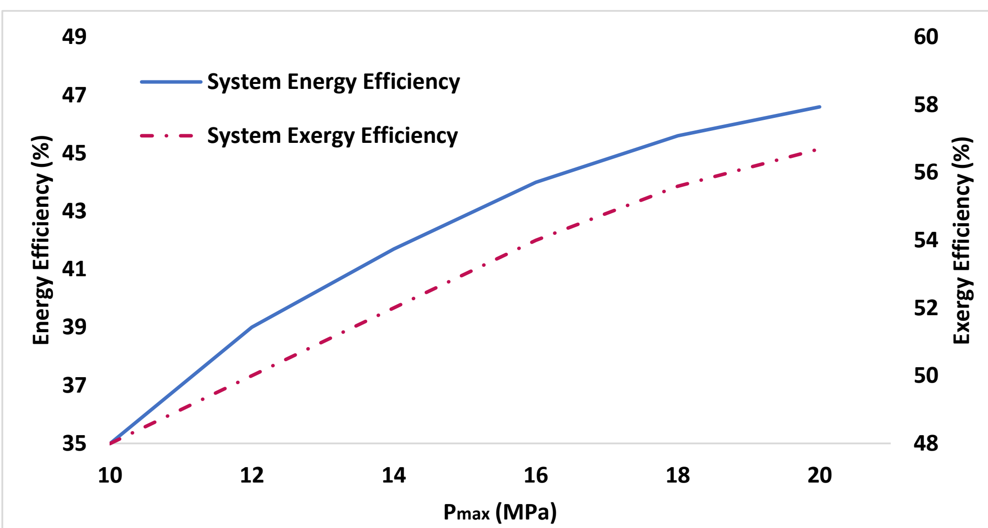


Figure 6.80 Overall energy and exergy efficiencies in relation to the maximum pressure for system II

6.8 Optimization Analysis Results

The optimization study was designed to get the optimal parameter values for this model. Therefore, 32 parameters were optimized using genetic algorithm optimization. The objective function was designed using the following functions:

$$Indicator\ Score = \frac{x_{qc}^{t}}{x_{qc=\bar{c}}^{t}} \tag{6.1}$$

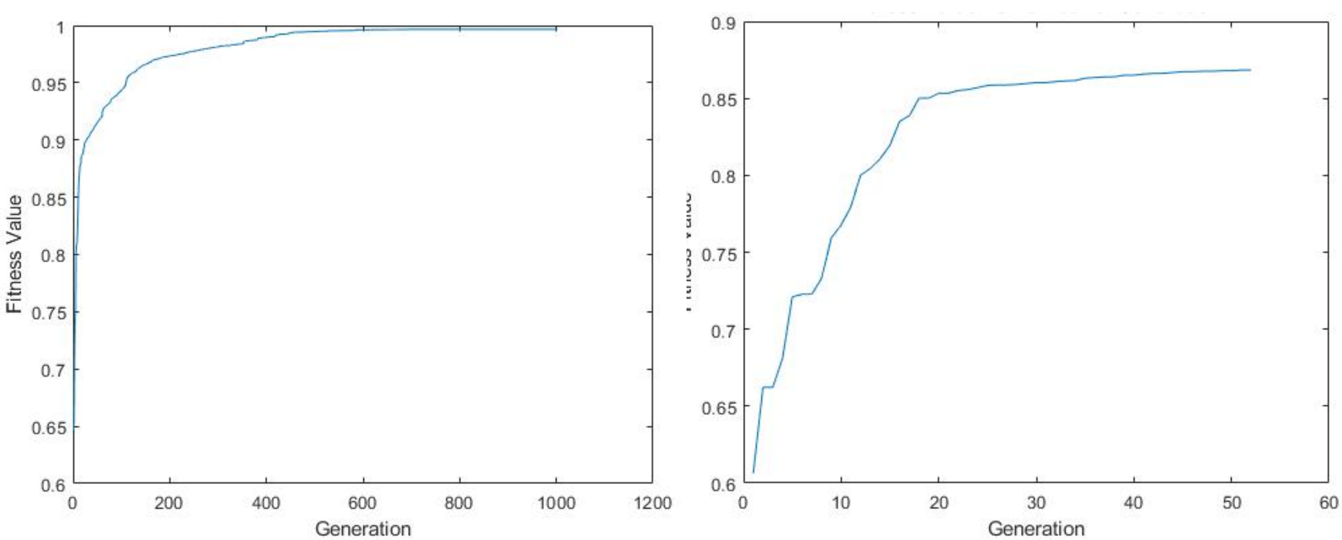
$$Final\ Score = Indicator\ Score \times weight \tag{6.2}$$

$$Index\ Score = \sum Fitness\ Score \tag{6.3}$$

$$Fitness\ Value = \sqrt[8]{\prod_{i=1}^{8} Index\ Score} \tag{6.4}$$

$$Fitness\ Cost = \frac{1}{Fitness\ Value} \tag{6.5}$$

In fact, the pseudo process flow diagram started by setting the population size N, cross over rate, mutation rate and number of generations. A random population is then created, which undergoes cross over and mutation to create more populations. Finally, the fitness value for all individuals in the population, both parents and offspring are computed, after which the individuals with the top best fitness values to the next generation are selected. Figure. 6.81 shows the process flow diagram used for this optimization study.



(a) (b)

Figure 6.67 Progression of fitness value optimization over (a) 1000 generations and (b) 50 generations

Furthermore, the optimal values for each indicator and each index based on the genetic algorithm after 50 generations are presented in Table 6.34. The indexes with the lowest optimal values are infrastructure, governance, energy, and society. Also, the progression of the optimization fitness values over the generation mutations is illustrated in Figure 6.82. After the 20th generation, the fitness values plateaued and reached a saturation point for 30 more generations. Therefore, the number of generations was limited to 50 generations.

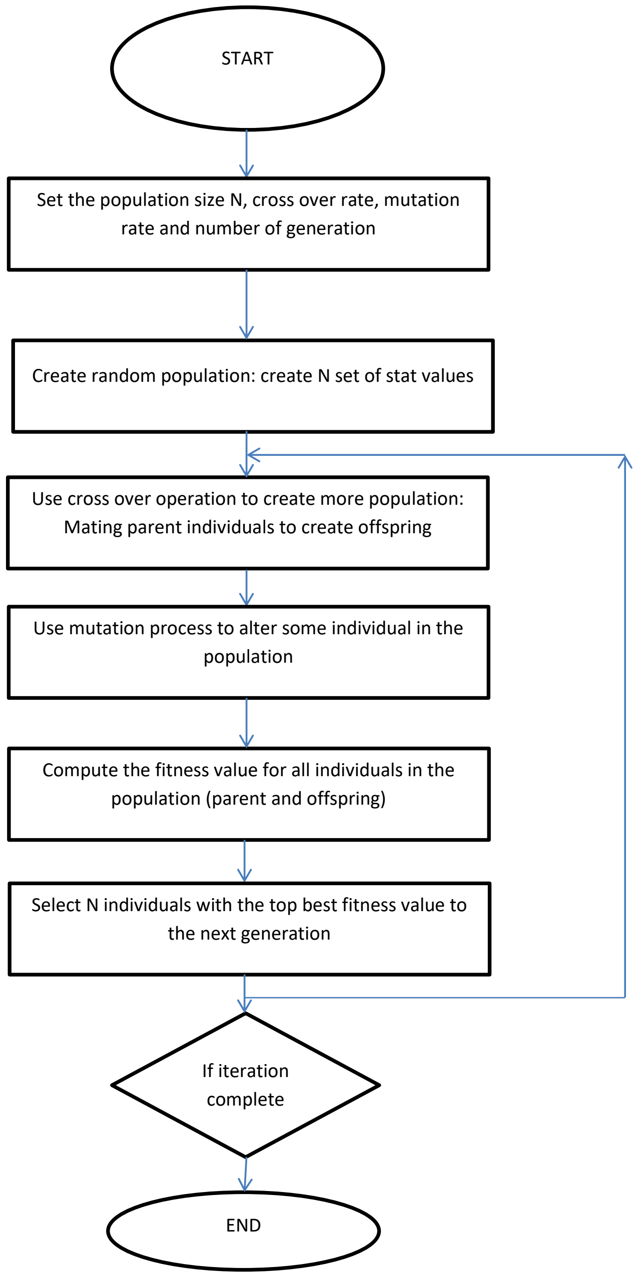


Figure 6.68 Pseudo process flow diagram used for model optimization

Table 6.27 Summary of optimal values based on genetic algorithm optimization

Sub-Index	Indicator	Optimal Value	Optimal Value
Smart Environment	Air Quality	0.955	**0.919**
	Climate Change - GHG Emissions	0.996	
	Waste Management	0.729	
	Biodiversity & Habitat	0.995	
Smart Economy	Gross Domestic Product per Capita	0.765	**0.863**
	R&D Expenditure in % of GDP	0.882	
	Unemployment Rate	0.701	
	Gini Coefficient	0.996	
Smart Society	Educational Level	0.856	**0.878**
	Poverty Rate	0.908	
	Gender Equality	0.980	
	Healthcare Index	0.769	
Smart Governance	Government Effectiveness	0.920	0.794
	Government Digitalization	0.828	
	Public Participation	0.875	
	Corruption Rate	0.552	
Smart Energy	Energy Efficiency	0.992	0.874
	Clean Energy Utilization	0.707	
	Energy Storage	0.695	
	Energy Cost	0.923	
Smart Infrastructure	Infrastructure Investment	0.582	0.787
	Sustainable Infrastructure	0.997	
	Smart Device Penetration	0.569	
	Water Resources	0.999	
Smart Transportation	Transport Efficiency	0.968	0.916
	Technology Integration	0.665	
	Traffic Congestion	0.980	
	Accessibility	0.988	
Pandemic Resiliency	Response Rate	0.816	0.929
	Death Toll	0.993	
	Confirmed Cases	0.987	
	Infrastructure Capacity	0.921	

Chapter 7: Conclusions and Recommendations

This thesis aims at providing net zero energy solutions for smart city applications. Environmentally benign and reliable energy sources are utilized in four distinct systems. These systems are 100% renewable and are processed in numerous ways with the integration of unique energy storage options to achieve the ultimate energy sustainability. Systems produce heating, cooling, electricity, and domestic hot water for a small city. The value that this thesis will bring is critical to the global sustainable development. The concept of net zero energy cities is novel, and the development and investigation of these systems will enrich the literature. This thesis will contribute to science by the following key deliverables:

- Developing a comprehensive smart city concept by integrating various domains
- Designing net zero energy systems for smart city applications
- Assessing the environmental perspective in a smart city model
- Investigating the economic implications of a smart city model

7.1 Conclusions

Based on the PCA analysis, the first two components account for approximately 80% of the variance in the original variable mix, which means that it is a reliable indicator for data analysis. The economy index is strongly correlated with the energy and infrastructure indexes, followed by a good correlation with the transportation, environment, and governance indexes. The energy index is strongly correlated with the infrastructure, environment, and governance indexes in sequence. The environment index is strongly correlated with the infrastructure index, followed by the energy and governance indexes. The governance index is strongly correlated positively with the energy and environment indexes. The smart society index is strongly correlated with governance, infrastructure, environment, and energy indexes. The infrastructure index is positively correlated with many other indexes, more strongly with the transportation, energy, and environment indexes and slightly strongly with the governance, society, and economy indexes. The last index, pandemic resiliency is interesting strongly correlated with the environment, energy, and the governance indexes.

According to the average results, the energy index has the lowest ratio, followed by governance and pandemic resiliency. On the other hand, infrastructure has the highest ratio, followed by the environment, economy, and transportation indexes. The smart index ratio for the environment index shows three clusters, where two clusters are below average and the last cluster is slightly above average, ranging from 0.75 and 0.86. Most of the cities in this study are below average on the society index. The average smart energy index ratio is 0.26, which reflects immense opportunities for improvements in this sector. Half of the cities in the study are below average, while the other half exceed the average smart index ratio for the energy index. The smart governance index ratio is 0.44 and cities vary on this front between 0.17 and 0.59. Montreal is the City with the highest smart governance index ratio, whereas Cairo has the lowest. Pandemic resiliency results also show considerable variation as some are performing very poorly with scores that are less than 0.2, while others are hitting the average, which is 0.45. Three cities were excluded from this averaging as they were considered outliers, namely Lima, Osaka and Sydney.

Based on the equal weighting scheme, the city with the highest SCI is Sydney at 0.72, whereas the city with the lowest SCI is Lima at 0.26. On the other hand, based on the sustainability triad scheme, the city with the highest SCI is Toronto at 0.77, whereas the city with the lowest SCI is Abuja at 0.31. Toronto, Vancouver, and Montreal remain part of the top 5 cities in the equal weighting, sustainability triad and energy focused schemes. In fact, the energy focused scheme places four Canadian cities at the highest SCI, with Montreal at the top, scoring 0.7 and Oshawa at 0.66. The lowest in this scheme remains Lima with a SCI score of 0.26. From a pandemic focused scheme, Sydney, Osaka, followed by Hämeenlinna score the highest with SCI scores of 0.81, 0.79, and 0.7, respectively. Energy and governance indexes are notably lower in values, suggesting that further investments and work need to be incorporated to achieve smarter cities across the world.

A clear exponential relationship is observed between the government effectiveness ratio and GDP per capita indicators with a p value of less than 0.05, suggesting a strong causative correlation between the two indicators. Considering COVID-19, digitalization and online services are booming, including government services. The impact of government digitalization on the smart governance index ratio show another exponential and a strong positive trend. This suggests that cities with higher percentages of digital services result in smarter governance. There is a mild positive relationship between smart governance and smart society indexes. In fact, the R value of 0.7 highlights that smart governance does positively correlate and lead to smarter societies. Based on this model, environment has an exponential positive relationship with economy. In other words, increases in the smart environment index ratio, results in exponential increases to the smart economy index with p value lower than 0.05, indicating significance between the two indexes. Similarly, the correlation between the society index and economy index shows significant positive exponential relationship. This means that enhancing the society index will result in exponential economic growth for the cities. The trend is supported with a relatively strong R value of 0.8.

The most efficient system performance is system 4, followed by system 5, achieving energy efficiencies of 74.6% and 60.8% respectively. The exergy destruction that these systems account for total up to only 30% of the total five systems exergy destruction rates.

Lifecycle assessment results followed the North American TRACI methodology. System 1, which is the BAU has the least environmental impact, due to Ontario's clean grid with emission factor of 0.000031 tCO_2eq/kWh. Human toxicity is the most impacted category that all systems contribute to, followed by global warming and acidification. Systems 2 and 3 account for a significant amount of emissions combined. The optimization study shows a saturation point reached after the 20th generation with the environment, transportation and pandemic categories achieving highest scores, using the genetic algorithm approach.

7.2 Recommendations

The concept of smart cities will evolve over time to refer to newly invented ideas. Therefore, it is critical for this concept to be boundless by time or space. In fact, there are numerous elements that are yet to be incorporated into the concept of smart cities.

- In the governance aspect for example, the emotional state of the city can be the focus for future work. What indicators accurately convey the emotional state of a city and how the data is processed methodically is also another aspect of research that can be explored.
- The lack of order and synchrony in government policies, when dealing with climate change and global warming is yet another aspect to be integrated to this vital concept.
- Other ethical-based attributes such as transparency, honesty and utilitarianism as opposed to capitalism, greed and mischief are examples of many soft-based points that can yield in

the happiness or misery of people and therefore, an important impact on the concept of smart cities.

- The introduction of a happiness index then can be useful for future researchers, yet challenging to develop and evaluate. While subjective wellbeing can be used, self-reporting and third party assessments can also be investigated.
- Future work can also upscale the smart city concept to evaluate bigger districts, states, and even countries by using this model as a reference infrastructure and curtailing the evaluation matrix to effectively reflect the evaluated entity, whether it be a small town, or a big state.
- On the social aspect, future studies can study the impact if any of key social parameters such as multiculturalism, equity, diversity and inclusion on the effectiveness of the city and its smartness.
- Further research is necessary on the impact and relationship of the pandemic resiliency aspect and the smart city concept. Furthermore, future investigations on the relatability of the pandemic to climate emergency scenarios need to be conducted and models need to be developed to articulate and visualize an accurate depiction of the catastrophes that cities must expect due to global warming.

These models need to highlight the economic repercussions, immediate and long-term threats that result from improper planning, and inconsiderate policy-making. International transparency needs to prevail in order to safely and meaningfully extract the lessons from the pandemic and build a resilient roadmap for the future to combat climate change and sustainably adopt effective strategies, infrastructure and policies. Lastly, further research is needed to develop effective and resilient energy policies and decabronization pathways to achieve carbon neutrality across cities by 2050 as per the Paris Agreement framework. These energy policies need to be developed at the municipal, provincial and federal levels simultaneously, collaboratively and seamlessly. Various sectors need to be addressed, including the residential, industrial, commercial, institutional and transportation sectors, all equally. Besides policy, the energy aspect need to be enhanced and further research is needed to invent and develop energy systems of various configurations and integrations for a wide range of applications, besides the main commodities of heating, cooling, domestic hot water and electricity.

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