A Resource Flow Typology of African Cities

By

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Declaration

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Abstract

Global urbanisation trends predict a future in which the already overburdened cities of Africa and Asia will house the bulk of the two billion new people born by 2050. This second wave of urbanisation will increase resource demands in these cities and extend the expanse of slums already surrounding them. Given the global imperative of sustainable development, and the existing imbalance of resource access, effective urban planning is necessary to meet this second urbanisation wave, and build resilient, equitable cities.

However, preliminary investigation suggests a lack of data-supported decision-making in cities of the global south, due either to limited collection of, or lack of access to, city-level data. This has led to many urban development programmes being implemented with minimal scientific backing to support the success of proposed policy or infrastructure innovations. This directly impacts a city's ability to reach service delivery, economic growth, and human development goals, let alone protect ecosystem services upon which it relies. This is particularly true in African cities, in which governments are (necessarily) more focused on delivery of basic services than on a greening or efficiency agenda. This is further compounded by the need for African cities to prepare adequate public services for the increased population expected in the second urbanisation wave. A quantitative assessment of cities' resource profiles can support policy makers in making informed decisions about infrastructure configurations in order to improve their resource management. To this end, methods to accurately estimate and analyse these data are necessary.

The primary objective of this study was to establish a resource consumption typology for African cities. Due to limitations in the availability and form of secondary data, this study shifted focus to explore how best to form a typology from limited data. It made use of data for 53 African nations and scaling theories proffered to estimate city-level economic and resource data for 120 African cities. The resultant resource profiles were then normalised and clustered in a number of ways to produce two national typologies and four city typologies.

Insights from these typologies both inform the method for categorising cities by socioeconomic or resource indicators as well as provide insights into the shape and magnitude of resource profile for multiple African cities. They also highlight the key drivers of resource consumption in these spaces. Future work involves validating the scaling method with locally acquired data so as to increase confidence in the city-level data, before settling on the preferred method for clustering cities.

Opsomming

Wêreldwye verstedelikingstendense dui op ‘n toekoms waarin die reeds oorlaaide stede in Afrika en Asië die grootste deel van die sowat twee biljoen nuwe mense teen 2050 sal huisves. Die tweede verstedelikingsgolf sal eise wat in hierdie stede op hulpbronne gestel word verhoog, en die uitgestrektheid van krotbuurtes wat hulle reeds omsingel, nog meer laat uitkring. In die lig van die wêreldwye noodsaaklikheid van volhoubare ontwikkeling en die heersende wanbalans wat toeganklikheid tot hulpbronne betref, is doeltreffende stedelike beplanning nodig om aan hierdie verwagte tweede verstedelikingsgolf te kan voldoen en lewenskragtige, gelyke stede op te rig.

Voorlopige ondersoek toon egter ‘n tekort aan data-gesteunde besluitneming in suidelike stede van die wêreld weens óf beperkte inwinning daarvan, óf gebrek aan toegang tot data op stedelike vlak. Dit het daartoe aanleiding gegee dat talle stedelike ontwikkelingsprogramme met minimale wetenskaplike steun, wat die sukses van voorgestelde beleids- of infrastruktuurinnovasies rugsteun, geïmplementeer is. ‘n Stad se vermoë om sy doelwitte ten opsigte van dienslewering, ekonomiese groei en menslike ontwikkeling te bereik, word sodoende gekortwiek om nie eens melding te maak van beskerming van die ekostelsel-dienste waarop hy staatmaak nie. Dit is veral die geval in Afrika-stede waar regeerders (uit noodsaak) meer gefokus is op die lewering van basiese dienste as op ‘n agenda vir vergroening en doelmatigheid. Dit word voorts verhewig deur die behoefte van Afrika-stede om doeltreffende openbare dienste op die been te bring vir die groter bevolking wat met die tweede verstedelikingsgolf in die vooruitsig gestel word. ‘n Kwantitatiewe vasstelling van die omvang van stede se hulpbronne, kan beleidskeppers help om ingeligte besluite te neem oor infrastruktuur-konfigurasie en sodoende die bestuur van hulle hulpbronne verbeter. Met dit as mikpunt, is metodes nodig om hierdie data korrek te bepaal en te analiseer.

Die hoofdoel van hierdie verhandeling was om ‘n hulpbronkonsumpsie-tipologie op te stel. Weens beperkinge wat betref die beskikbaarheid en vorm van sekondêre data, is die verhandeling se fokus verskuif om te bepaal hoe daar ten beste ‘n tipologie uit beperkte data gevorm kan word. Daar is van data rakende 53 Afrika-nasies, en skaal-teorieë aangebied deur gebruik gemaak om data oor die ekonomieë en hulpbronne van 120 Afrika-stede te bekom. Die hulpbron-vasstelling wat hieruit voortgevloei het, is vervolgens genormaliseer en

saamgevoeg op ‘n verskeidenheid van wyses om twee nasionale tipologieë en vier stadstipologieë te lewer.

Insigte wat dié tipologieë voortbring, lig die metode toe waarvolgens stede deur sosio-ekonomiese of hulpbron-aanwysers gekategoriseer word en bied ook insigte rakende die voorkoms en omvang van hulpbron-bepaling vir menige Afrika-stede. Hulle benadruk ook die sleutel-aandrywers van konsumpsie in hierdie opsig. Toekomstige werk sluit die bevestiging van die skaalmetode met plaaslik aangeskafde data in ten einde die vertroue in stadsdata te vermeerder alvorens daar op die voorkeurmetode vir die bondeling van stede besluit word.

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List of Abbreviations

AIRP	Average Income of the Rural Poor
AIUA	Average Income of the Urban Affluent
AIUP	Average Income of the Urban Poor
AUI	Average Urban Income
AUMRN	African Urban Metabolism Research Network
CDD	Cooling Degree Days
CP	City Population
CR	City Resource consumption
EoL	End of Life
EPA	Environmental Protection Agency
DMI	Direct Material Input
DMO	Direct Material Output
DPO	Direct Processed Output
GDP	Gross Domestic Product
GEC	Global Environmental Change
GNI	Gross National Income
GSS	Ghana Statistical Services
GWP	Gobal Warming Potential
HDD	Heating Degree Days
HDI	Human Development Index
LCA	Life Cycle Analysis
LEPO	Local and Exported Processed Output
MFA	Material Flow Analysis
MIT	Massachusetts Institute of Technology
MOSPI	Ministry of Statistics and Programme Implementation
NAS	Net Addition to Stock
NR	National Resource consumption
PWC	Price Waterhouse Coopers
RP	Rural Population
RPV	Rural Poverty
SFA	Substance Flow Analysis
TA	Transitions Analysis
TDO	Total Domestic Output
TMI	Total Material Input
TMO	Total Material Output
TMR	Total Material Requirement
UA	Urban Activity
UM	Urban Metabolism
UM-LCA	Urban Metabolism – Life Cycle Analysis
UN	United Nations

UP	Urban Population
UPV	Urban Poverty
UR	Urban Resource consumption
USA	United States of America
USD	United States Dollar

Resource Designations

TE	Total Energy Consumption
EL	Electricity Consumption
FF	Fossil Fuel Consumption
CO2	Carbon dioxide Emissions
TM	Total Material Consumption
Con	Construction Material Consumption
Ind	Industrial Mineral Consumption
Ore	Ore Consumption
Bio	Biomass Consumption
H2O	Water Consumption

Glossary of Terms

Africa - The use of *Africa* as a descriptive term has become popular throughout the world, conjuring the negative images of malnutrition, disease, slum dwelling, civil war, corruption, and harsh environments, while proffering some local *African identity*, internalising positive vibes of origins, ingenuity, shared identity and nebulous, red sunrises (Wainaina, 2005; Kuper, 2013). It began as an external title, and is propelled by rather summary references and limited focus in international media, which overlooks the subtleties of its different spaces and cultures (Kuper, 2013). However, this unity is fictitious in many aspects and every space in the continent is subject to its own histories, realities, and goals. The unfortunate outcome of this popularisation is that many academic studies, local and international, fall prey to this generalisation and their results may be questionable. For this study, Africa is simply a geographical term, and not meant to summarise or reduce the multitudinous ways of being throughout the continent.

Global North and Global South - The United Nations categorises nations of the world by their level of development, and we still find literature making use of the distinction between developed and developing nations, which elevates the status of developed nations. The distinction between Global North and Global South offers a terminology for even comparison of the different situations and agendas present in each space. Countries of the global north conventionally include the USA, Canada, Japan, Australia, New Zealand, the Asian Tigers (Hong Kong, Singapore, Taiwan and South Korea) and nations in Europe. Countries of the global south include all others.

Urban Metabolism - Urban metabolism refers to a complexity of socio-technical and socio-ecological processes by which flows of materials, energy, people and information shape the city, service the needs of its populace, and impact the surrounding hinterland. This is my own definition, synthesised from many in the literature. The usefulness of establishing the metabolism as an emergent property of the city is that it becomes a tangible attribute which can be measured, analysed and changed. Of course, as a complex emergence, any changes to singular city processes will have effects on the overall urban metabolism.

Sustainable Development – As popularised in the 1980s, sustainable development is development which meets the needs of the present without compromising the needs of the future. Understandably, there have emerged many responses to this, based on differing contexts, differing visions for the future and differing mechanisms towards achieving them (see Blewit, 2008). The most referenced conceptualisation of sustainability is finding an acceptable balance between three aspects of our world: the environment, the people and the economy, visualised as the three pillars, the three spheres or the three E's (environment, economics, equity) of sustainability.

Typology – A typology is a classification according to identified types or characteristics. It is an organisational tool which can be used for comparing individuals or groups by similarity or difference in characteristics.

Urbanism - Urbanism refers to the process of urbanisation (becoming urban space), to the urban proportion of a nation, and to the attributes of an urban space, be it the urban form, lifestyle of urban dwellers or mechanisms which shape their behaviours. For this study, urbanism will refer to way in which urban dwellers access necessary resources. This is typically determined by the value system engaged by city leadership.

Chapter 1: Introduction

1.1. Background

Humans have become an urban species. As of 2008, more than half of the human population occupies urban hives of activity (Brown, 2008; Grimm, Faeth, Golubiewski, Redman, Wu, *et al.*, 2008; UN-DESA, 2011). This number will continue to increase in what is described as the second urbanisation wave (Robinson, Swilling, Hodson & Marvin, 2012; Swilling & Annecke, 2012), which expects to see an additional 3 billion people living in African and Asian cities by 2050. Cities are concentrators of people and economic production, and therefore require large inputs of resources to fuel their development and growth. Cities currently produce 80 per cent of the global GDP and consume 75 per cent of global energy and materials (Robinson *et al.*, 2012). The concentration of resources forms large quantities of pollutants and wastes which, despite having originated in other regions are typically discarded into the surrounding environment, threatening natural systems as well as the ecosystem services upon which the city relies, such as water filtration, nutrient cycling in soil, or absorption of carbon by vegetation. Ozbekhan's (1970) *problematique,* Morin and Kern's (1999) *polycrisis* and Price Waterhouse Coopers' (2014) *collision of megatrends* are apt terms to describe the emergent issues of overpopulation, pollution, ecosystem degradation, biodiversity loss, scarce materials, social inequality, climate change and a loss of human connection to the natural world. As the concentrators of these crises, cities are where the desire for a sustainable existence must also be cultivated.

With the desire to achieve sustainable cities, it must be understood that the polycrisis is directly linked to the sourcing, conversion, use and discharge of resources in various forms. These flows of resources are intimately related to the social makeup and processes of cities (Hall, 2011), and make up the *urban metabolism*. Urban metabolism is defined as the "sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy, Cuddihy & Engel-Yan, 2007: 44). Analysis of the urban metabolism is necessary for understanding how cities may develop in the future and how they can support a growing population. The primary challenges in analysing urban metabolism are (i) a lack of city-level data required to undertake such analysis, particularly in Africa; (ii) a lack of standardised methodologies for assessing resource flows at city level; and (iii) the open nature of the city system (Ferrao & Fernández, 2013; Hoekman, 2015).

As an open system, requiring resource inputs and waste sinks which are outside of the city, it is questionable whether a city can become sustainable in its own right (Ferrao & Fernández, 2013). Despite this, mainstream sustainability approaches race to install technologies and programs that can undo environmental damage and shrink the toxic footprint. As an illustration, the ‘greening’ movement is marching through the developed world (or *global north*), though little has been examined about the expected results, and there is minimal scientific backing to demonstrate that it will be successful (Saldivar-Sali, 2010). It is also a march which most nations of the global south do not participate in, as they are focused on priorities of basic service delivery (Ferrao & Fernández, 2013), many without the networked infrastructures to which the world aspires: those which keep the waste out of sight, out of mind.

African cities are prime examples in which development aspirations conflict with a context of limitations, yet they may play an important role in achieving a sustainable future, as most have yet to establish widespread formal settlement and infrastructure systems. Africa currently shows the world’s highest population growth rates, focused in the cities of West, Middle and East Africa (see Figure 1-1 for a map of Africa). In addition, 62 per cent of urban dwellers in sub-Saharan cities live in slums, experiencing minimal or ineffective service provision. The millions of expected new urbanites will most likely increase this percentage (Robinson et al., 2012). With more funding poured into African nations for infrastructure development, an opportunity is created for identifying the most appropriate infrastructures (Robinson et al., 2013), systems which suit the needs of already overburdened cities, those which are expected to bear the brunt of the second urbanisation wave.

Figure 1-1: Political map of Africa, displaying capital cities, political boundaries and regional groupings (Nations Online Project, 2013).

Informed by the above issues, multiple groups are interested in how Africa's demographic change will affect its future resource consumption. The key interest of this investigation lies in quantifying material flows in an urban context, with the objective of informing appropriate design or policy interventions. A collaborative effort between Stellenbosch University and Massachusetts Institute of Technology, recognised as the African Urban Metabolism Research Network (AUMRN), has been investigating the resource consequences of a rapidly urbanising Africa. This study forms the initial part of this project. It is based on three recent documents:

The *City-Level Decoupling* report published by the United Nations Environment Program (UNEP) (Robinson *et al.*, 2012) builds on the assertion that cities hold a central role in addressing sustainable development goals and demonstrates the importance of infrastructure in the transition to sustainable systems. Global material and energy use is shown to be rising rapidly as cities have developed, with income levels rising even faster. In this way, income, or economic activity, has shown relative dematerialisation: this means that it takes fewer resources per unit to produce more income (Behrens, Giljum, Kovanda & Niza, 2007; Krausmann, Gingrich, Eisenmenger, Erb, Haberl, *et al.*, 2009). However, the aggregate amount of resources used is still rising. To address this, the report ties sustainable development to the imperative of decoupling: reducing the amount of resources needed for the same level of economic activity. Figure 1-2 demonstrates this goal, showing that resource decoupling is not enough, but suggesting that economic production needs to decouple from its environmental impact (ie. impact decoupling or absolute decoupling). As the conveyor of resources, infrastructure can be re-configured to achieve the resource efficiency required. Noting the uniqueness of city locations and functions, the report stresses the importance of developing alternative approaches to infrastructure implementation, suited to each city's context.

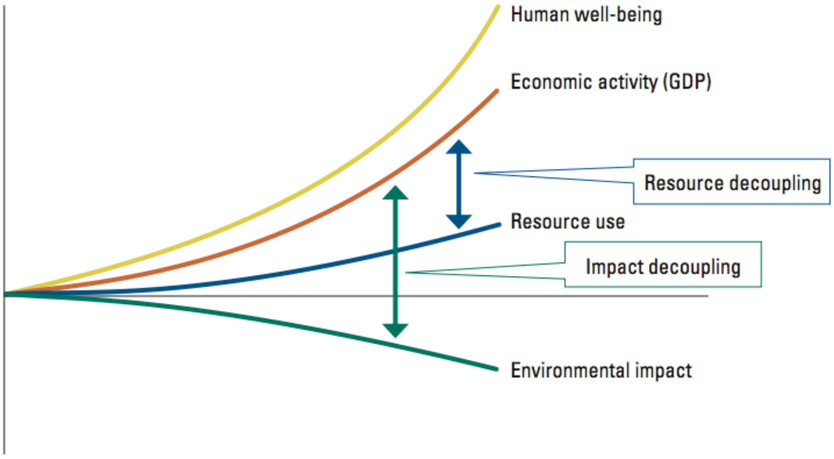


Figure 1-2: A representation of resource decoupling and impact decoupling (Robinson *et al.*, 2012)

Urban metabolism assessment tools for resource efficient cities, compiled by Robinson et al. (2013), takes its lead from the above report. With resource decoupling as the goal and noting that infrastructure investments are costly and time consuming, it proposes a rapid assessment tool framework for achieving urban resource efficiency. This framework aims to give city planners better insights into the tools which can potentially be utilised to answer specific questions relating to resource profiles, resource use and efficiencies of their cities as they relate to specific indicators; in this way, appropriate infrastructure choices can be made. For example, cities in water scarce climates may require infrastructure which conserves or recycles water. The steps of the proposed framework are shown in Table 1, along with the associated questions and tools for enacting them. This study focused on step one: forming urban resource profiles for African cities.

Table 1-1: Rapid assessment tool framework (Robinson *et al.*, 2013: 58)

STEP	RESEARCH QUESTION	PROPOSED TOOL
1. Understand the city's resource profile	What are the city's resource challenges and opportunities?	City Categoriszation Tool
2. Establish a resource efficiency baseline	How resource efficient is the city?	Resource Efficiency Baseline Assessment Tool
3. Set resource efficiency goals with timelines	What levels of resource efficiency should the city aim to achieve over time and which areas should be prioritised?	Goal Setting Tool
4. Identify suitable infrastructural approaches	What are the city's options for improving resource efficiency based on their circumstances?	Infrastructure Option Scoping Tool
5. Identify best infrastructure approaches	Which interventions will be most effective in achieving the city's resource efficiency goals?	Infrastructure Approach Selection Tool
6. Formulate an integrated infrastructure strategy	What milestones need to be achieved in order to reach resource efficiency goals?	Integrated Infrastructure Strategy Formulation Tool
7. Monitor progress	Is the city on track to reach its resource efficiency goals?	Resource Efficiency Performance Assessment Tool

A Global Typology of Cities, a master's thesis completed by Saldivar-Sali (2010), further explored in Section 2.7.3, is the first categorisation of global cities by resource profile. The primary arguments used in creating the typology of cities are that: (i) it is possible to track some of the important resources that urban dwellers consume using a limited number of attributes; (ii) cities can be classified into different types based on their metabolic profiles (Saldivar–Sali, 2010). The city attributes used by Saldivar-Sali (2010) included population, population density, climate zone, affluence and inequality. These predictor variables, when correlated to resource and energy consumption data, organised 155 cities into 15 metabolic profiles (Saldivar-Sali, 2010). The typology can be utilised to compare the resource consumption efficiency of one city relative to others.

The need for a resource consumption typology of cities is informed by the need to (i) examine the global impact of cities, (ii) understand future urban growth and consumption trends, and (iii) determine the efficacy of sustainability initiatives. A typology demands less research time and funding than individual city analysis and allows the examination of cities' relative consumption. The typology acknowledges that while all cities demonstrate unique consumptive behaviours, cities also share many behaviours (Fernández et al., 2013). To this end, grouping 'like cities' allows the formation of recommendations applicable to many cities and situations. The formation of an *African* city typology aims to provide insights into the more subtle differences between cities on this continent, which are overshadowed in comparisons with cities of the global north.

1.2. Problem statement

The preliminary investigation suggested a lack of data-supported decision-making in developing cities, due either to limited collection of, or lack of access to, city-level data. This has led to many urban development programmes being implemented with minimal scientific backing to support the success of proposed policy or infrastructure innovations. This directly impacts a city's ability to reach service delivery, economic growth, and human development goals, let alone protect ecosystem services upon which it relies. This is particularly true in African cities, in which governments are (necessarily) more focused on delivery of basic services than on a greening or efficiency agenda (Ferrao & Fernández, 2013). This is further compounded by the need for African cities to prepare adequate public services for the increased population expected in the second urbanisation wave. A quantitative assessment of cities' resource profiles can support policy makers in making informed decisions about infrastructure configurations in in order to improve their resource management. To this end, methods to accurately estimate these data are necessary.

1.3. Research objectives

The main objective of this study was to establish a resource consumption typology for African cities. This objective included the following sub-objectives:

1. To identify and select representative cities for investigation that captures relevant attributes, such as demography, region, climate zone, income, poverty level, or function
2. To demonstrate the scope of available resource consumption and socioeconomic data for selected African cities
3. To establish and use robust statistical methods to estimate city-level data
4. To group cities appropriately based on available raw and estimated data

5. To determine the predictor variables which influence resource consumption

1.4. Delimiting the scope of the study

The scope of this study was limited to examination of:

- Cities within the 54 recognised African nations
- At least three cities per country, where possible and appropriate, and all discoverable cities with populations over one million people
- Stellenbosch, South Africa was included as this study was completed at Stellenbosch University, and its inclusion would be useful to reference in future local research.
- The most recently obtained data after the year 2000
- Eight resource indicators, including consumption of total energy, fossil fuels, electricity, biomass, industrial minerals, construction materials, total materials and water, as well as emissions of carbon. Solid and liquid waste was not accounted for and no gaseous wastes besides carbon dioxide.
- Only formal resource flows were considered. The informal or illegal use of resources was not necessarily accounted for.
- Data were gathered from open sources. While some data were available for purchase, the cost was prohibitive.

1.5. Chapter outline

Chapter 1 has provided an introduction to some challenges and opportunities present in African cities, presented the concept of urban metabolism as a means for understanding cities and stated the desired research objectives of this study

Chapter 2 reviews the literature, beginning with differing city definitions, urban border delineation, conceptions of city systems and the concept of socio-metabolic flows. This leads into a discussion of urban metabolism, the various methods for its analysis, and its usefulness as a concept, particularly in relation to global resource impacts and meeting urban sustainability goals. This is followed by a reflection on the global socio-metabolic transition and its relation to city development and modes of urbanism, which affect resource distribution. A discussion of differing sustainability imperatives in the global north and global south leads into an examination of African urbanism, and the potential manifestation of a sustainable African city. Finally, an overview of urban scaling techniques and existing city typologies and indices concludes with the results of the global typology of cities and some expectations for the typology of African cities.

Chapter 3 provides the method for this study. It outlines the quantitative procedure for building a robust categorisation of African cities using resource variables. The methods involve sourcing and scaling data from national level, estimating missing indicators such as urban income and degree of urban primacy, and selecting the cities to include in the typology. The chapter presents various pathways for scaling and clustering cities, and identifies the methods utilized in this study. These pathways prove useful in extending the typology to cities that lack resource data and for which only minimal demographic or economic data are available.

Chapter 4 describes the results of the study, offering initial insights for the samples of nations and cities. It shows the resultant values of an urban primacy indicator and estimated income. It then shows two typologies of nations and four versions of city clustering based on different clustering methods. The resource profiles for each cluster of cities are described and their validity and limitations are explored.

Chapter 5 provides the conclusions and recommendations of the study.

Chapter 2: Literature Review

2.1. Introduction

The future of African urbanism is necessarily one of imagination. In much of the discourse surrounding the importance of cities in achieving goals of sustainable development, scholars voice a frustration in the lack of attention given to the African continent (Parnell & Pieterse 2014; Swilling & Annecke, 2012; Pieterse, 2009; Fernández, 2014). In discussions ripe with impending global crises, there are minimal strategies emerging on how to take charge of these overburdened, rapidly growing cities. Any such developments must contend with a majority-slum populace lacking healthcare, education and employment, hindered by their political leaders' denial of urbanisation or sense of helplessness with policy options (UN-DESA, 2011; Pieterse, 2014). They also face an assumptive faith in the socioeconomic benefits of urbanisation (Turok, 2014), and the realities of ecological limits to growth. While most of the world's cities have developed without limits, Africa is in a unique position of having to bound its development with concerns for the global impacts of climate change and resource scarcity (Parnell & Pieterse, 2014). Despite facing multiple crises and limited government responses (Pieterse, 2014), the literature includes a clear optimism for the cultural, political, economic and technical innovations which will usher in new forms of Africa-specific urbanisms.

Having already established cities as concentrators of population, economic activities, the consumption which accompanies these, and therefore of environmental impacts, this chapter first explores some definitions of a *city*, including as a socio-ecological system and using the conception of *resource* or *socio-metabolic flows*. It then demonstrates how the concept of *urban metabolism* has shaped the understanding of resource consumption in cities, and how it explains different forms of urbanism and the transition towards a *sustainable city*. This transition is motivated by differing sustainability agendas of the global north and global south, an exploration of which provides further context for discussions surrounding the growth of African cities. Finally, the chapter provides an overview of some existing national and city-level typologies and the global typology of cities that have informed the development of the typology of African cities in this study.

2.2. Defining the city

This section explores a diversity of city definitions with the aim to demonstrate the inconsistency with which city borders are delineated and the implications for collecting reliable data. Additionally, two conceptualisations of cities are introduced: that of socio-ecological systems, by which we can understand the interrelation of city structures and functions; and that of flows, a conception for illustrating the movements of resources through space. This sets the stage for discussions of urban metabolism.

2.2.1. Demographics, function and character

A difficulty pervading urban studies is that a suitable definition of a city has not been agreed upon (Weisz & Steinberger, 2010). This relates with the changing nature of cities as well as their diverse incarnations. For this study, a city definition is needed to enable consistent data collection and allow valid comparison. Frey and Zimmer (2001: 25) consider the city "to be an administrative definition that places a boundary on a contiguous urban area". In this way, defining the city is dually concerned with the definition of urban space as well as delineation of a city boundary. Contemporary definitions of urban areas are mostly focused on distinguishing between urban and rural space, suggesting that the entire planetary landscape fits into either category (Frey & Zimmer, 2001). This is somewhat limiting, as it ignores the forms of suburban or peri-urban space. The attributes used to distinguish urban space vary by country. In a United Nations overview of African definitions of urban space, criteria include minimum population, minimum number of constructions within a specified range of each other, presence of a local authority or administration, and a majority non-agricultural economy (United Nations, 2012: 100).

Frey and Zimmer (2001) identify three elements of urban definitions. These include: (i) a spatial or ecological element, (ii) an economic or functional element, and (iii) a description of social character of a city. The first two are described in Weisz and Steinberger's (2010: 186) conception of a city as a "specific form of human settlements that is characterised by high concentration of biophysical structures, inhabitants and socioeconomic activities along with a minimum size". The spatial distinction remains a matter of determining a specific inclusion threshold. For example, Ethiopia indicates settlements of more than 2,000 people as urban, while Senegal's minimum is 10,000. Definitions based on population do not yet provide an explicit guide for how to bound these settlements. Algeria states that urban settlements demonstrate more than 100 constructions no less than 200 meters from each other (United Nations, 2012).

The economic or functional element of a city is typically associated with predominantly non-agricultural activity. However, as many cities still retain agricultural industries, Frey and Zimmer (2001) suggest that a diversity of functions is more indicative of a city. This is what several authors regard as an *agglomeration economy*, which results from the concentration of multiple industries (Frey & Zimmer, 2001; Fernández, 2014). Fernández (2014: 597) explains that "cities arise from the combination of diverse and differentiated skills (workers) coupled to organised labour opportunities (firms) within the context of close proximity of housing and provision of transportation to produce the magic elixir that catalyzes the local urban economy". This image captures the hopes for what a modern city of the global north should be, an image to which many cities of the south aspire (Watson, 2009). However, it may not necessarily hold true for African cities, in which the primary economic drivers are not necessarily diverse, whose workers are often migratory, and whose progress through industrialisation is often suggested to be limited (Fay & Opal, 1999; Parnell & Pieterse, 2014; Turok, 2014). This aspiration towards a modern city may also be detrimental to its development, as 'undesirable' activities or citizens are shunned to the periphery, by the interests of a growing middle class (Watson, 2009). Such examples include barring informal vendors from the city center or providing preferential service delivery to affluent areas, such as with Accra's biased electricity load-shedding implementation (Aidoo, 2015). Watson (2009) suggests that a new image of a city of the global south should be cultivated and idealised amongst its inhabitants.

The *social character* of a city indicates specific lifestyles molded by the concentration of people and technologies in cities (Guy & Marvin, 2001). The social character can be a positive attribute such as the ease of lifestyle afforded by networked infrastructure (e.g. the instant delivery of water into one's home through piped infrastructure). It can also be a negative attribute like crime or pollution, or an abstract sense of place. An illustration of social character is provided by Swilling and Annecke (2012: 109–10), who analyse a juxtaposition of public space in Lagos and London: "what allows us to distinguish each place is not reducible to a particular economic structure or spatial configuration or mode of governance, but rather the recognisable pattern created by … complex mixes of flows that cannot be predicted with any precision prior to the actual experience". There are many allusions to the city as a flexible, changing entity. Simone (2010) uses the term *cityness* to demonstrate that the city is continuously remaking itself, with multiple operations upon each other that are separate but aware of the other. Cityness is something imbedded in all urbanites, yet taken for granted, as simply "the common sense of our urban experience" (Simone, 2010: 3). Social character may also be demonstrated in the epithets of cities, used to attract visitors or demonstrate the pride or frustration of its citizens. African examples include Cape Town as South Africa's 'Mother City,' Addis Ababa as 'Diplomatic Capital,' Johannesburg as the 'City of Gold,' Kumasi as 'The Garden City,' Niamey as 'La Ville Coquette' (The Charming Town) or Cairo as the "City of a Thousand Minarets".

Contrary to these qualitative visions of uniqueness of cities, some researchers argue that cities are more alike than they appear. Many aspects of a city's character are in fact calculable as relationships to city size or affluence. In the first incarnation of an oft repeated experiment, Bornstein and Bornstein (1976) demonstrated that walking speed is positively correlated to city size: people in larger cities tend to walk faster. They suggest this occurrence could be psychological protection against an increased number of stimuli. Wirtz and Ries (1992) take this further in demonstrating that walking speed is dependent (among other factors) on age (younger people walk faster) and sex (males walk faster). They offer an examination of city makeup, which showed that larger cities tend to have larger proportions of youngsters. This explains why some large cities showed slow walking speeds: Berlin, for example had a larger proportion of older people, and slower walking speeds (Wirtz & Ries, 1992). Bettencourt et al. (2007) collect a comprehensive set of empirical data with which to determine relationships between population size and multiple city attributes. Such attributes range from human needs, such as housing, water supply, electricity consumption, and infrastructure rollout, to outcomes of urbanisation, such as new patents, inventors, wages, cases of disease and crime. Each of these attributes present different forms of growth in relation to city population growth, outlined more specifically in Section 2.8 of this study. The unique perspective offered by this research is that urban processes are rather homogeneous (Gabaix, 1999) and, despite vast historical and contextual differences, cities are all essentially versions of each other, simply at different stages of growth, along very similar paths. The tangible, yet unnamable uniqueness of a city's social character remains a worthy discussion.

City definitions also vary depending on intended use, be they for administrative, research or policy purposes. The UN defines multiple levels of urban form, from *city proper* to *city-*

regions, as listed in Table 2-1. An oft-used definition is that of *urban agglomeration,* which refers to “a built-up or densely populated area containing the city proper, suburbs and continuously settled commuter areas or adjoining territory inhabited at urban levels of residential density”. With flexible definitions of urban space, defining urban boundaries remains a challenge; in attempts to categorise Belgian city formations and boundaries, Tannier and Thomas (2013) note that, like urban definitions, boundaries are dependent on either functional or morphological attributes. This is shown by Barles (2009), who demonstrates the different incarnations of Paris when examined from three different scales: city proper, city and suburbs, and whole bioregion. This distinction showed how the distribution of functions around a city impacts resource flow analysis. Administrative boundaries may underbound or overbound the actual built area and offer insights into how much space the city has available for expansion. While researchers may wish to stay clear of administrative borders, in hopes of studying the true form of the city, administrative boundaries are typically accepted in research because data is often unavailable or difficult to collect (Frey & Zimmer, 2001). For example, a city could be effectively bound by mapping the commuting patterns into and out of central hubs, particularly as this pertains to economic productivity (“economic advantages of proximity diminish with distance from the city core” (Turok, 2014:73, citing Rice et al., 2006). Kennedy et al. (2014) assert that the form of megacities could be understood as a common *commutershed*, sharing labour and real estate markets. However, commuter data is difficult to attain. Additionally, any administrative or definitional changes to boundaries lead to challenges in collecting consistent data over time (Frey & Zimmer, 2001).

Table 2-1: Definition of urban formations (Source UNICEF, 2012:10–11)

Designation	Description
City proper	The population living within the administrative boundaries of a city.
Urban agglomeration	The population of a built-up or densely populated area containing the city proper, suburbs and continuously settled commuter areas or adjoining territory inhabited at urban levels of residential density.
Metropolitan area	A formal local government area comprising the urban area as a whole and its primary commuter areas, typically formed around a city with a large concentration of people
Urban sprawl	Also ‘horizontal spreading’ or ‘dispersed urbanisation’.

Peri-urban area	An area between consolidated urban and rural regions.
Megacity	An urban agglomeration with a population of 10 million or more.
Metacity	A major conurbation – a megacity of more than 20 million people.
Urban corridor	A linear ‘ribbon’ system of urban organisation: cities of various sizes linked through transportation and economic axes, often running between major cities.
Megaregion	A rapidly growing urban cluster surrounded by low- density hinterland, formed as a result of expansion, growth and geographical convergence of more than one metropolitan area and other agglomerations.
City Region	An urban development on a massive scale: a major city that expands beyond administrative boundaries to engulf small cities, towns and semi-urban and rural hinterlands, sometimes expanding sufficiently to merge with other cities, forming large conurbations that eventually become city-regions.

The choice of administrative boundary is important, as 45 per cent of the 1.4 billion urbanites expected by 2020 will be in peri-urban areas, spaces typically outside of local administrative boundaries. These areas display what Allen (2014: 523) terms *shifting urbanism*: areas shared by different and competing interests such as farming, mining, industry, city management facilities (e.g. water treatment), middle class residence, and informal settlers. Allen (2014: 522) asserts that it is in these peri-urban areas or ‘the city to be’ where the battle for sustainability will take place. In fact, the State of African Cities report (UN Habitat, 2010: 20) suggests that cities would benefit by extending their administrative boundaries to account for the expected future growth, so as to include citizens in the neighboring urban nodes.

There remains no consensus for how to delineate borders of urban agglomerations. For the purposes of this study, primarily involved with demographic attributes, the UN definition of *urban agglomeration* is used for consistency. In gathering data, both the administrative area and built area were examined to potentially include areas of the city excluded by any underbound administrative borders or demonstrate areas for growth.

2.2.2. Socio-ecological systems

Cities have been recognised as open systems by various scholars (Du Plessis, 2008; Weisz & Steinberger, 2010; Swilling, Robinson, Marvin & Hodson, 2011; Golubiewski, 2012; Robinson *et al.*, 2012), though they may contain multiple closed systems. They are also conceptualised as complex systems (Grimm *et al.*, 2008; Ravetz, Roberts & George, 2009; Ferrao & Fernández, 2013) though Swilling and Annecke (2012) caution against letting this title guide a search for complexity when some aspects of a city may not be complex (see Cilliers, 2000a, b, for characteristics of complex systems). Studying systems requires examining the relationships between elements, instead of the elements themselves (Morin, 1992). Along these lines, Ravetz et al. (2009: 28) conceive of the *human urban environment* as "the relationships between the people, the economy, the city form and fabric, and the environmental qualities, flows, pressures and patterns which interact with these". Cities are the subject of many discourses which reference the adaptability of an ecosystem, such as new ecological thinking, industrial ecology, and ecological design. In this way, a city can be conceived of as its own ecosystem in which humans are participants and influencers (Du Plessis, 2008; Golubiewski, 2012). Indeed, Barles (2010) offers a conception of a city as an *anthroposystem*, while Grimm et al. (2008: 756) describe cities from the urban ecology perspective as "heterogeneous, dynamic landscapes and as complex, adaptive, socio-ecological systems, in which the delivery of ecosystem services links society and ecosystems at multiple scales". In a classification of human settlements by resilience, Alessa et al. (2009: 31) define these socio-ecological systems as "comprised of feedbacks among human values, perceptions and behaviours, and the biophysical components of the ecosystems in which people live". Complexity theory may describe the city as an emergence of multitudes of relationships along many levels of internal socio-technical functions (Swilling & Annecke, 2012), which is nested in a hierarchy of systems: from city subsystems, to regional, national and global systems (Geels, 2002).

These references to systems and feedbacks allude to the notion that urban infrastructure systems involve a certain lock-in of social behaviours to specific technologies, thus their description as *socio-technical systems* (Guy & Marvin, 2001; Swilling *et al.*, 2011; Hodson, Marvin, Robinson & Swilling, 2012). Lock-in is inversely related to a city's capacity for change and any intended changes must necessarily involve both a social and technical approach (Fernández, 2014). In their discussion on building capacity for infrastructure innovations, Swilling et al. (2011: 11) explain that "managing change in existing cities and infrastructures demands a focus on the complexity of incumbent socio-technical arrangements, and reconciliation of the competing interests of multiple stakeholders".

2.2.3. A society of flows

As centers of economic and industrial production, fueled by a populace which needs resources and services in order to lead quality lives, cities must process huge amounts of resources. This concentration of resources and their associated wastes has impacts on the city's environmental hinterland, the area upon which a city relies to procure resource inputs and to disperse wastes. The hinterland may also be conceived as the provider of ecosystem services, or *green infrastructure*, which feeds the city, filters its water, disperses its pollutants and cleans its air (Hall, 2011; Cilliers, Cilliers, Lubbe & Siebert, 2013). Describing cities in terms of resources requires a conceptualisation which captures this dependence on the movement, use and disposal of resources for building and sustaining cities.

Castells (1996: 412) describes society as "constructed around flows: flows of capital, flows of information, flows of technology, flows of organisational interactions, flows of images, sounds and symbols… by flows I understand purposeful, repetitive, programmable sequences of exchange and interaction between physically disjointed positions held by social actors". This concept has been adapted by industrial ecologists who establish infrastructures as the conveyors of material or energy resources, described as flows (Robinson *et al.*, 2012; Swilling & Annecke, 2012; Ferrao & Fernández, 2013). Describing resources this way allows the categorisation of similar materials and associated infrastructures. This is invaluable in addressing targets for resource and impact decoupling (UNEP, 2011). It also provides a medium for describing resource relationships in simple terms, enabling easy communication with policy makers, while still allowing detailed quantitative analysis (Kennedy, Pincetl & Bunje, 2011). Finally, it offers a way to show the connectivity and similarity of urban processes, be they social or material (Hall, 2011).

These flows may describe a single substance, such as nitrogen or water, or a system which includes multiple forms of material or energy. For example, a nutrient flow may include food, faeces and water, or may track specific chemicals. Flows enter the city from a local or global hinterland and are converted for use; some may remain in the system and build on the material stock, while the rest can either be recycled as a new internal input or become a waste output (Robinson *et al.*, 2012). For example, an energy flow could consist of an input of coal, conversion into electricity that is used in city processes, and an output of carbon dioxide. Figure 2-1 is a Sankey diagram for a water flow in New Delhi. Sankey diagrams were named for Matthew Sankey, who first used the diagram to demonstrate energy flows in a steam plant (Schmidt, 2008). Using quantitative measures, sankey diagrams visually demonstrate the magnitude of each flow and the ways in which they are made usable by a city. In so doing, it provides simple insight into where resource flow interventions can be made. The arrows on the right denote stages of flows as *sources, converters, demands, re-converters* and *sinks*. These are the points at which socio-technical innovation would be able to transform flows (Robinson *et al.*, 2012). For example, Figure 2-1 shows a grey water reclaimer returning a portion of water to the demand level.

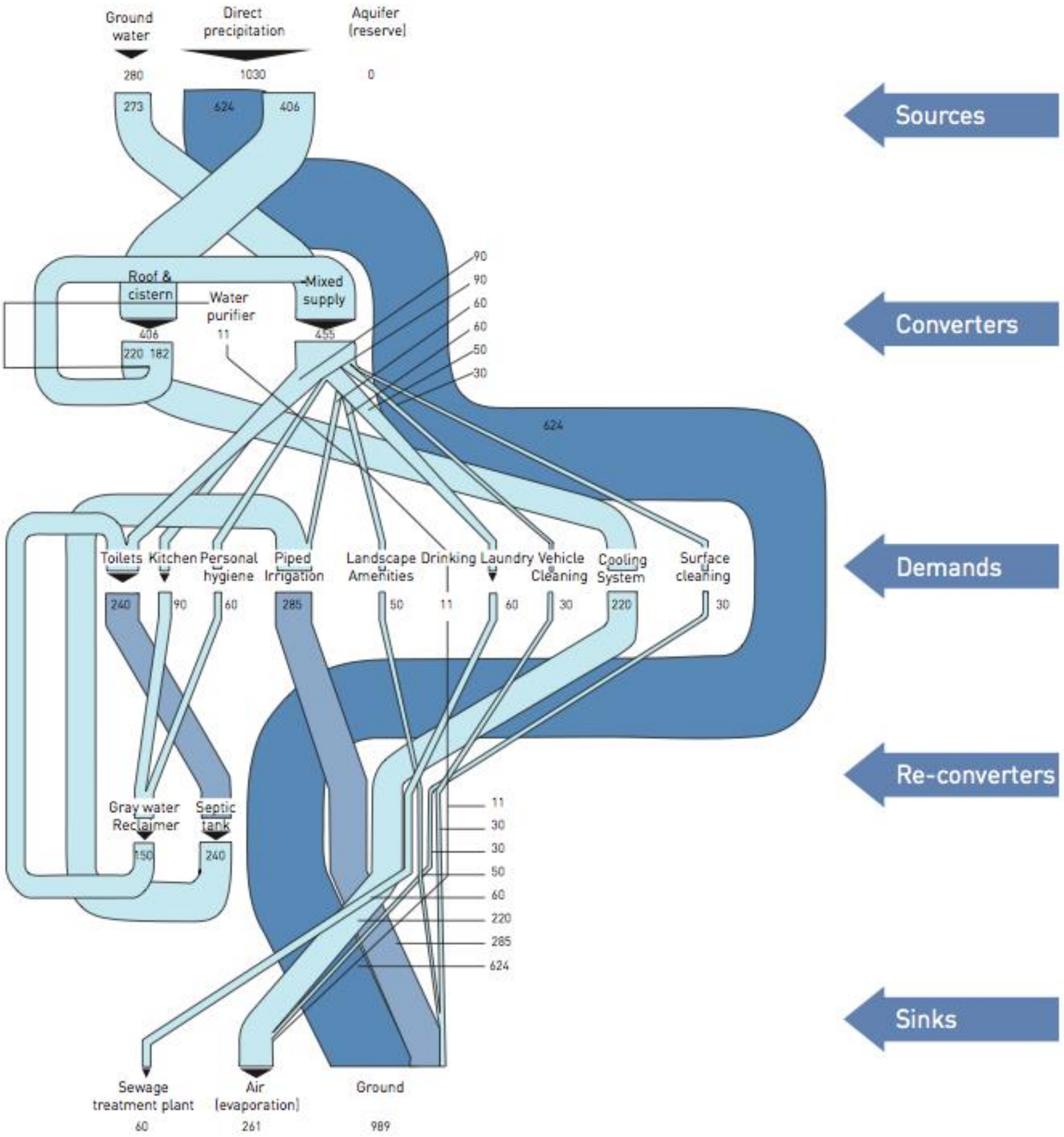


Figure 2-1: A Sankey diagram which observes the flow of water through a system in New Delhi (Robinson *et al.*, 2012: 26).

Industrial ecologists (e.g. Barles, 2009, 2010; 2013; Kennedy et al., 2011; Zhang, 2013) identify four flows: energy, water, materials, and nutrients. These bespeak a technological approach, while social scientists, such as Annecke and Swilling (2012), promote a socio-technical approach. Similarly to Guy and Marvin (2001), they identify flows as *socio-metabolic flows*: by how they are used in society. These are the flows of energy, water and sanitation, municipal waste, goods and people, information, and food. As the concept of flows expands across disciplinary borders, this conception may become useful: for example through viewing people as both systemic change agents as well as flows in the system. However, given the focus of this study on exploring resource consumption, it retained focus on the industrial ecology flows of energy, materials, water and nutrients.

2.3. Urban metabolism

This section explores the study of urban metabolism, through definitions and applications. With the occurrence of multiple definitions of urban metabolism come multiple approaches for analysing it and as such, there remains no consensus for the appropriate method of analysis. Additionally, while urban metabolism studies are increasing in quantity, there are limited utilisations of this concept in the global south. This may be predominantly due to data scarcity and suggests a need for investing in more research capacity on the continent. It may also be beneficial to develop a specific method for urban metabolism analysis in African urban contexts. While consensus on urban metabolism analysis methods is still developing, lessons from these analyses are already vital to shaping cities, and cities would benefit from the promotion of a practice of flow management by city decision makers. Finally, urban metabolism fits into a larger agenda of sustainable development; hence there is a voiced need to extend urban metabolism studies to include indicators of sustainability.

2.3.1. Definition and concepts

The popularity of the urban metabolism concept in multiple disciplines has generated many definitions which, by necessity, have reduced its complexity to remain within particular foci of study. The challenge voiced by many (e.g. Barles, 2010; Kennedy et al., 2011; Mostafavi et al., 2014; Musango, 2013; Weisz & Steinberger, 2010) is that no common understanding exists for how to explain metabolism in the urban context, and the extent to which the concept can draw on definitions from other fields, such as biology. There is a call to define some common conventions surrounding the future of this potentially transdisciplinary topic, in order to provide better decision-making tools for urban design, management and policy (Barles, 2010; Kennedy *et al.*, 2011; Musango, 2013). Zhang (2013) and Wachsmuth (2012) identify Karl Marx as the first to appropriate the term *metabolism* for the social sciences. In 1881 he used it to describe firstly "the human transformation of nature through labor and [secondly] the capitalist system of commodity exchange. Marx was also the first to use the concept of social metabolism to question the apparent separation between human beings and their environment" (Wachsmuth, 2012:506–7).

The first use of metabolism in reference to a city is attributed to Abel Wolman, in his explanation of the processes of a hypothetical American city. Wolman (1965: 156) explains that "the metabolic requirements of a city can be defined as all the materials and commodities needed to sustain the city's inhabitants at home, at work and at play". A few of scholars (Warren-Rhodes & Koenig, 2001; Kennedy *et al.*, 2007), taking the lead from the context of Wolman's (1965) article, suggest that the discipline of urban metabolism evolved in response to increasing air and water pollution caused by the city. Warren-Rhodes and Koenig (2001: 429) also explain urban metabolism as a quantitative measure of "a city's load on the natural environment". Barles (2010), however, argues that the concept, though as yet untitled, was present in 19th century explorations into how to supply growing cities, particularly surrounding the cycle of nutrients (this study of *urban chemistry* diminished with the advent of fertiliser). While Wolman (1965) demonstrates the usefulness of urban metabolism in understanding the polluting nature of cities, his definition refers not to environmental impact, but to the needs of a city's people. This focus relates neatly with the 'needs' agenda of sustainable development, particularly in the global south, where improving people's access to resources is a priority (to be discussed in Section 2.5.2). However, resource access is a topic which seems to have become lost in discussions of resource flows.

The increase in urban metabolism studies has given rise to a methodological description (Kennedy *et al.*, 2007; Barles, 2009; Ferrao & Fernández, 2013; Musango, 2013; Fernández, 2014). For example, Abou-Abdo et al. (2011: 1) reference urban metabolism as "a *methodology* for examining the resource demands of cities". Yet such a definition precludes the opportunity to directly describe the metabolism of a specific city, for example when comparing the metabolism of Johannesburg with the metabolism of Cape Town. In an explanation of what the urban metabolism actually consists of Broto et al. (2012: 851) suggest that it refers to “the exchange processes whereby cities transform raw materials, energy, and water into the built environment, human biomass and waste”. Along similar lines, Kennedy et al. (2011: 44) offer their oft-quoted description of urban metabolism as “the sum total of the technical and socioeconomic processes that occur in cities resulting in growth, production of energy, and elimination of waste”.

Further attempts to explain urban metabolism have led to a reliance on the legacy of *metabolism* as a biological and ecological term. In biology, ‘metabolism’ denotes the chemical processes by which organisms break down substances (catabolism) and build new molecules (anabolism) to release, store or utilise energy (Smith & Smith, 2006). Likening a city to an organism suggests similarities between the functional networks which distribute energy, water and goods throughout a city, and the vessels or cellular links, for example, which keep an organism alive. This has led to a conception in which the un-sustainability of a city is attributed to a disorder of its metabolism (Newman, 1999; Brunner, 2007; Zhang, 2013). This similarity is further supported by the linearity of an organism’s metabolism (input, throughput and output) to which modern cities conform. Multiple studies reference the organism metaphor (e.g. Gandy, 2004; Reddy, 2013; Rosado et al., 2014), yet this biological understanding is conflicted with the growing conceptualisation of a city as its own ecosystem. In ecology, ‘metabolism’ refers to the aggregate processes of all organisms in the ecosystem, generally represented as circular flows of energy through production, consumption and decomposition (Smith & Smith, 2006; Golubiewski, 2012). While biology focuses on individual organisms, ecology examines the relationships between organisms and between their environments. In this way, the ecosystem concept is more intuitively connected to systems thinking (Grimm *et al.*, 2008; Musango, 2013). Urban ecology is specifically focused on the relationships within cities, leading to a more internal examination of how functional systems can be reworked in more ecological ways; that is, to include more circular systems which limit waste output (Girardet, 2004; Grimm *et al.*, 2008). As mentioned earlier, many assert that rather than simply *similar* to ecosystems, cities *are* unique ecosystems in their own right (Du Plessis, 2008; Grimm *et al.*, 2008; Golubiewski, 2012), conducting their own flows and fit with their own drivers and responses. However, Gasson (2002: 3) reminds us that cities differ critically from natural ecosystems, by demonstrating “broken” flow cycles (linear systems) and a clear lack of adherence to dynamic equilibrium, by which an ecosystem manages populations of its inhabitants. Some studies use the metabolism of ecosystems as their central analogy (e.g. Bristow & Kennedy, 2013; Kennedy et al., 2007; Newman, 1999);

however, more often than not, both metaphors are used in tandem (e.g. Broto et al., 2012; Ferrao & Fernández, 2013; Gasson, 2002; Graedel, 1999; Huang & Chen, 2009; Kennedy et al., 2011; Wachsmuth, 2012; Zhang, 2013).

The use of these analogies, however, often includes: (i) a lack of consistency with the terms' definitions in their original disciplines, (ii) attempts to utilise both analogies in the same discussion, without noting inconsistencies, (iii) attempts to align irrelevant aspects of cities to biological systems in order to preserve the consistency of these analogies, and (iv) a tendency to incorrectly use ecological or biological concepts (Golubiewski, 2012). The end result is to confuse those who are familiar with these concepts or an educational disservice to those who are not. This is unfortunate, as stronger understandings of biology and ecology would be beneficial to the study of urban metabolism, particularly due to the close relationship between a city and the ecological services of its hinterland. To fill this gap, urban metabolism studies could seek further participation by natural ecologists and ecological designers, and adopt the aspirations of biomimicry: to learn from nature (see Benyus, 1997). Golubiewski (2012) calls for the removal of *metabolism* from the disciplinary title, yet it has become imbedded in discussions of cities and resources. Indeed, some studies bypass the biological legacy of the term and explain it effectively nonetheless (e.g. Abou-Abdo et al., 2011; Barles, 2009; Brunner, 2007; Fernández, 2014; Guo et al., 2014; Wolman, 1965).

For the remainder of this study, urban metabolism will refer to the collection of complex socio-technical and socio-ecological processes by which flows of materials, energy, people and information shape the city, service the needs its populace, and impact the surrounding hinterland. This allows a conception in which minute changes to the system may affect the overall metabolism, and we are presented with the potential to (re)design an urban metabolism for sustainable cities (Brunner, 2007; Kennedy *et al.*, 2011)

2.3.2. Transdisciplinary potential of the urban metabolism concept

The need for city planners and political leaders to address the imperatives of sustaining a city's needs with minimal environmental damage requires complex approaches and many scholars (e.g. Kennedy et al., 2011; Mostafavi et al., 2014; Musango, 2013; Zhang, 2013) attest to the importance of understanding urban metabolism in achieving sustainable development goals in cities. Many disciplines have intuitively appropriated urban metabolism as a way to understand complex problems in cities. While the concept would lend itself to transdisciplinary engagements, in practice each discipline tends to reduce the concept to its own specific research interests. Despite some assertions of its interdisciplinary use (e.g. Kennedy et al., 2011), urban metabolism is predominantly multidisciplinary. Musango (2013) believes a transdisciplinary foundation could be developed through a tightening of concept conventions to develop a transdisciplinary foundation. Musango (2013) suggests some key questions for establishing consensus:

- How is the urban area conceptualised: as an organism or ecosystem? Or neither?
- What scale of urban area is studied: Urban area, administrative boundaries, city subsystems or the region as a whole? Barles (2010) comments that this choice of scale must also navigate statistical limitations, and adds a question of delimiting boundaries which separate demographic attributes or socioeconomic activities from natural systems which support them.
- How are flows conceptualised: as linear, circular or networked?
- How is infrastructure conceptualised: as conveyor of flows or demander of resources
- What do metabolic profiles measure? Barles (2010) asks what indicators can be inferred from material balance.
- Finally, who is politically responsible for distributing flows?

Mostafavi et al. (2014) explain that approaches to understanding urban metabolism may be qualitative in nature, including studies in history, political science, political ecology and social metabolism, or quantitative, such as with urban ecology, ecological economics and industrial ecology. However, most work is visible in the discipline of industrial ecology (e.g. Barles, 2009; Bristow & Kennedy, 2013; Kennedy et al., 2007; Rosado et al., 2014; Schulz, 2007).

2.3.3. Approaches to, and limitations of urban metabolism analysis

Industrial ecology examines material and energy flows in industrial and urban systems, as well as the economic and social factors which shape them (Graedel, 1999). Barles (2009, 2010) notes that resource flow studies have typically been completed at the national level, with more urban studies only recently emerging. Multiple authors (Weisz & Steinberger, 2010; Robinson *et al.*, 2013; Simon & Leck, 2014), remark that urban studies are reliant on data rich environments, with minimal studies undertaken in areas with limited research capacity and funding. This means that there are minimal studies of cities in the global south (Barles, 2009; Fernández, 2014). Only a few published city-level metabolism analysis exist in

Africa: an ecological footprint analysis of Cape Town, South Africa (Gasson, 2002), with an MFA analysis of Cape Town forthcoming (Hoekman, 2015), and Lagos and Cairo included in Kennedy et al's (2015) investigation of resource flows in megacities. Only a few studies account for complete material and energy flows, with most documenting a few specific substances, such as nitrogen, water or carbon emissions, or using flow or data proxies (Zhang, 2013). Finally, understanding the significance of a city's metabolic profile is typically undertaken by comparing results between cities. However, due to the multiple methods applied in the analyses of a city's metabolism, such comparability is limited.

Reviews by Kennedy et al. (2011), Mostafavi et al. (2014) and Zhang (2013) each offer a thorough history of urban metabolism studies and identify two primary approaches for metabolic accounting, namely through use of either energy balances or mass fluxes. Barles (2010) offers an overview of substance flows, a more specific analysis of mass flux. This section explores these predominant approaches for analysing the energy and material flows of an urban metabolism (by which we may understand a city's metabolic profile), and some of their criticisms.

2.3.3.1. Energy balance

The first approach, analysis of energy balance, was introduced by Odum (1996) in the 1970s and follows the principles of thermodynamics (Mostafavi *et al.*, 2014); this is primarily the first law of energy conservation, but "sometimes [associated] with the second: 'the entropy of the universe always increases'" (Barles, 2010: 444). Odum developed a system of accounting using *energy equivalents* or *emergy* (embodied energy), favoring solar energy as an equivalence unit. Another energy balance method is that of *exergy*, which "represents the amount of useful work that can be performed by the energy in a system" (Zhang, 2013: 466). The benefit of using an equivalence measure is the ability to combine material or energy flows of different unit measurements for an integrative analysis, thus allowing the comparison of relative importance, impact or 'weight' of different flows. It also allows inclusion of renewable resource sources, and both direct and indirect flows (Huang & Chen, 2009). However, this approach faces difficulties in finding appropriate conversion rates for each flow (Zhang, 2013). While this is no longer the predominant method for assessing flows in cities, some researchers still use energy equivalents. Zhang et al. (2009) use emergy synthesis to demonstrate various attributes of the metabolic profile of Beijing. Huang and Chen (2009) offer an emergy synthesis of Taipei in in relation to socioeconomic indicators.

Both studies use a measure of solar equivalent joules (seJ). Figure 2-2 shows an energy flow diagram of an urban ecological system. Each arrow would typically have a quantity affixed to it.

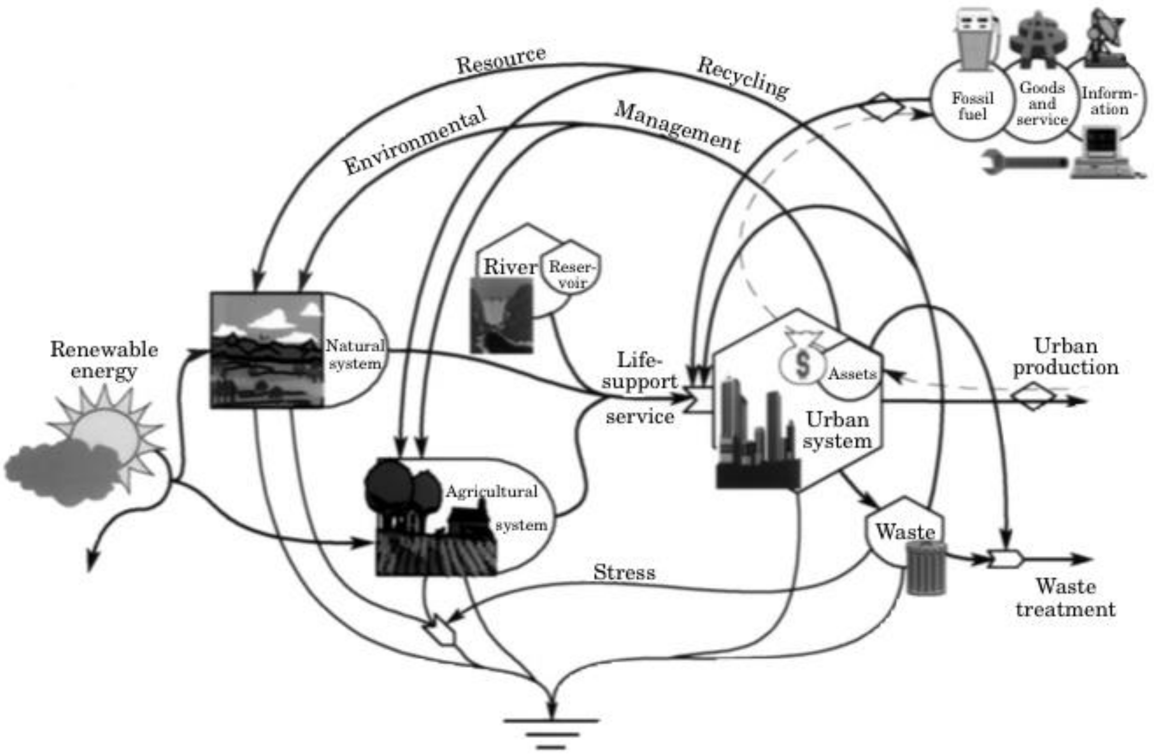


Figure 2-2: Energetic hierarchies in an urban ecosystem (Huang, 1998)

2.3.3.2. Material flux

The approach of material flux has been utilised since urban metabolism was coined, and became the dominant approach with the reemergence of the concept in the 1990s (Zhang, 2013). Material accounting methods aim to produce a quantitative inventory of inputs and outputs of resources required for, and wastes produced by, specific city functions. They account for stocks and flows of resources using the law of mass conservation, in which net outputs must equal the inputs minus any stocks retained by the city (Barles, 2009, 2010; Musango, 2013; Zhang, 2013). The dominant material accounting method is Material Flow Analysis (MFA), having been endorsed by the *Statistical Office of the European Community* (Eurostat) for national analyses (Eurostat, 2001), and adapted for use in cities. Such studies utilise the same units of weight, converting energy products into tonnes equivalent. Table 2-2 shows the material category breakdown utilised in the Eurostat method (2001). Unlike the energy balance approach, this assumes substitutability of materials, which is beneficial for demonstrating aggregate amounts processed, but overlooks materials' relative quality (importance, impact, or ‘weight’) (Huang & Chen, 2009; Zhang, 2013). Despite this, MFA has become the mainstream urban metabolism analysis method. Kennedy et al. (2011) attribute its popularity to the use of actual units which are easily recognised by government officials, allowing better assimilation of analysis into practice. Despite some calls for equal focus on energy and materials (embodied by emergy approaches) (Zhang, 2013), Barles (2010) suggests that a material accounting approach does actually offer enough understanding of energy use. For example, tons of fossil fuels or carbon emissions offer insights into energy consumption intensity. Satterthwaite (2009) adds that greenhouse gas emissions, a function of consumptive behavior, offers insights into the consumption of goods in general.

Table 2-2: Material classification for raw domestic extraction adapted from Eurostat (2001: 29)

Material Category	Subcategory 1	Subcategory 2
Fossil Fuels	Hard coal, lignite, crude oil, natural gas, other (crude oil gas, peat for combustion, oil shale, etc)	
Minerals	Metal Ores	Iron ores, non-ferrous metal ores (bauxite, copper ores, other)
	Industrial Minerals	Salts, special clays, special sands, peat for agricultural use, other
	Construction Minerals	Sand and gravel, crushed stones (incl. limestone for cement making), common clays (for brick making etc.), dimension stone, other
Biomass	Agriculture	Agriculture harvests (cereals, roots and tubers, pulses, oilcrops, vegetables, fruits, treenuts, fibre crops, other crops), Harvest byproducts (crop residues used as fodder, straw for economic purposes), Grazing (permanent pastures not harvested, other land)
	Forestry	Wood (coniferous, non-coniferous), materials other than wood
	Fishing	Marine fish catch, Inland water (freshwater) fish catch, other (aquatic mammals and other)
	Hunting	
	Other	Honey, gathered mushrooms, berries, herbs, etc)

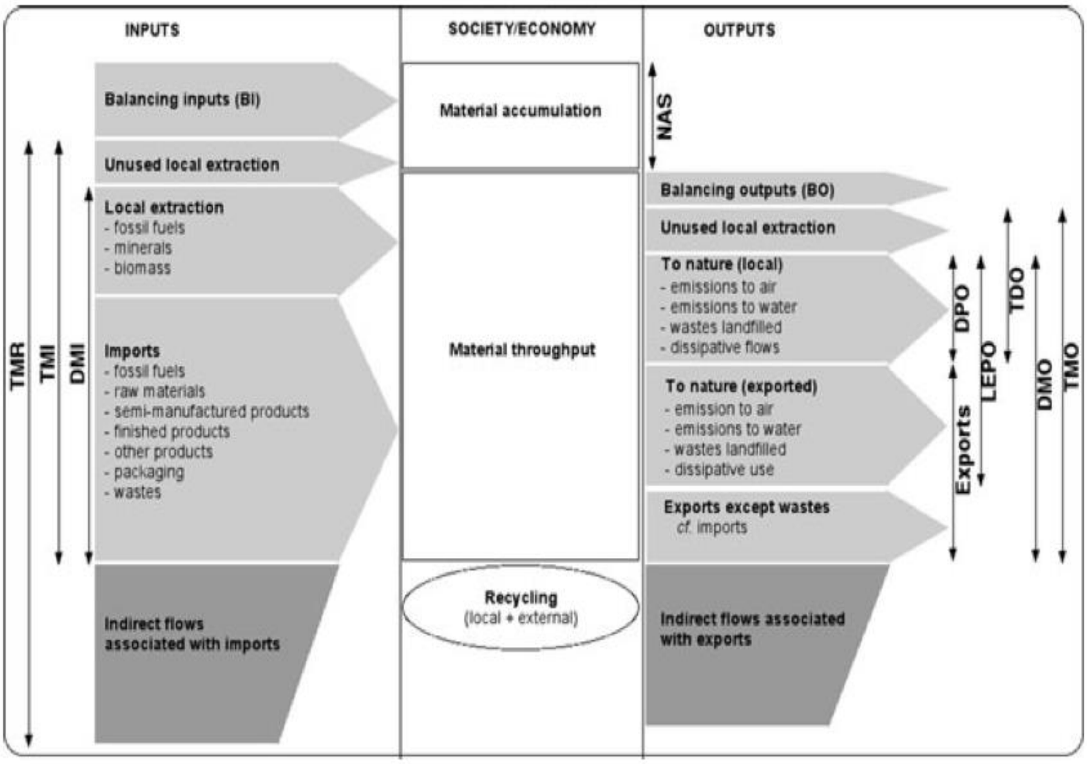


Figure 2-3: A material flow diagram adapted from Barles (2009: 900)

In her examination of Paris, Barles (2009, 2010) adapts the National Balance Method of Eurostat (2001) to demonstrate the ‘Local Bulk Material Balance,’ visualised in Figure 2-3. As MFA is based on the conservation of mass, *balancing input* and *balancing output* are important variables to account for. Barles (2010) explains this using a combustion reaction, which consumes oxygen (balanced input) and produces water vapor (balanced output). The analysis calculates a number of resource indicators (Barles, 2009):

- DMI: Direct Material Input which are any materials used for economic production or consumption in the city;
- TMI: Total Material Input which includes DMI as well as any materials extracted in the city which do not serve the economy (for example, surplus industrial minerals).
- TMR: Total Material Requirement which includes TMI and any indirect material flows due to imports
- DPO: Direct Processed Output which are byproducts of local city processes which dissipate into surrounding natural systems
- LEPO: Local and Exported Processed Output which are all materials which will find their way through the city and into natural systems. This indicator is to distinguish between wastes which are locally treated and those which are exported.

- TDO: Total Domestic Output which are materials of local origin, including unused local extraction.
- DMO: Direct Material Output which includes LEPO and specified, non-waste exports.
- TMO: Total Material Output; as its title expects, this includes all accounted outputs of the city.
- NAS: Net Addition to Stock which is what remains in the city as the "physical growth of the economy" (Saldivar-Sali, 2010: 24), represented as new construction or durable goods.

Barles' (2009) multi-scalar examination of the Paris urban region showed that urban metabolism is affected by density and the distribution of economic functions. Barles (2009) identifies the distinction between, and interdependence of, flows of the city center (consumptive and waste exporting) and those of agricultural or sprawling areas (fuel and construction material reliant). Bulk MFA is also meant to give a reading of a city's global impact; with this in mind, Barles (2009) argues that urban-regional interactions are necessary for effective planning and governance. This approach is reflective of Bai's (2007: 4) call for "expanding the spatial and temporal scale of concerns by city governments and managers". The method developed in Barles' (2010) study is supported as the tool which can aid the "proliferation of MFAs for cities across all regions of the world," and aid global city-level comparisons (Swilling *et al.*, 2011; Hodson *et al.*, 2012: 797; Robinson *et al.*, 2012, 2013). While a promising notion, the challenge it faces is that most developing regions, where such analysis is important, lack complete or reliable data.

2.3.3.3. Substance flow

Barles (2010) highlights the approach of *substance flow analysis,* classified by numerous methods which relate to analysing specific substance flows such as water, nutrient flows or carbon emissions. Using nutrient flows as example, Barles (2007) shows a historical account of the increase in food-born nitrogen flows into Paris from 1817 to 1913 and an increase in its agricultural reuse from 20 to 40 per cent (through increased use of sewage as fertiliser). A more contemporary study by Forkes (2007) shows the nitrogen balance of Toronto between 1990 and 2004. Over this period, no more than 4.7 per cent of food-waste nitrogen is recovered a year, with an observed overall decrease from 3.35 to 2.3 per cent in 2004; Forkes attributes this to more strict regulations for application of sewage to agriculture and prioritisation of policies for diverting organic wastes to landfills, rather than nutrient recovery programs. This historical comparison demonstrates a decline in flow management practices due to the advent of synthetic fertilisers, to the detriment of the environment (as food-waste nitrogen saturates surrounding ecosystems) (Barles, 2007, 2010). Studies of substance flow give quite detailed insights into specific systems enabling more targeted responses where desired.

2.3.4. Urban metabolism and sustainable development

A key challenge with flow accounting is that it tends to be a snapshot of material or energy intensity and offers no insights into a system's own level of sustainability (Zhang, 2013; Mostafavi *et al.*, 2014). Any insights must be gleaned from time studies, which compare different resource intensities in the history of one city (e.g. the Singapore time study by Schulz, 2007). Huang and Chen's (2009) analysis of Taipei compared urbanisation levels, land use, and material and energy intensity for the years of 1982, 1992 and 2002. It demonstrated that changes in land use affect the metabolism of a city: even the seemingly simple difference in choice of agricultural crop affects the emergy of a region, as observed in the shift from rice to vegetable crops. Additionally it showed an increased reliance on fossil fuels, and an associated increase in environmental impact.

Alternatively relative impact can be understood by comparing metabolic profiles of multiple cities (e.g. Decker et al., 2000; Kennedy et al., 2007; Zhang et al., 2009a). These provide a baseline from which to compare resource efficiency, potentially with socioeconomic indicators (Zhang, 2013; Fernández, 2014). For example, Decker et al. (2000) compare energy and material flows for the 25 largest cities in 2000, using differences in climate zone, national GDP, density, and growth rate as predictors of resource consumption. Zhang et al's (2009) results from their Beijing emergy study were compared to their concurrent study of four Chinese cities (Zhang, Yang & Yu, 2009): Batou, Guangzhou, Ningbo and Shanghai. This comparison demonstrated that Beijing had higher metabolic fluxes (imported and internal material and energy), higher metabolic density (impact on the environment), higher metabolic intensity (city resource requirements, and indicator of the populace's living standards), and lower metabolic efficiency (an economic indicator of resource utilisation). Kennedy et al. (2007) examine previous studies of 8 cities and demonstrate that the per capita metabolic intensity increased over time for flows of water, energy, wastewater and material, with only one city showing increased efficiency in water and energy use. Kennedy et al. (2007) further highlight metabolic effects which undermine the sustainability of a city such as "altered ground water levels, exhaustion of local materials, accumulation of toxic materials, summer heat islands, and irregular accumulation of nutrients".

Despite offering baseline comparisons, time studies and city comparisons are both relative measures and do not offer insights into particular sustainability indicators for one city. To remedy this, some studies have utilised Rees and Wakernagel's (1996a) concept of an ecological footprint. Ecological footprint is defined as "the total area of productive land and water required continuously to produce all the resources consumed and to assimilate all the wastes produced, by a defined population, wherever on earth that land is located" (Rees & Wackernagel, 1996b: 229). Zhang (2013) remarks that this perspective is beneficial in determining a level of sustainability, and highlighting the relationship between the ecological factors and socioeconomic development. However, it assumes a single land function, instead of the reality of multiple ecosystem services, many of which are difficult to quantify. This leads to an underestimation of the urban impact on the hinterland. Ecological footprint remains a useful concept if used with other indicators. Gasson (2002) distills six criteria for assessing resource sustainability in cities:

1. What are the comparative area of a city's ecological footprint, and its administrative area? This could be alternatively examined by comparing the per capita ecological footprint to the per capita area of productive land.
2. What is the proportion of non-renewable resources upon which the city relies?
3. How reliant is the city on global resource inputs, and how vulnerable to supply disruption?
4. How resources are distributed; is there equitable access to resources?
5. To what extent are flows cyclical? What proportion of wastes is reused or recycled?
6. To what extent have unrecycled, untreated wastes polluted environmental sinks? Gasson (2002) notes the additional consequences this has on public health.

2.3.4.1. Extended metabolism conceptions

Bai (2007) explains that urban metabolism consists of three aspects: input, output and utilisation of flows. The approaches above tend to be concerned primarily with input and output, particularly as efficiency interventions have traditionally focused on the conversion threshold where resources enter and leave the city. Comparing resource inputs and outputs demonstrates some simple characteristics of cities. Young cities tend to have larger inputs than outputs, as they are growing and need resources to build stock; over time, this accumulation of built stock will contribute to waste flows, as it breaks down. As cities mature, the inputs and outputs become more similar in magnitude and reuse and recycling initiatives have more impact on the city's metabolic intensity (Bai, 2007; Kennedy *et al.*, 2011). In addition, Gasson's (2002) six criteria for assessing resource sustainability (see Section 2.3.4) are predominantly concerned with inputs and outputs, with only number 4 concerned with internal distribution of resources, and number 5 relevant to some extent. However, multiple authors (eg. Bai, 2007; Brunner, 2007; Kennedy *et al.*, 2007, 2011; Fernández, 2014) critique this lack of internal analysis, arguing for the need to understand the stock in the city, for urban mining, or containment of harmful wastes (e.g. from asbestos insulation or lead piping). Urban mining is the reuse of old building stock within the city and Fernández (2014: 607) asserts that it is the fourth essential aspect of agglomeration economies, "alongside provision of shelter to residents and firms, the presence of transportation, and the provision of goods and services". Cities would benefit from attaching value to their internal waste flows, which are particularly visible in the global south, and employing urban mining as a means to utilise this waste buildup and provide informal employment. This is another example which requires robust flow management practices.

While the specifics of internal socioeconomic functions of a city are notably absent in MFA, certain city attributes are identified to affect city metabolic profiles. These include population density, climate conditions, cultural factors, land use choices, distribution of city functions, as well as the political, economic and geographic roles of a city (Barles, 2009; Weisz & Steinberger, 2010). Arguing that cities are more than resource and waste processors, Newman (1999) would extend metabolism analysis to include analysis with livability indicators such as housing, health, employment, education, leisure, and community activities. Just as material flows affect the quality of life in the city, so too does "human decision-making serve as a means to direct, control or enhance metabolism" (Musango, 2013: 11). In this way, Newman (1999) requires that, not only the material or waste outputs of the city should be analysed, but the social outputs as well. An example could be Newton's (2012) correlation of livability with resource consumption, which is further detailed in Section 2.4.1. Inclusion of such indicators would demonstrate how changing metabolism affects livability outputs and vice versa.

In an attempt to include these social indicators and demonstrate metabolism contributions by sector, Mostafavi et al. (2014) suggest a holistic tool, offered in Figure 2-4, which targets specific urban problems, through an analysis of urban metabolism indicators differentiated by sectors of activity. Buildings are highlighted as recipients and transmitters of flows, or embodiments of Newman's (1999) livability indicators. This tool would relate to sustainability by being embedded in the three priorities of social, economic and environmental welfare (Mostafavi *et al.*, 2014).

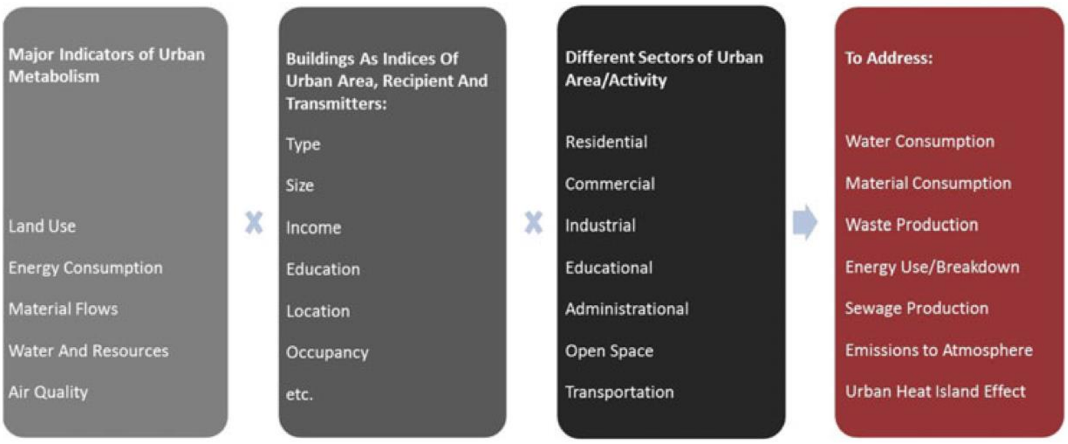


Figure 2-4: The integrated urban metabolism analysis tool developed by Mostafavi et al. (2014)

Goldstein et al. (2013) follow Pincetl et al. (2012) to suggest that the inclusion of Life Cycle Assessment (LCA) would benefit urban metabolism analysis. This would involve (i) quantifying environmental impacts with a cradle-to-grave perspective, from extraction to disposal (ii) easy communicability of units and indicators and (iii) reliance on a large group of existing LCA practitioners who will continue to improve the method. By extending urban metabolism analysis beyond consumption and into other realms of material or energy life cycle, such as extraction, production, and disposal, analysis will yield more information and therefore more areas for potential intervention. Goldstein et al. (2013) present a hybrid analysis model titled Urban Metabolism Life Cycle Analysis (UM-LCA). The model is visualised in Figure 2-5, and shows how the accounting techniques of MFA might be utilised at each stage of the life cycle. LCA typically uses comparison of impacts as the basic unit, demonstrating a difference between examined processes; for cities, this comparison was normalised to *per capita impact*, with the results communicable as “life cycle inventories, midpoint environmental indicators, endpoint indicators or weighted impact scores” (2013: 4). Goldstein et al. (2013) test their method with an analysis of five case cities (Beijing, Cape Town, Hong Kong, London, Toronto). The key benefit of their UM-LCA method is the ability to see the internal differences at play with the city; for example, in each city, energy consumption shows differing magnitudes at different stages of life cycle. A more specific example is in their examination of global warming potential (GWP): in wealthier cities, transport, building energy and waste disposal were the main contributors to GWP, while less affluent cities demonstrated less impact from private consumption than from industrial boilers or inefficient energy infrastructure systems. While the method offers a useful comparison between cities, the reliance on comparative units may limit understanding of gross impact, and may propagate mainstream sustainability priorities of efficiency and substitutability, over more radical systemic reforms or transitions.

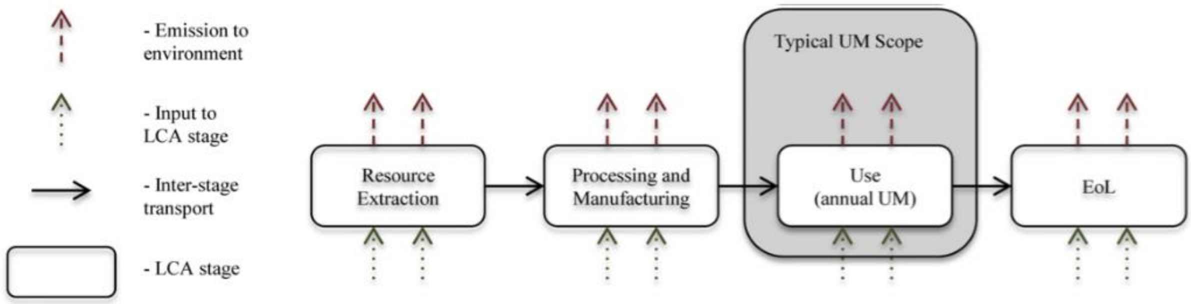


Figure 2-5: Goldstein et al’s (2013) hybrid model of LCA and urban metabolism.

Following themes of infrastructure vulnerability highlighted in Graham’s (2010) *Disrupted Cities*, Bristow and Kennedy (2013) demonstrate the benefit of examining internal stocks and processes as they attempt to determine the resilience of Toronto’s metabolism. Their propositions for increased resilience aim to develop what Hodson and Marvin (2010) have described as *secure urbanism*. It also contributes towards emphasising the conceptual distinction between *smart cities*, described as having centralised, integrated and automated infrastructure systems, and *resilient cities*, which suggest adaptability to change or defense against disasters (Zhou & Williams, 2013). Starting with energy systems, Bristow and Kennedy (2013) determine that locally installed renewable systems would not provide enough capacity to power the city, so regional power stations are definitely required (preferably close by). Should electricity provision fail, they ask how long water stocks would last. Grey water reuse and treatment would enhance local resilience. Additionally, they determine that there is more potential chemical energy in Toronto’s wastewater than the energy required to run the wastewater systems; making use of this would reduce energy imports required for the system. The resilience of transport is made easier with diversity of transport options; hybrid cars are hailed for their substitution of electricity or fuel. Diverse shopping habits and product shelf lives are determinants in food security; urban farms are potential reductions in risk as well as transport costs. Finally, internal building temperatures, as the most quickly altered, may benefit from efficient heating systems or thermal storage options.

Hodson et al. (2012) explore the potential for connecting MFA with Transitions Analysis (TA) in order to better understand sociotechnical systems, particularly how infrastructures both convey resources and shape resource use behaviours. MFA is identified from a quantitative, ecological perspective, in which resource flows, dynamics and intensity are examined towards achieving the goal of decoupling. TA is described as a primarily qualitative approach to analyse inherent pressures and changes in the system, and the city's capacity for shaping transitions; the aim is to explore sociotechnical relationships of infrastructure to understand and develop new forms of infrastructure provision. The combination of TA to MFA is cited by Hodson et al. (2012: 796) as necessary for a complete study of urban metabolism in which "cultural, social, political, and ethical issues are made visible through TA".

2.3.5. Applications of urban metabolism studies

Urban metabolism tools are critiqued by Robinson et al. (2013: 55) as demonstrating problems without supporting decision-making processes. In the studies cited in Sections 2.3.3 and 2.3.4, multiple resource flow problems are simply observed, many pertaining to sustainability issues. However, this identification *is* key to decision-making. Urban metabolism studies offer knowledge which is useful to inform and support appropriate decisions. This is particularly important in the global south where minimal data is collected, shared or utilised in decision-making.

Kennedy et al. (2011) enumerate four potential, and proven uses for findings of urban metabolism studies: Firstly, urban metabolism studies offer sustainability indicators of energy efficiency, material cycling, waste management and infrastructure reach. Secondly, they are good tools for quantifying emissions of carbon or carbon equivalents, natural aspects of productive cities. Thirdly, they lend themself to mathematical models to display city sub-processes, material flows, and economic output. These first three are informational tools, necessary as a first step in any decision-making process. Finally, and perhaps most importantly, urban metabolism studies are a tool for redesigning cities by redirecting material flows in ways informed by social values; this includes forming circular resource flows and awareness of flows entering surrounding ecosystems. Kennedy et al. (2011: 1970) cite

Oswald and Baccini's (2003) Netzstadt paradigm demonstrates long-term reconstruction processes using "four principles for redesigning cities: shapability; sustainability; reconstruction; and responsibility". This is done using an assessment of Baccini and Brunner's (1991) four primary urban activities: "to nourish and recover; to clean; to reside and work; and to transport and communicate," in relation to specific material and energy flows. Zhang (2013) comments that the desire to design sustainable systems is based on the primary assumption that doing so is possible, despite a lack of supportive evidence. Nevertheless, he suggests that lessons from natural systems can be used to design more resilient systems.

Brunner's (2007:13) optimistic sentiments may be the best way to conclude discussion on a such a multifaceted concept: "The task of redesigning the urban metabolism in view of sustainability goals seems enormous when looking ahead. But looking back, even larger changes have taken place: Just consider that a century ago, one of the main problems of New York City was to get rid of all the horse manure piling up on the sidewalks in Manhattan". (Brunner, 2007:13).

2.4. Transitions and modes of urbanism

This section explores how cities shape, and are shaped by, shifts in regimes of resource consumption. The prime consequences of industrial transitions are identified as increased material consumption and participation in global trade. It then details the value-laden urbanism strategies of city dwellers and city planners which determine the configurations of infrastructure and resource delivery in cities.

2.4.1. The socio-metabolic transition

Cities throughout the world have developed as part of the *global socio-metabolic transition* described by Kraussman et al. (2008). An abbreviated description of this transition follows. The transition involves a regime shift from an agriculture-based economy with biomass as the primary energy source to an industrial- and eventually service-based economy, predominantly reliant on fossil energy. This can also be described as a shift from predominantly primary economic sector activities, to predominantly secondary- or tertiary-sector activities. Communities in the agrarian regime are spatially limited by the energyexpense of transporting food, feed, fiber and fuel, and innovatively limited due to most community members' need to labour so as to maintain themselves. In continuing surplus of food, some people are freed from agricultural labour, and are able to innovate in diverse ways. With the discovery and utilisation of fossil fuels, industrialisation begins; this happens in stages: improved agricultural productivity means more people can survive on the same amount of land, and so urban agglomeration becomes feasible. Human labour shifts into industrial systems, eventually to be replaced by machines then computers. Agriculture shifts to industry, which shifts to service with each sector being outsourced to other locales that are in their own stages of transition. Functional changes to the economy are associated with changes in the type of resources used and an increase in quantity (Krausmann *et al.*, 2008). In this way, a country or city's level of industrialisation may be understood through its resource use, as discussed in Section 2.4.1 and with visual examples in Section 2.7.3.

Cities are both outcomes and catalysers of this industrial transition, as manifestations of socio-technical innovation and agglomeration economies. While economic growth is often hailed as the marker of successful industrialisation, Turok (2014) warns that the assumed correlation between urbanisation and economic growth is not a guaranteed occurrence as both processes follow diverse paths. This is important for the debate on Africa's epithet of "urbanisation without growth" (Fay & Opal, 1999; Fox, 2014; Kessides, 2007; Parnell & Pieterse, 2014; Turok, 2014).

Bai (2007) notes that within this regime transition, a nation's primary socio-ecological concerns shift from poverty to industrial pollution to lifestyle-oriented interventions, and the impact scale shifts from local to global. Cities' progression through industrialisation greatly extends their transport and communications capabilities; as part of the transition, industry is outsourced, and cities begin to rely on global hinterlands for the sourcing and disposal of their goods and resources (Rees & Wackernagel, 1996b; Bai, 2007). This does not suggest that their environmental impacts have been outsourced as well. Bai (2007) suggests that the transition from industry- into service-economies does not necessarily bring reduced input of materials, but rather an increase, as cities are part of the global system. He cites Schultz's (2007) time-study of Singapore, which showed that the city-state's 20-fold economic growth occurred with a comparable increase in material consumption. This suggests that the urban demand for resources remains high and adds to the aggregate global impact. This is in addition to the energy needed for global material transport. Bai (2007) notes that unfortunately this impact is rarely measured or accounted for, as it is generally outside of a city's political purview. To achieve sustainability in cities, such externalities should be included in the examination, along with ecological services, such as Lookingbill et al's. (2009) extended watershed regions. City governance must necessarily include awareness of regional or global concerns (Bai, 2007).

Urbanisation and industrialisation typically affords citizens a higher quality of life, typically through occurrence of more service industries. This is represented as high livability or a high ranking on the human development index (HDI) (Newton, 2012; Fernández, 2014). *Livability* is grouped by Newton (2012: 81–82) as one of four city performance indicators, alongside *competitiveness and productivity*, *environmental sustainability*, and *social inclusion and equity*. Newton (2012) comments that, to the detriment of a holistic understanding of cities, these indicators are typically assessed individually. Using the concept of ecological footprint and The Economist's (2009) livability ratings, Newton's (2012) study demonstrates that the cities rated most livable have the largest ecological footprints, and thus the largest resource consumption. Fernández (2014) and Krausmann et al. (2008) attest to this correspondence of high HDI with high resource and energy consumption, and a correspondingly high environmental impact. Here we are reminded why decoupling human wellbeing from resource consumption is imperative.

2.4.2. Types of urbanism

Five industrial stages, demonstrating a shift from agricultural to industrial regime, are identified by Perez (2002) and described in Table 2-3. Each of these is associated with a particular technological revolution, which took place with the emergence of new resources and associated technologies which determined new infrastructure systems and social practices.

Table 2-3: Five successive technological revolutions, adapted from Perez (2002:11-14)

Technological Revolution	Popular Name for the period	Year	New or redefined infrastructures
FIRST	The 'Industrial Revolution'	1771	Canals and waterways Turnpike roads Water power (highly improved water wheels)
SECOND	Age of Steam and Railways	1829	Railways (Use of steam engine) Universal postal service Telegraph (mainly nationally along railway lines) Great ports, great depots and worldwide sailing ships City gas
THIRD	Age of Steel, Electricity and Heavy Engineering	1875	Worldwide shipping in rapid steel steamships (use of Suez Canal) Worldwide railways (use of cheap steel rails and bolts in standard sizes) Great bridges and tunnels Worldwide Telegraph Telephone (mainly nationally) Electrical networks (for illumination and industrial use)
FOURTH	Age of oil, The Automobile and Mass Production	1908	Networks of roads, highways, ports and airports Networks of oil ducts Universal electricity (industry and homes) Worldwide analog telecommunications (telephone, telex and cablegram) wire and wireless
FIFTH	Age of Information and Telecomm-unications	1971	World digital telecommunications (cable, fiber optics, radio and satellite) Internet/Electronic mail and other e-services Multiple source, flexible use, electricity networks High-speed physical transport links (by land, air and water)

The first four industrial stages delivered rapid growth in numbers of cities and city populations; this period of growth from 1750 to 1950, termed the *first urbanisation wave,* saw the formation of the contemporary cities of the global north (Swilling & Annecke, 2012). The *second urbanisation wave*, describing urban growth from 1950 to 2050, sees rapid growth in urban population and number of cities in the global south, and will forge new forms of cities. This wave comes with limitations of resource availability, or as Krausmann (2008) puts it, without new wilderness frontiers to explore. These limits or pressures define the transition into what Swilling and Annecke (2012) hope to be a new socio-metabolic regime (or *epoch* as they describe it) of sustainability.

Patterns of infrastructure distribution and therefore access to services by the public is determined by differing geographical locations, resource availability, historical legacies, demands of its citizens and level of development. Jabareen (2006) and Watson (2009) add that urban planning and service provision is hugely affected by social values. In this way, urbanisation can be viewed as a “socio-ecological process of change” (Mostafavi et al., 2014:55, citing Heynen et al. 2006). This is demonstrated by five types of value-determined urbanism, summarised by Swilling and Annecke (2012):

- Inclusive urbanism followed values of equal access to services, in which the state orchestrated vigorous urban planning, embodied by extensive, typically state monopolised, networked infrastructures and large projects bent on achieving very specific visions for inclusion and pride in the city space. However, despite the ostensible commitment to inclusivity, many of these projects resulted in displacement of marginalised people who did not fit the state’s visions.
- Splintered Urbanism, a term coined by Graham and Marvin (2001), moved away from public monopolies through commodification of urban services. This is praised for improving competition and breeding new innovation (Swilling & Annecke, 2012), which truly allowed the functioning of megacities too complex for single management. Privatisation of services, however, meant that the public could only receive the services they could afford. This led to a divided public and the need for the displaced poor to find alternative ways to tap into service flows (Pieterse, 2009, 2014; Watson, 2009; Allen, 2014).
- Slum urbanism, or Pieterse’s (2014: 201) “surreptitious urbanism,” emerged from this splintering and describes the ability of large numbers of people to carve out an existence in the city, either through informal connection to formal infrastructures, or by forming their own localised flows. The success of this form of urbanism is demonstrated by the continued existence and growth of slums, as well as by the ingenuity of its actors in ensuring their continued access to resources. Swilling and Annecke (2012) stress that slum dwelling is not a phase, but a functioning urban strategy in its own right. However, the sustainability of slum dwellers’ resource use is difficult to measure, as most of their approaches to service provision are informal and the stability and longevity of specific slums is unpredictable. Hendrick-Wong and Angelopulo’s (2014) ‘exclusive urbanisation’ speaks to the negative consequence of cities overlooking a majority slum population, with wealth and resources enjoyed by an elite few, ultimately reducing the city’s potential for inclusive development.
- Green urbanism is Swilling and Annecke’s (2012) description of the contemporary eco-modernist movement which encourages eco-efficiency. This involves retrofitting existing infrastructures with energy efficient technologies or encouraging ‘green’ demand-side-management behaviours like habitually switching off unused lights or

appliances. This strategy is effective, yet will not solve long-term problems as eco-efficiency is simply a delaying tactic: less use by individuals in a growing population may still show increased aggregate use (Hawken, Lovins & Lovins, 1999; Korhonen, 2008).

These urbanism strategies are each visible in contemporary cities to varying degrees, and their manifestation falls in the spectrum between inclusive or exclusive cities. In approaching the notion of a sustainable city, a synthesis of the positive elements of each urban strategy listed above is recommended in what Swilling and Annecke (2012) term *livable urbanism*. Their vision involves relying on local communities and taking advantage of competitive innovation to form resource-efficient technologies which are appropriate to resources of the local bioregion, while embodying the vision of inclusive cities which are equitable for both citizens and nature.

2.5. Sustainable cities

This section examines the conception of a *sustainable city* and the ways in which this may be achieved. In doing so, it acknowledges that sustainable development has different agendas in the context of the global north and global south, related to primary emphasis of either technological efficiency or social equity. The global south is marked by under-developed cities which tend to result in large informal settlements and informal resource acquisition.

2.5.1. Towards sustainable cities

There exists no universally accepted definition of a sustainable city (Elle, Nielsen, Jensen & Hoffmann, 2003). This may be a continuation of the ambiguity of the oft quoted 1987 Brundtland definition of sustainable development as development which meets the needs of the present without compromising those of the future (WCED, 1987). Gasson (2002: 3) defines a sustainable city as “one that meets its present and future human development objectives without growth in throughput of matter and energy beyond the regenerative and absorptive capacities of its local, national or international hinterland”. As an open system, reliant on its hinterland for food, water, goods and materials, there are doubts as to whether a city can actually be sustainable in its own right (Rees & Wackernagel, 1996b; Andersson, 2006; Bai, 2007). In practice it seems easier to say what a sustainable city is not. Campbell

(1996) proposes that sustainable cities can only be achieved indirectly by managing the conflicts between economic, social and environmental interests. In this way, each city can be represented on a continuum, in which it can approach, but perhaps never achieve complete sustainability. Elle et al. (2003) suggest that the sustainable city should not be conceptualised as an entity, but rather focus on the sustainable development of a city, in which different levels of sustainability could be comparatively measured or different aspects of a city could be measured with appropriate sustainability indicators. This lack of definition is problematic as prescribed systemic transitions require a vision (Swilling *et al.*, 2011). Nevertheless, the literature offers multiple themes pertaining to achieving sustainability. Weisz and Steinberger (2010) propose a reduction in high-income livelihoods; Andersson (2006: 37) argues for building resilience through utilisation of a "diverse set of management practices based on different values;" Jabareen (2006) suggests changing urban form to follow sustainable design concepts; Rees and Wackernagel (1996b) would reduce global trade to create need for local resource responsibility; Barles (2010) promotes *dematerialisation*, *decarbonisation and dewatering* as a way of addressing problems at their source, instead of reacting to symptoms; Krausmann et al. (2009: 2704) voice a similar goal as a "strategic withdrawal from overconsumption" and Krausmann et al. (2008: 652) suggest a re-imagined system "that does not build human communities, creativity, happiness on [resources]".

Elle et al. (2003) identify four strategies used for approaching sustainability in cities:

1. Employing green building techniques, which focus on passive energy design or technological fixes to reduce resource use; this technical approach follows an eco-efficiency agenda. For example, orienting house windows for maximum solar gain in winter or using automatic security lights
2. Changing the behavior of people or organisations to reduce their resource use. For example, turning off lights or appliances when not in use
3. Implementing regulations or changing policies to discourage resource use or encourage use of particular sources. For example, carbon taxing to encourage a shift to alternate energy sources.
4. Replacing or reforming infrastructure with more efficient systems. This may include using solar panels to power traffic signs and signals, but also refers to changes to functional systems like waste removal. Here, Giradet's (2004) conception of cities as eco-technical systems is useful: cities may employ circular infrastructure systems to reduce both their waste outputs and the need for virgin material inputs.

These strategies demonstrate a clear connection between effective resource management and achieving sustainability. As previously explained, technical systems are connected with social behaviours, so none of these strategies may succeed alone. Campbell (1996) notes that sustainability goals may remain vague to allow city planners to determine short-term steps. Robinson et al. (2012) agree that sustainable city visions cannot manifest instantaneously as they involve multiple stakeholders along differing time frames. Instead, "innovation in relations between cities, infrastructure systems and resource flows can best be understood through projects and initiatives building up over time", as opposed to singular large-scale interventions (Robinson *et al.*, 2012: 16). These innovations require coordination as part of a focused strategy, led by government or intermediaries within the city. Their success will be shown by their ability to navigate between imbedded socio-technical systems and behaviours, and the creative and technical capability of *transformative niche innovations* (Robinson *et al.*, 2012).

Fernández (2014) notes that cities typically learn from each other's initiatives, as opposed to from academia. Due to the only recent integration of sustainability and infrastructure, minimal programs yet exist as guides (Swilling *et al.*, 2011). The rapid assessment tool highlighted by Robinson et al. (2013), and described in Section 1.1, remains the guiding framework for this paper. This proposed tool exists for cities to find unique, context appropriate infrastructure reforms. This is particularly important given that current urban planning tools have typically been borrowed from the global north by the global south (Watson, 2009), and implemented with limited concern for differing needs or contexts.

2.5.2. **Sustainability in global south**

Fernández (2014: 598) puts it well in saying that "the urban global south confounds an easy definition of urban sustainability if it is framed in terms of the conditions of the developed and industrialised context of the north". Historically, culturally and economically, the global south has followed a different development trajectory, and therefore, despite moving through a familiar industrial transition, is faced with different needs compared to the north. Despite these varied needs, Watson (2009: 154) shows that urban planning in much of the global south remains strongly informed by "planning traditions which emerged in other parts of the world … in response to urban conditions very particular to an earlier time and context". Simon and Leck (2014) identify two categories of research and policy surrounding global environmental change: those of mitigation, such as reducing greenhouse gas emissions, and adaptation, which involves building ability of people to adapt to changing conditions. Mitigation has traditionally been utilised in the global north while adaptation is tied to the global south. Simon and Leck (2014: 613) remark that due to “unequal geographies of research capacity and funding”, the mainstream sustainability discourse remains focused on mitigation. This is visible in Elle et al. (2003) four strategies, which follow the eco-modernist agenda of efficiency and reduction of resource use (Hawken *et al.*, 1999; Blewit, 2008; Korhonen, 2008). The eco-modernist agenda assumes a status quo of overconsumption, present in much of the north, yet quite clearly lacking in most of the south. In developing countries, governments are struggling simply to provide their population with basic services, let alone addressing the efficiency or environmental quality of the systems which do so (Saldivar-Sali, 2010; Ferrao & Fernández, 2013). Fernández (2014) quips that if one did not know the context of a city of the south, it would appear to be quite efficient in resource use, compared to a demographically similar northern city. Thus the differing sustainability goals could be summarised as achieving ‘efficiency versus equity’.

Allen (2014: 522) describes southern cities as occupying a “spatially irregular landscape manifesting in the form of a lumpy rural-urban continuum that challenges conventional distinctions between the urban and the rural”. It is in these peri-urban areas, usually on the periphery of the city, that we find ecosystem services like watersheds or forests, upon which the city relies. Allen (2014) notes that cities remain unsure of how to manage these areas. The priority seems to be on stopping unplanned urbanism from threatening the natural capital, yet informality tends to sidestep this. Moffat and Kohler (2008: 251) suggest it would be beneficial to conceptualise ecosystem services as more than simply natural space, but as the city’s ‘green infrastructure,’ and to manage them accordingly. While this is a beneficial title in bestowing value on these areas, Bai (2007) suggests caution in relying only on green space to mitigate environmental impacts. He cites Oliver-Sola et al’s (2007) study of Montjuic urban park in Barcelona which showed that the energy and material cost of park maintenance and service provision to visitors would have required 12 times the area of the green space to offset.

Peri-urban areas are also where there are huge disparities in access to resources and the livelihoods they afford, as informal settlements are typically built in this open space. The UN characterises people who live in these settlements as *slum dwellers* only if they are lacking at least one of five prescribed securities: “access to improved water, access to improved sanitation facilities (minimally, a pit latrine with a slab), sufficient living area (not more than three people sharing the same room), structural quality and durability of dwellings, and security of tenure” (UN Habitat, 2010; Swilling & Annecke, 2012: 113). In this way, slums can display diverse levels of livability, with some residents merely lacking formal leases, while other settlements may exhibit obvious social and environmental detriments. It is important to see that while the above deprivations may be linked to poverty indicators, poverty or *poorness* do not feature in defining slum dwellers and their settlements. Indeed even linking poorness to poverty greatly limits the conceptions of poverty in developing spaces. This may be seen in the form of people enjoying self-sufficient livelihoods while not surpassing a certain monetary threshold, or by surpassing this threshold yet still facing difficulties in accessing social services.

Angotti (2006: 962) disputes the polarised conceptions of formal/informal and the assumptions that slum dwellers are separate from formal systems: indeed they are “far from ‘marginal’ and the connections between formal and informal activity are multiple and complex”. Fay and Opal (1999: 26), identifying Africa particularly, add that the rural/urban and formal/informal distinctions may not be helpful conceptions in the global south as “many workers straddle these divisions, whether by seasonal or circular migration between town and country, or moonlighting in the informal sector while holding a formal sector job during the day”. Turok (2014), despite arguing that informality halts growth, bemoans the traditional response of displacing or demolishing informal settlements. By doing this, residents lose shelter and objects into which they have invested years of their labour and modest funds. They are therefore undermined in their ability to save and become viable contributors to the economy.

This all suggests a need for new approaches to urban planning and the values behind them. In these peri-urban areas, sustainability efforts must focus most on improving service delivery, yet it is where it is most difficult to do so, either because city limits restrict provision of services or informal settlements defy the logic of traditional city planning (Watson, 2009; Allen, 2014). The lack of formal infrastructure and service provision may be seen as an opportunity to shape new systems along novel pathways (Fernández, 2014). Contrary to the predominant visions of slums as unattractive centers of squalor and pollution, propagated by works like Davis’ (2006) *Planet of Slums*, new visions have emerged which champion the ingenuity and the importance of engaging with the urban poor (Angotti, 2006; Watson, 2009; Simone, 2010; Swilling & Annecke, 2012; Pieterse, 2014). Simone (2010) disputes the need for a city to be tamed or ordered by urban planning, but suggests that the city has a life of its own, and can evolve with lessons from the periphery. Turok (2014) suggests that this perspective is still unbalanced, as it fails to grasp the impacts of large scale urbanisation. However, he does highlight informal settlements as crucial “stepping stones to urban labour and housing markets” and suggests that government policies should be sympathetic, by investing in their upgrading, or showing “benign neglect where lack of affordability inhibits any immediate improvements” (Turok, 2014: 78). Pieterse (2014) acknowledges that slums threaten the political stability of a city with increased social unrest and volatility, and suggests some simple pathways which the government might take to ensure incremental yet steady change. For example, a city may help slum dwellers to reprioritise education by offering better protection from extortion by their landlords; from this could emerge extra funds to be invested in their children’s education, offering them economic inclusion and self-empowerment (Pieterse, 2014). Despite the understanding that slums are here to stay, along with the socioeconomic instability they represent, Parnell and Pieterse (2014) note a lack of urgency among governments and business elites in Africa to address their existence.

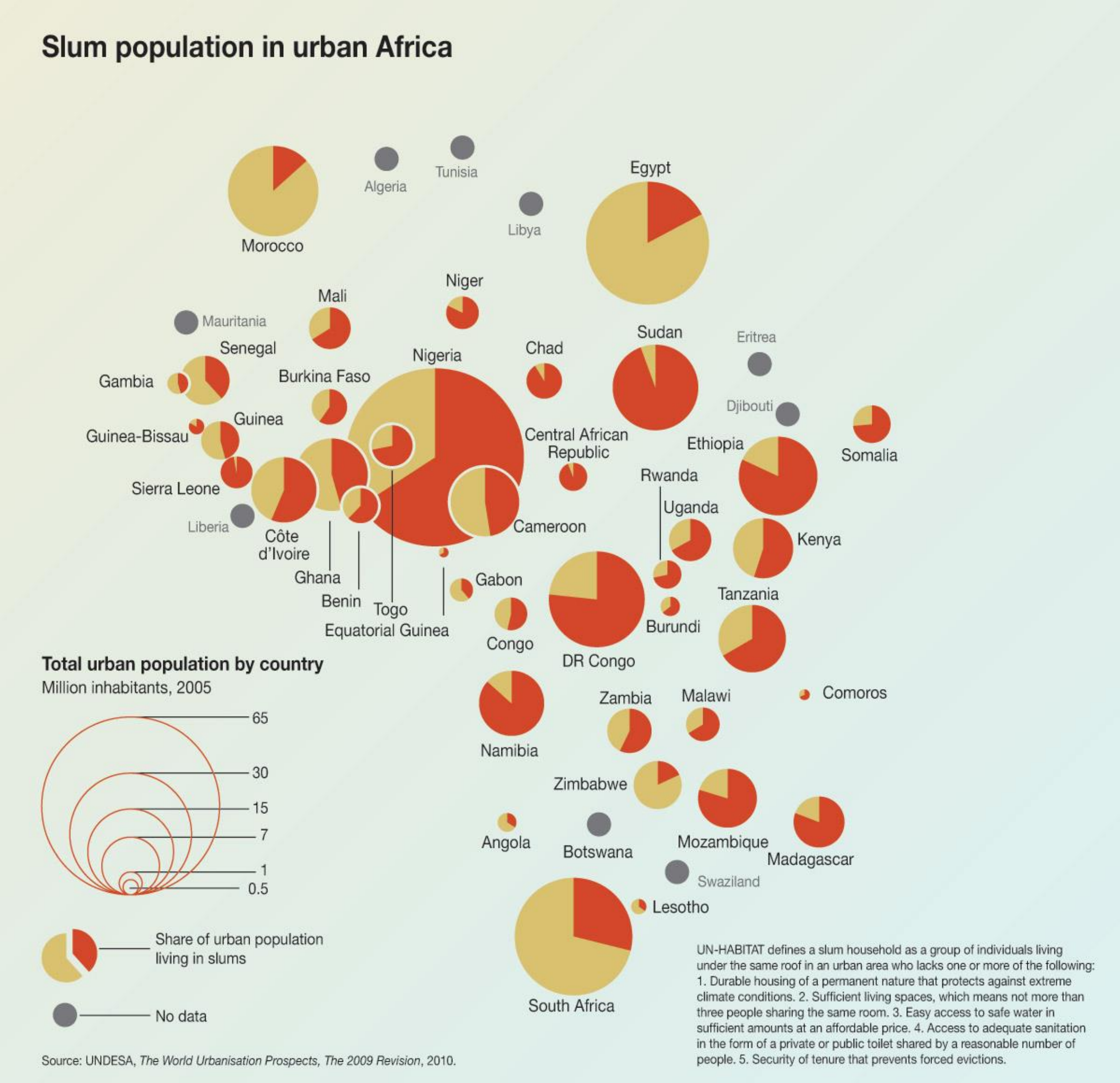
2.6. Urban Africa

The section offers with an overview of statistical and social themes present in African cities as well as an exploration of what shaping a sustainable African city might require.

2.6.1. Demographic shifts in African cities

The 58 UN-recognised African territories are all categorised as developing, or of the global south, with 34 of them labeled as the least developed countries in the world, in addition to only 15 other countries in the world. Unlike cities of the global north, most of African cities do not have the legacy of inclusive urbanism which promoted widespread networked infrastructure; instead cities are historically splintered (Kooy & Bakker, 2008 in Allen, 2014). This is visualised in the city by a high percentage of slum dwellers. Figure 2-6 shows the proportion of urban dwellers in slums for each African country. Sub-Saharan Africa houses 62 per cent of its urban population in slums of varying deprivation levels. This is a staggering proportion with a range from 17.9 per cent in Zimbabwe to 95 per cent in the Central African

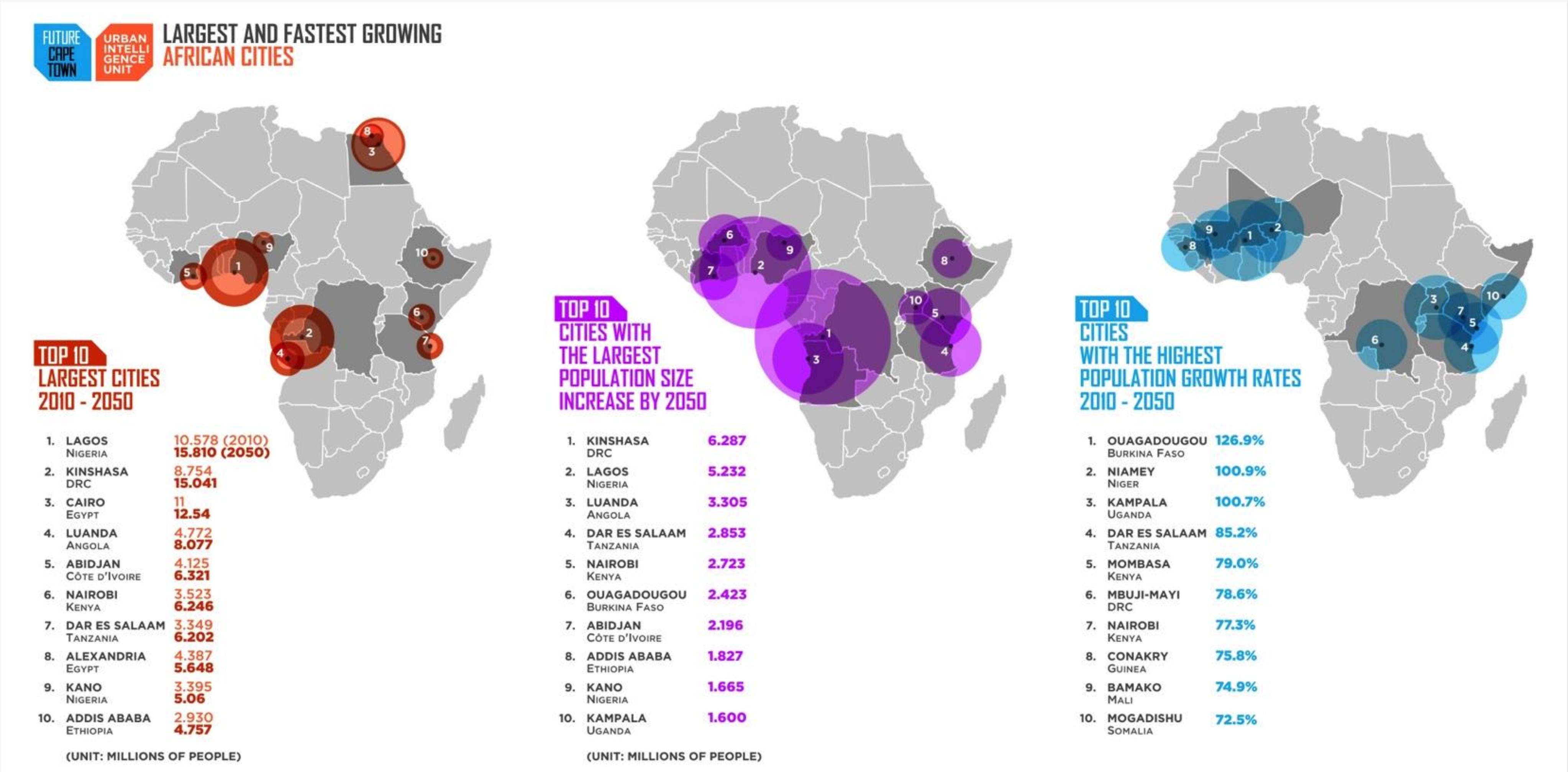
Republic. With the exception of Sudanese cities (94.1 per cent slum), Northern Africa has managed to reduce its slum population quite drastically; Egypt for example has dropped from 50.2 per cent in 1990 to 17.1 per cent in 2010. For comparison, the next largest proportion of slum urbanites are found in Asia at anywhere between 24 (Western Asia) and 42 per cent (Southern Asia) (Swilling & Annecke, 2012).


Slum population in urban Africa

UN-HABITAT defines a slum household as a group of individuals living under the same roof in an urban area who lacks one or more of the following: 1. Durable housing of a permanent nature that protects against extreme climate conditions. 2. Sufficient living spaces, which means not more than three people sharing the same room. 3. Easy access to safe water in sufficient amounts at an affordable price. 4. Access to adequate sanitation in the form of a private or public toilet shared by a reasonable number of people. 5. Security of tenure that prevents forced evictions.

Source: UNDESA, *The World Urbanisation Prospects, The 2009 Revision*, 2010.

Figure 2-6: Proportion of African urbanites living in slums (Pravettoni, 2010).



LARGEST AND FASTEST GROWING AFRICAN CITIES

TOP 10 LARGEST CITIES 2010 - 2050

1.	LAGOS NIGERIA	10.578 (2010)	15.810 (2050)
2.	KINSHASA DRC	8.754	15.041
3.	CAIRO EGYPT	11	12.54
4.	LUANDA ANGOLA	4.772	8.077
5.	ABIDJAN CÔTE D'IVOIRE	4.125	6.321
6.	NAIROBI KENYA	3.523	6.246
7.	DAR ES SALAAM TANZANIA	3.349	6.202
8.	ALEXANDRIA EGYPT	4.387	5.648
9.	KANO NIGERIA	3.395	5.06
10.	ADDIS ABABA ETHIOPIA	2.930	4.757

(UNIT: MILLIONS OF PEOPLE)

TOP 10 CITIES WITH THE LARGEST POPULATION SIZE INCREASE BY 2050

1.	KINSHASA DRC	6.287
2.	LAGOS NIGERIA	5.232
3.	LUANDA ANGOLA	3.305
4.	DAR ES SALAAM TANZANIA	2.853
5.	NAIROBI KENYA	2.723
6.	OUAGADOUGOU BURKINA FASO	2.423
7.	ABIDJAN CÔTE D'IVOIRE	2.196
8.	ADDIS ABABA ETHIOPIA	1.827
9.	KANO NIGERIA	1.665
10.	KAMPALA UGANDA	1.600

(UNIT: MILLIONS OF PEOPLE)

TOP 10 CITIES WITH THE HIGHEST POPULATION GROWTH RATES 2010 - 2050

1.	OUAGADOUGOU BURKINA FASO	126.9%
2.	NIAMEY NIGER	100.9%
3.	KAMPALA UGANDA	100.7%
4.	DAR ES SALAAM TANZANIA	85.2%
5.	MOMBASA KENYA	79.0%
6.	MBUJI-MAYI DRC	78.6%
7.	NAIROBI KENYA	77.3%
8.	CONAKRY GUINEA	75.8%
9.	BAMAKO MALI	74.9%
10.	MOGADISHU SOMALIA	72.5%

Figure 2-7: Largest and fastest growing African cities between 2010 and 2050 (Urban Intelligence Unit, 2013).

The second urbanisation wave will witness two trends (Swilling *et al.*, 2011; Robinson *et al.*, 2012; Swilling & Annecke, 2012): firstly, there will be an absolute growth of urban population. The world passed the 50 per cent urban mark in 2008, yet overall Africa is currently only 40 per cent urban, with projections of passing 50 per cent before 2035 and reaching 60 per cent urban by 2050. Putting this in context, the world average is projected to be 67 per cent urban by 2050, with Africa housing 20 per cent of all global urbanites while Asia houses 53 per cent (UN-DESA, 2011). This suggests a huge potential shift in innovation, wealth and resource impact from the historical powers of the USA and Europe to Asia and Africa. Between 2011 and 2050, there are expected to be 2.5 billion more people in cities of the global south. African cities are expected to house 0.9 billion of these new urbanites (UN-DESA, 2011). Contrary to popular belief, 60 per cent of this growth is attributed to natural births and deaths, not rural-urban migration (Parnell & Pieterse, 2014; Swilling & Annecke, 2012; United Nations, 2011). African cities are demonstrating the largest growth rates in the world as illustrated in Figure 2-7. In particular, Middle, Western and Eastern Africa show annual growth rates of over 3.5 per cent (UN-DESA, 2011).

The second expected trend is an increase in the number of cities. This rapid population growth is not only expected to produce more megacities, but to form multitudes of satellite cities, primarily populated by less than 500,000 people (Swilling & Annecke, 2012). Over half of the world's urban dwellers live in such-sized cities already. By 2015 it is expected that 54 per cent of the urban population will live in settlements of fewer than 500,000 people, 9.9 per cent in cities between 500,000 and 1 million, 26.1 per cent in cities of between 1 and 5 million, 2.4 per cent in cities of between 5 and 10 million, with 7.5 per cent living in megacities (over 10 million people) (Parnell & Pieterse, 2014:8). The fastest growth rates are expected for cities of 1 to 5 million and, against previous observations, for megacities (UN-DESA, 2011), though the proportions will remain relatively similar. This abundance of new cities demonstrates the importance of building strong urban development plans, and employing decentralised governance strategies.

2.6.2. Challenges in African urbanisation

Beyond statistical trends, and accepting that close examination of places denies generality, Parnell and Pieterse (2014) highlight certain themes present in many African cities:

- As observed in Figure 2-6, informal modes of urbanism predominate with urbanites relying less on the state for social wellbeing and access to resources (Fernández, 2014;

Pieterse, 2014). Difficulties emerging from informality include a diminished tax base for governments to utilise and uncertainty in residents and organisations for whom to engage with to make improvements.

- Resulting from, and reinforcing informality is a tendency for circular migration of residents, connected to multiple rural and urban areas in order to maintain livelihoods without the risks associated with permanently settling in 'precarious towns'.
- As explored earlier, peri-urban areas can be sites of much informality, with differing government strategies surrounding their management.
- Seventy per cent of Africans earn their living from vulnerable employment. Additionally, despite youth being important for economic productivity, only 17 per cent of working youth in low income countries have full time jobs, with 39 per cent in middle income countries and 52 per cent in upper-middle income countries (Parnell & Pieterse, 2014:13). Low youth incomes add to the difficulty in achieving future transitions.
- Planetary limits and efficiency imperatives set a different tone for African urban management, from the unbound urban expansion of other regions; as discussed in Section 2.5.2, the sustainability priority for Africa is one of equitable service provision, a difficult task to balance with reducing environmental degradation.
- A colonial legacy of *urban primacy* exists in which a central or capital city dominates the political and economic decision-making of a country (Parnell & Pieterse, 2014). Rosen and Resnick (1980) note that urban primacy typically appears in dictatorships, typically showing the largest city to be 50 per cent greater than the next largest city as compared to a more modest number in democracies. To better handle the rapidly increasing population, UN-Habitat (2014) recommends national governments to encourage the active development of satellite cities which can share the burden. These satellite cities are already occurring as part of the second urbanisation wave and may benefit from developing decentralised solutions. Decentralisation may also be driven by limitations in long distance transport due to rising fuel costs, which will shift cities away from the global hinterland (Krausmann et al., 2009). Cities may be forced to embed themselves more tightly within "their respective uniquely configured bio-economic regional systems of production and reproduction" (Swilling & Annecke, 2012: 113). Following Wolman's (1965) argument that any failures of service supply are not due to limitations in the hinterland, but due to poor foresight and management, decentralisation of power will become necessary for cities to handle their unique and complex problems (Pieterse, 2014). After all, it was the privatisation and competition present in splintered

> urbanism which enabled megacities to flourish. Some decentralisation is already observable in countries which have moved capitals from their most populous or productive city: Lagos and Abuja in Nigeria are examples of this.

The challenges offered by these themes paint a simple picture for why many political leaders may voice denial around African urbanism. This has three incarnations: (i) denial that urbanisation is happening; (ii) denial that natural growth, not migration, is the prime cause; and (iii) denial of the benefits of urbanisation. Denial may be the chief limitation to overcome as it has resulted in urban policies which aim to reduce migration or limit urban growth, instead of improving urban conditions or building robust urban economies (Parnell & Pieterse, 2014; Turok, 2014). Parnell and Pieterse (2014) argue that this denial is outmoded, reminding us that urbanisation was a feature of colonialism and not a recent occurrence. However, Turok (2014) suggests that denial is justified due to a lack of studies which elucidate the benefits of African urbanism. In fact many studies point to a failure of African urbanism in generating the economic growth expected in cities (Kamete 2001 in Njoh, 2003; Bouare, 2006; Bloom & Khanna, 2007; Ravallion, Chen & Sangraula, 2007), describing Africa as urbanising in the absence of industrialisation or showing urbanisation without economic growth (Davis, 2006; Fay & Opal, 1999; Parnell & Pieterse, 2014; Watson, 2009).

While Section 2.4 presented the mainstream perspective that urbanisation necessarily causes industrialisation and economic growth, Fox (2014), Melin (2014) and Turok (2014: 61) argue that this assumption should be questioned: “The arguments put forward for cities being engines of growth are often rather general and imprecise. The timescales are vague and the supporting evidence from Africa is decidedly thin. The connection between urbanisation and economic growth is sometimes portrayed as automatic and inevitable, like some kind of universal law governing a single, simple process. It is striking how little attention is paid to the possibility that the character and composition of urbanisation may vary in different places”. While cities do create opportunities for agglomeration of economic production, this only leads to economic growth if the costs involved in city growth are managed and balanced. Such externalities are described as *agglomeration diseconomies*, and include crime, traffic congestion, overburdened infrastructure, pollution or anything that contributes to poor business climates (Turok, 2014).

Multiple studies have shown that urbanisation in most places is correlated to economic growth and an increase in quality of life. However, some studies show that Africa, and sub-Saharan Africa in particular, does not show this correlation. Ravallion et al. (2007) demonstrate that globally, while urban poverty is increasing, rural poverty is decreasing twice as fast: thus aggregate poverty is decreasing. Again, Africa is an exception in their study with no clear trends surrounding the occurrence and distribution of poverty. In an examination of 80 countries in 1960 and 2004, Bloom and Khanna (2007) demonstrate that urbanisation and income are correlated, but that the link is weaker at low levels of development than at high. Bouare's (2006) study showed a negative correlation between urbanisation level and GDP for 23 of 32 sub-Saharan African countries between 1985 and 2000. Kessides (2007) offers a contradictory study, showing negative correlations for only 9 of 24 sub-Saharan countries between 1990 and 2003. Each study finds similar results for only half of their shared countries (9 of 18), potentially explained by the difference in selected time periods. Bouare's study shows negative correlations for 11 of the 14 countries not included in Kessides'. Turok (2014) speculates that the cause of negative correlations of urbanisation to economic growth could be immigration undermining economic productivity by adding congestion to the system and diverting resources to build social infrastructure. Investment in social services, such as HIV/AIDS treatment, is also noted as a possible limiter of development by Kessides (2007), along with spatial constraints of urbanising in arid or tropical climates. Fay and Opal (1999) suggest that economic growth is hampered by dysfunctional cities which cannot serve private sector needs or provide adequate markets. With such contradictory results, an Africa-wide conclusion is not forthcoming; however, the variation in correlation does demonstrate that each country has its own urbanisation patterns and that *urbanisation without growth* is not a universally African experience (Fay & Opal, 1999; Kessides, 2006).

Despite suggestions of limited growth, Njoh (2003) finds a positive link between urbanisation and human development (using HDI) in 40 sub-Saharan African countries. African countries with higher HDI have a larger national proportion of urban residents, and, as would be expected, lower proportions of slum dwellers (UN Habitat, 2010). This returns to cities' primary attribute as concentrators: in this case, concentrators of healthcare facilities, educational institutions and providers of higher living conditions (Njoh, 2003).

This section does not aim to suggest that African cities are not important to their national economies. Gasson (2002) notes that in 2002, 60 per cent of African GDP was generated in cities, with the State of African Cities report suggesting 80 per cent generated in 2010 (UN Habitat, 2010). Kessides (2006: xxii) remarks that "the economic growth that has taken place in the past decade derives mainly from urban-based sectors. But cities have clearly not lived up to their productive potential because of widespread neglect and bad management". Policy should therefore be focused, not on anti-urbanisation, but on making urban space economically viable, specifically by reducing negative externalities and diversifying economic interests to shift African products up the value chain (Turok, 2014).

2.7. City typologies and indices

This section provides an overview of how cities have been previously categorised, with a brief introduction of national categorisation by energy consumption and level of development. Most city comparisons are in the form of rankings by certain indicators, to find the largest populations, strongest economies, level of livability, or most sustainable. A key aspect of this section is to notice the absence of most African cities from these classifications, due either to lack of data, or inability to compete or compare with more developed cities. It concludes with an overview of the global cities typology.

2.7.1. National classifications

Most typologies are done for nations (Saldivar-Sali, 2010). This allows for smaller samples and results which consider familiar boundaries. This abundance also allows for comparisons between national classifications (Krausmann *et al.*, 2008). Classifications include: geographic clusters which rely on joint political boundaries, neighboring trade and shared history; levels of development, typically divided by the developed global north and the developing global south; rankings by income levels, HDI, the Gini coefficient for inequality, and financial risks involved in investing in a country (Saldivar-Sali, 2010; United Nations, 2012).

In describing the global socio-metabolic transition, Krausmann et al. (2008) assert that energy is the most basic constraint to growth and therefore socio-ecological systems which have the same energy source and conversion technologies will share other basic characteristics. These include resource use, or a metabolic profile, settlement patterns, use of human time and labour, institutional characteristics and communication patterns. In the transition from predominantly biomass energy to fossil fuel energy, countries move through specific

industrial stages with corresponding attributes, as explored in Section 2.4.2. Due to the energy requirement of transporting resources, sparsely populated areas require more energy to achieve the same level of production per person as a densely populated area; in this way population density is demonstrated to be an important factor in metabolic profiles (Krausmann *et al.*, 2008). High population density across a large area suggests longevity of human settlement, as gaining density within an agrarian regime is a slow process. Population density also distinguishes between high or low availability of resources, and the length of time a society might have been exploiting them. Using population density, the length of agricultural activity (embodied by 'old world' or 'new world' locations) and the level of industrialisation. Krausmann et al. (2008) form six metabolic profiles, shown in
Table 2-4. These denote the resource intensity of countries within different stages of industrialisation.

Table 2-4: Six metabolic profiles, determined by level of development, population density and agricultural legacy. Adapted from Krausmann et al. (2008: 646)

Density and History of agrarian colonisation	Industrialisation	
	Industrialised countries	Developing countries
High population density	High-density industrial: European countries, Japan, South Korea (N=30)	High-density developing: Most of southern/eastern Asia, including India and China, Central America, some African countries (N=63)
Low population density, New World Agriculture	Low-density industrial – New World: North America, Australia, New Zealand (N=4)	Low-density developing – New World: South America (N=22)
Low population density, Old World Agriculture	Low-density industrial – Old World: Countries of the former Soviet Union, Scandinavian countries (N=15)	Low-density developing- Old World: Northern Africa and Western Asia, parts of Africa, some Asian countries (N=41)

African countries fall into two of the categories: *High density developing countries*, categorised as closer to the agrarian regime than industrial, and containing a very poor populace with the lowest per-capita levels of resource and energy consumption in the world. Due to dense population, the total consumption levels are still quite large. The other category is *low-density developing countries* with long agricultural histories. Despite being predominant exporters of fossil fuels and ores, the countries display very low resource and energy consumption, with a higher reliance on biomass energy. Transition-informed metabolic profiles can also be visualised for cities, as demonstrated in Section 2.7.3.

2.7.2. City classifications

Krausmann et al. (2008: 646) note that countries are useful but odd quantities to classify as they are formed as “political entities that share a certain – and in some cases only a short – history”. As more importance is placed on cities as agents of environmental impact reduction, they have become more appropriate entities for classification; indeed they may lend themselves better to an understanding of resource analysis as they are purposefully founded upon resources: water as their primary requirement, arable land for agriculture, or minerals necessary for construction, industry or wealth accumulation.

The most basic categorisation of cities is according to population, with the largest cities providing a sense of pride, achievement and cultural fascination (Beaverstock, Taylor & Smith, 1999). Figure 2-8 shows their distribution of cities throughout the world and Table 2-5 shows a UN ranking of megacities for 2011 and 2025 (UN-DESA, 2011). Cairo and Lagos were Africa’s only two megacities, and the 2014 revision of the UN’s World Urbanization Prospects has just included Kinshasa in the list of current megacities (UN-DESA, 2014). Interestingly, most megacities are found in the global south, where urban planning is less structured.

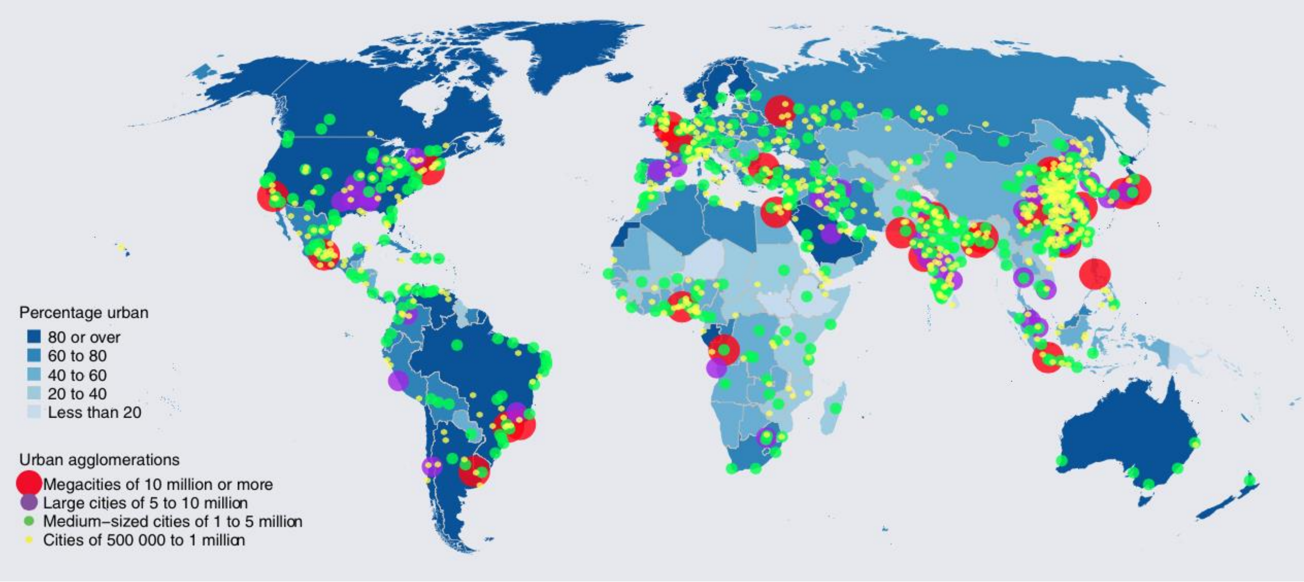


Figure 2-8: Global city distributions by size (UN-DESA, 2014)

Table 2-5: A ranking of megacities by population for 2011 and 2025 with population in millions (UN-DESA, 2011)

	2011			2025	
Rank	*Urban agglomeration*	*Population*	*Rank*	*Urban agglomeration*	*Population*
1	Tokyo, Japan	37.2	1	Tokyo, Japan	38.7
2	Delhi, India	22.7	2	Delhi, India	32.9
3	Ciudad de México (Mexico City), Mexico	20.4	3	Shanghai, China	28.4
4	New York-Newark, USA	20.4	4	Mumbai (Bombay), India	26.6
5	Shanghai, China	20.2	5	Ciudad de México (Mexico City), Mexico	24.6
6	São Paulo, Brazil	19.9	6	New York-Newark, USA	23.6
7	Mumbai (Bombay), India	19.7	7	São Paulo, Brazil	23.2
8	Beijing, China	15.6	8	Dhaka, Bangladesh	22.9
9	Dhaka, Bangladesh	15.4	9	Beijing, China	22.6
10	Kolkata (Calcutta), India	14.4	10	Karachi, Pakistan	20.2
11	Karachi, Pakistan	13.9	11	Lagos, Nigeria	18.9
12	Buenos Aires, Argentina	13.5	12	Kolkata (Calcutta), India	18.7
13	Los Angeles-Long Beach-Santa Ana, USA	13.4	13	Manila, Philippines	16.3
14	Rio de Janeiro, Brazil	12.0	14	Los Angeles-Long Beach-Santa Ana, USA	15.7
15	Manila, Philippines	11.9	15	Shenzhen, China	15.5
16	Moskva (Moscow), Russian Federation	11.6	16	Buenos Aires, Argentina	15.5
17	Osaka-Kobe, Japan	11.5	17	Guangzhou, Guangdong, China	15.5
18	Istanbul, Turkey	11.3	18	Istanbul, Turkey	14.9
19	Lagos, Nigeria	11.2	19	Al-Qahirah (Cairo), Egypt	14.7
20	Al-Qahirah (Cairo), Egypt	11.2	20	Kinshasa, Democratic Rep. of the Congo	14.5
21	Guangzhou, Guangdong, China	10.8	21	Chongqing, China	13.6
22	Shenzhen, China	10.6	22	Rio de Janeiro, Brazil	13.6
23	Paris, France	10.6	23	Bangalore, India	13.2
			24	Jakarta, Indonesia	12.8
			25	Chennai (Madras), India	12.8
			26	Wuhan, China	12.7
			27	Moskva (Moscow), Russian Federation	12.6
			28	Paris, France	12.2
			29	Osaka-Kobe, Japan	12.0
			30	Tianjin, China	11.9
			31	Hyderabad, India	11.6
			32	Lima, Peru	11.5
			33	Chicago, USA	11.4
			34	Bogotá, Colombia	11.4
			35	Krung Thep (Bangkok), Thailand	11.2
			36	Lahore, Pakistan	11.2
			37	London, United Kingdom	10.3

Examining the role of a city, Beaverstock et al. (1999) attempt to define the term *world city*, with the explanation that even non-megacities have as much need to respond to globalisation needs. They determine world cities to be those which provide the advanced producer services of accounting, banking, advertising and law. The presence of major firms of four service sectors in cities is scored to produce a Globalization and World Cities (GaWC) inventory. The inventory finds 55 cities separated by score, into *alpha*, *beta* and *gamma* world cities, and highlights 68 cities which show potential to develop into world cities. Beaverstock et al. (1999: 457) state that the GaWC is a “concrete expression of what has been called *uneven globalisation*,” visualised in Figure 2-9, with most world cities noticeably in the global north. Johannesburg, ranked as gamma, is the only African city on the list, noted to be an oddity as perhaps an “outlier of European capital” (Beaverstock *et al.*, 1999: 457). Cairo and Cape Town are noted as having potential to grow into world cities.

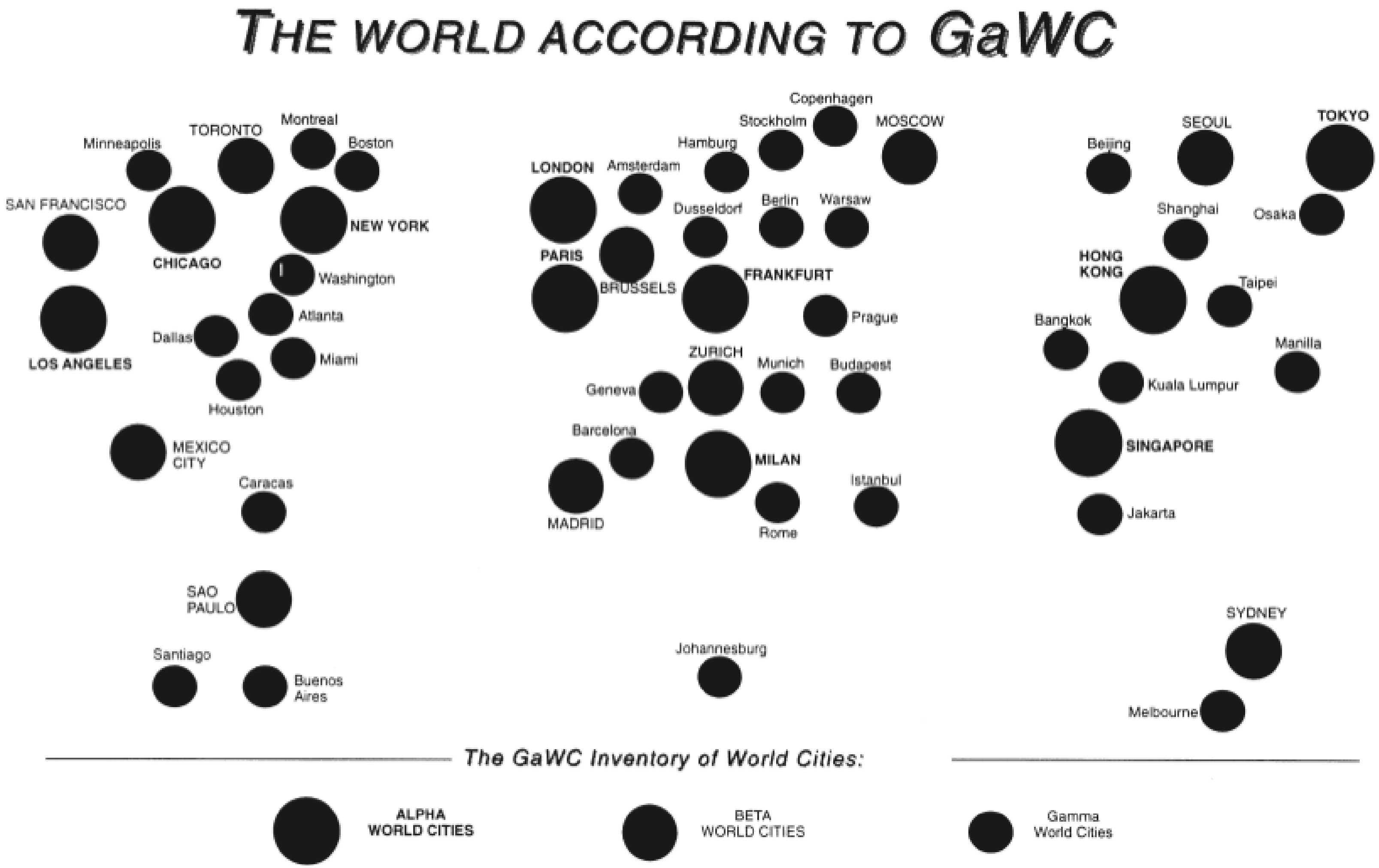


Figure 2-9: Mapping of world cities demonstrates signs of ‘uneven globalisation’(Beaverstock *et al.*, 1999)

Along similar lines, AT Kearney (Hales & Pena, 2012) have generated a more recent Global Cities Index which ranks cities by weighting various of their outputs or functions, including business activity, information exchange, political engagement, human capital and cultural experience. Inclusion of cultural and social indicators is an interesting departure from Beaverstock et al's (1999) categorisation of city success. The 2012 edition showcases 66 cities with Cairo ranked 50th, Johannesburg 52nd, Nairobi 56th and Lagos 59th. Interestingly, the largest documented economic sector for each of these is 'information exchange'

Placing African cities in the global transit network, Otiso et al. (2011) rate African cities by their level of Airline connectivity, mapping their role in inter-urban transit. Ranked by number of passengers, Johannesburg is the largest hub, followed by Cairo, Cape Town, Durban, Casablanca, Nairobi, Tunis, Port Louis, Lagos and St. Denis de la Reunion.

The most complete collection of city indices is 'The Business of Cities 2013' by Moonen and Clark (2013), who analyse 150 city reports, covering themes of (i) finance, (ii) macroeconomic performance, (iii) quality of life, (iv) knowledge creation, human capital and technology, (v) infrastructure and real estate, (vi) sustainability and environment, (vii) image and branding, (viii) culture and diversity, and (ix) cost of living. They suggest that indices are powerful tools for governments, businesses and investors, providing diagnostic assessment, comparative pegging, leverage and persuasion, pedagogy, or home truths. Their analysis consolidates the top six performing 'world cities' as New York, London, Tokyo, Paris, Hong Kong and Singapore. Moonen and Clark (2013) describe African cities' absence from most indices as due to high investment risk and poor infrastructure, yet cite high youth populations and rapid growth as huge potentials for increasing city exposure. "The traditional urban powerhouses in Africa were in the far north and south -Cairo, Casablanca, Cape Town and Johannesburg - but urban growth in East and West Africa is a defining characteristic of the recent phase of economic development" (Moonen & Clark, 2013: 29). Accra, Lusaka and Luanda are noted as having the greatest potential for growth.

A more complete index of African growth potential was developed by Hendrick-Wong and Angelopulo (2014), who examine 74 African cities and 6 international comparison cities. Growth potential is determined with both lagging indicators, attributes which have contributed to the current state of the city, and leading indicators, attributes which demonstrate potential for future development. These 24 indicators are couched in the concepts of inclusive or exclusive urbanisation, which refer to the level of participation of, or benefits reaped by, the city's population. Inclusive urbanisation describes a city making use of economy of scale to support flows of knowledge and wealth, enabling a good business climate, wealth creation and a middle class, which increases consumer demand. Exclusive urbanisation suggests that most of the city's wealth benefits an elite few, while the majority of the population is in slums or excluded from resource or social services. Hendrick-Wong and Angelopulo (2014) rate Accra as the city with the highest potential for growth, followed by Tunis, Casablanca, Lagos, Kumasi, Victoria, and Port Louis. The lowest cities by growth potential are noted as Harare, Huambo, Antananarivo, Bangui, Asmara, Malabo and Mbabane.

Forming a typology based on resource indicators, Creutzig et al. (2015) measure urban energy consumption for 274 cities and identify an 'urbanisation mitigation wedge,' essentially suggesting that urbanisation can reduce energy consumption with some appropriate interventions. Urban transportation energy is noted to increase with GDP until a threshold of $13,500 at which energy decouples from GDP, suggesting more efficient transport or higher gasoline prices. The remark on the balanced occurrence of density and gasoline price: affluent cities tend to be less dense due to land required for economic activity, requiring more energy for transport; however, energy is reduced due to high gasoline prices found in affluent cities. Creutzig et al. (2015) demonstrated that final energy consumption is most reliant on economic activity, with climate as the next most important variable.

2.7.3. A city resource typology

According to Fernández (2014: 601), "a statistically robust and rigorous classification based on distinctive urban resource profiles would be helpful in understanding the distinct opportunities for resource efficiency for one type versus another. Without such analytical comparisons, the study of urban resources will remain relatively labour intensive and expensive as researchers approach cities of interest individually and separately". The Global Typology of Cities (Saldivar-Sali, 2010) is the first such comparison using resource profiles. The study was based on the assertion that while cities may consume resources in many different ways, they do follow similar patterns (Fernández *et al.*, 2013), as discussed in Section 2.3.4.1 of this chapter. While expressing the need for context specific strategies, Fernández et al. (2013) ask whether strategies can be formed for 'like' cities, and asserts that (i) grouping cities by key attributes may allow deeper understanding of resource consumption

and (ii) linking resource consumption intensity to these attributes may provide insight into the global impact of cities. This is a similar assertion to Krausmann et al's (2008), discussion that areas with similar energy and material consumption display similar demographic attributes, particularly involving population density. Linking the variables of population, population density, GDP and Koppen climate zone to resource intensity allowed the grouping of cities into metabolic profiles. Further, for data-scarce cities, the material and energy consumption intensity was predicted using the variable-resource relationships observed in data-rich cities.
The cities were grouped by intensity of eight resources, prescribed in the Eurostat Method (2001), namely "biomass (Bio), fossil fuels (FF), total energy (TE), electricity (EL), carbon dioxide emissions (CO2), industrial metals and minerals (Ind), total materials (TM), and construction materials (Con)" (Fernández, 2014: 602). Consumption intensity is simplified to high, medium and low intensity, to allow simple comparison of profiles.

Figure 2-10 compares the resource profile of two cities. Figure 2-10a depicts a developing city with low HDI, and predominant reliance on biomass, while Figure 2-10b suggests one of high HDI and predominantly service industries. A city's transition from agrarian regime to industrial regime, as discussed in Section 2.4, is visualised in terms of resource consumption in Figure 2-11. It depicts the increase in resource consumption associated with physical urban growth and urban economic growth while in transition, and the later reduction due to stabilisation, increases in resource efficiency, and benefits of economies of scale.

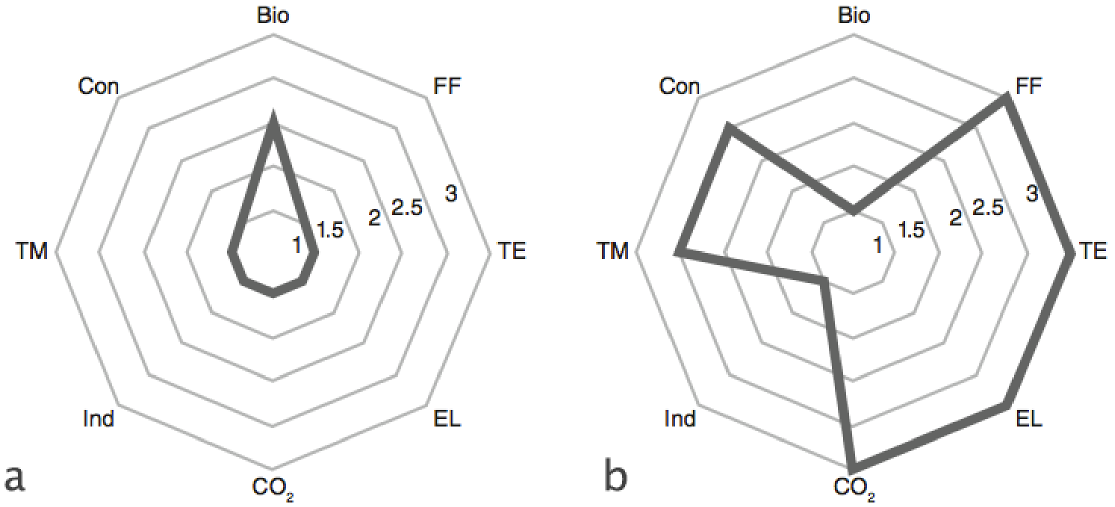


Figure 2-10: Comparison of two urban metabolic profiles. (Fernández, 2014: 602)

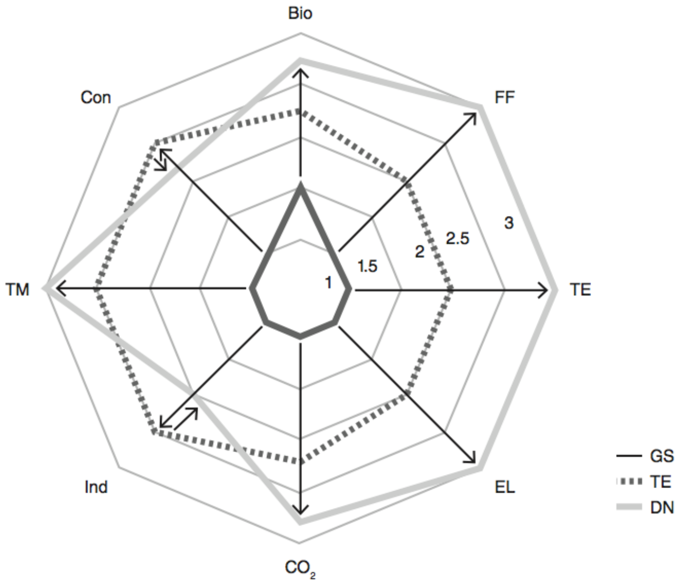


Figure 2-11: Resource consumption pathways through industrialisation and economic growth. (Fernández, 2014: 603).

Saldivar-Sali’s (2010) work formed phase 1 of the city typology project by the Urban Metabolism Group at the Massachusetts Institute of Technology, and produced a categorisation of 155 global cities into 15 types, shown in Figure 2-12. The radar charts demonstrate the level of resource intensity, from low in the middle to high on the outer ring. What is key to note from these diagrams is the ‘shape’ of the resource profile, which suggests the importance of each resource within the city, and the magnitude of resource intensity, which indicates how consumptive or impactful the city is.

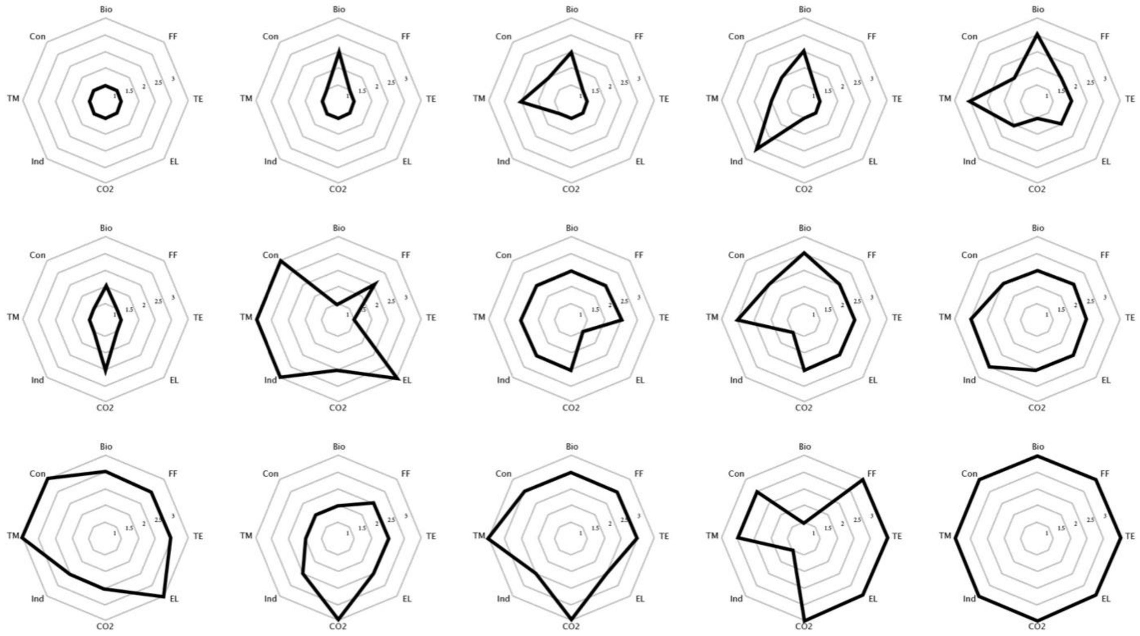
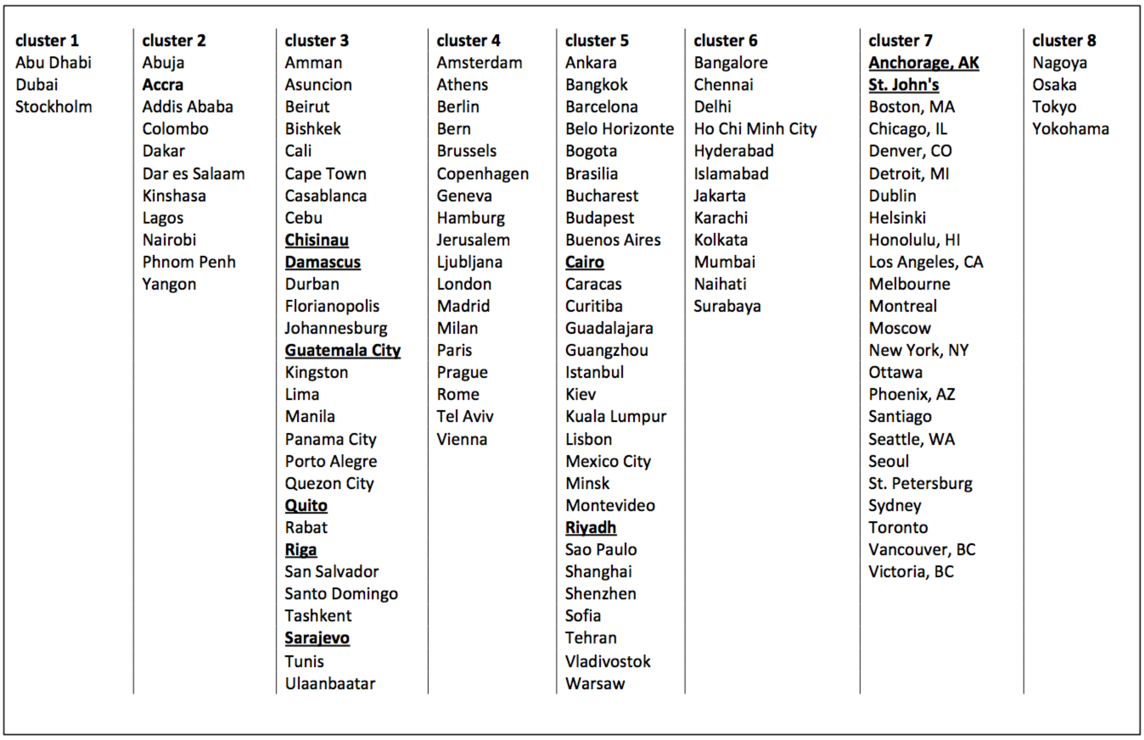


Figure 2-12: Fifteen types of city, categorised by consumption intensity of 8 resources. Source: (Fernández *et al.*, 2013)

Phase two of the Urban Metabolism Group's process reclassified Saldivar-Sali's (2010) 15 clusters into eight metabolic profiles, whose city members are shown in Table 2. The clusters are simply explained: cluster 1 forms the United Arab Emirates cities and Stockholm, showing high energy and construction material consumption; cluster 2 holds typically-equatorial developing African and Asian cities, with largest consumption being biomass. Cluster 3 contains temperate to arid cities with medium consumption of biomass, construction materials and total materials, with low energy use. Cluster 4 shows mostly European cities, producing high GDP and HDI while using medium levels of materials and energy. Cluster 5 differs from cluster 2 with twice higher construction material consumption and 10 per cent higher HDI; cluster 6 cities have low levels of consumption, despite having higher densities and producing slightly higher HDI and GDP than cluster 2. Cluster 7 contains very high consumers of energy and materials and the largest producers of CO2, with high HDI and GDP and low density, mostly from North America and Australia. Cluster 8 contains Japanese cities, noted for being the largest consumers of water and construction materials, with medium electricity, fossil fuel and material consumption, and lowest biomass and per capita energy, despite large populations.

Table 2-6: A list of the cities in each of the clusters from phase II of MIT's city typology project.



cluster 1	**cluster 2**	**cluster 3**	**cluster 4**	**cluster 5**	**cluster 6**	**cluster 7**	**cluster 8**
Abu Dhabi	Abuja	Amman	Amsterdam	Ankara	Bangalore	**Anchorage, AK**	Nagoya
Dubai	**Accra**	Asuncion	Athens	Bangkok	Chennai	**St. John's**	Osaka
Stockholm	Addis Ababa	Beirut	Berlin	Barcelona	Delhi	Boston, MA	Tokyo
	Colombo	Bishkek	Bern	Belo Horizonte	Ho Chi Minh City	Chicago, IL	Yokohama
	Dakar	Cali	Brussels	Bogota	Hyderabad	Denver, CO	
	Dar es Salaam	Cape Town	Copenhagen	Brasilia	Islamabad	Detroit, MI	
	Kinshasa	Casablanca	Geneva	Bucharest	Jakarta	Dublin	
	Lagos	Cebu	Hamburg	Budapest	Karachi	Helsinki	
	Nairobi	**Chisinau**	Jerusalem	Buenos Aires	Kolkata	Honolulu, HI	
	Phnom Penh	**Damascus**	Ljubljana	**Cairo**	Mumbai	Los Angeles, CA	
	Yangon	Durban	London	Caracas	Naihati	Melbourne	
		Florianopolis	Madrid	Curitiba	Surabaya	Montreal	
		Johannesburg	Milan	Guadalajara		Moscow	
		Guatemala City	Paris	Guangzhou		New York, NY	
		Kingston	Prague	Istanbul		Ottawa	
		Lima	Rome	Kiev		Phoenix, AZ	
		Manila	Tel Aviv	Kuala Lumpur		Santiago	
		Panama City	Vienna	Lisbon		Seattle, WA	
		Porto Alegre		Mexico City		Seoul	
		Quezon City		Minsk		St. Petersburg	
		Quito		Montevideo		Sydney	
		Rabat		**Riyadh**		Toronto	
		Riga		Sao Paulo		Vancouver, BC	
		San Salvador		Shanghai		Victoria, BC	
		Santo Domingo		Shenzhen			
		Tashkent		Sofia			
		Sarajevo		Tehran			
		Tunis		Vladivostok			
		Ulaanbaatar		Warsaw			

Fernández et al. (2013) explain that the most important variable responsible for forming these clusters is energy per capita. If it were omitted, the eight metabolic profiles would be clustered as one. The next most important are fossil fuels and water, resulting in four and five clusters respectively if removed. The least impactful variable is noted to be industrial minerals, which leaves the clusters unchanged if removed. Changes in each of the remaining variables makes small alterations to cities comprising each cluster.

It is interesting to note how cities of the same country are typically in the same cluster. Only Porto Allegre and Sao Paolo, and Barcelona and Madrid are same-nation cities that are in separate groups. This suggests that while their per capita consumption, or resource profile, may not be the same, they may be more similar to each other than they are to other cities. This may also relate to the availability of city-level data and the method used to scale from national level, which relies on population size and therefore produces very similar per capita consumption data. This is relevant, as much of the African city data for this study were estimated in a similar manner.

2.8. City scaling

Forming a city resource typology requires detailed city-level data, much of which is not readily available. Therefore, a robust method for estimating this data is required. This section describes some basic theory of city scaling relationships. Gibrat's law for cities declares that city growth processes are effectively homogeneous for all cities and are independent of the initial size of the city (Gabaix, 1999). Whether dependent on shifts in a city's population or on its particular industry or function, cities tend to change in similar ways as they grow. Thus, cities can be conceptualised as scaled versions of each other, simply at different stages of growth. Empirical proof of this phenomenon comes in the form of a rank-size relationship, the most popular demonstration of *Zipf's law*. Ranking the cities of a nation from largest population to smallest and plotting log of the rank by the log of the population demonstrates that the size distribution of cities fits a power law. In other words, "the number of cities with populations greater than S is proportional to 1/S" (Gabaix, 1999: 739). This has been shown for cities of the United States, India and China (Rosen & Resnick, 1980). Figure 2-13 shows an example of cities of the United States.

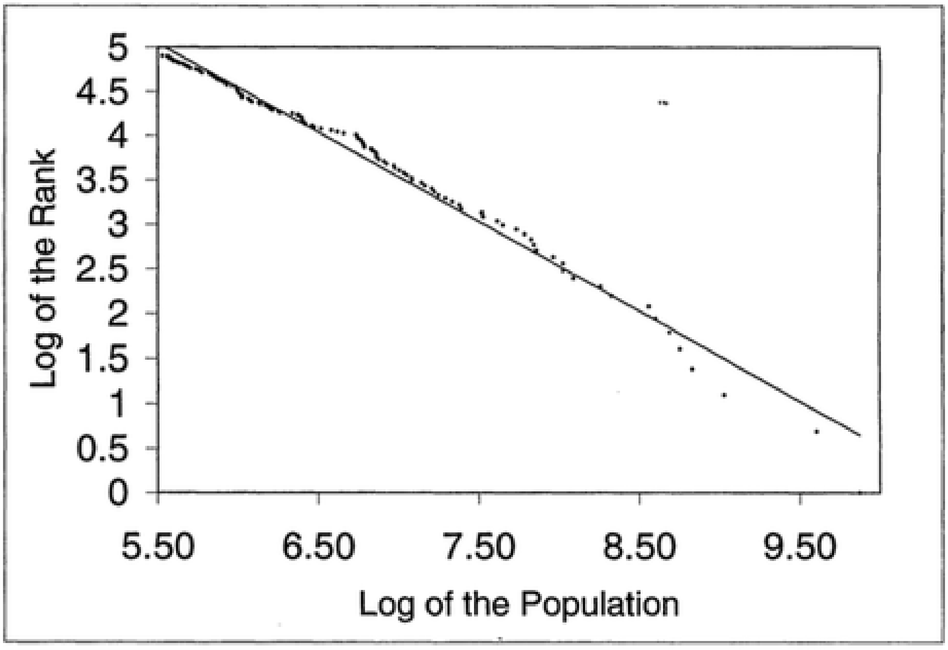


Figure 2-13: Rank-Size relationship of the 135 largest Metropolitan Areas in the US for 1991. (Gabaix, 1999: 740)

The log (population) by log (rank) graph demonstrates a relationship which, on average, barely deviates from a -1 slope. Gabaix (1999) notes that Zipf's law describes an approximate relationship, from which cities do deviate: the variance from the power law is higher when comparing cities of similar rank. For example, the size ratio between the largest city and second largest city is expected to be 0.5, however, the standard deviation is 0.2887. This is comparable to the standard deviation of 0.0299 between the 10th largest and 100th largest cities (Gabaix, 1999: 753). Deviation is visible in the bottom right of Figure 2-13, in which larger cities stray from the relatively linear upper part.

The quality of data is important in analysing this relationship. Rosen and Resnick (1980) explain that city-proper data (that which is more available) yields higher Zipf's exponents than agglomeration data, as the arbitrary administrative boundaries tend to misrepresent the true city size. However, the consistency of population data within each country would offer a valid distribution.

With a large body of empirical evidence, Bettencourt et al. (2007: 7301) further substantiate Gibrat's law, demonstrating that many socioeconomic dynamics related to urbanisation "appear as nontrivial quantitative regularities common to all cities, across urban systems". Taking the lead from biological systems, they explain the relationship of mammalian body size to speed of metabolism: A mouse, a small mammal with a fast heart-rate, fast metabolism and a short lifespan is compared to an elephant, a large mammal with a slow heart-rate and metabolism, and a longer lifespan. The processes which serve this larger creature are slower. Not only are they slower, but are, in fact, calculable as a power law relationship between the elephant's metabolism and body size. In simple terms, as mammalian body size increases, heart rate and metabolism both slow down. Bettencourt et al. (2007) shift discussion to urban metabolism, noting that this relationship exists in many city processes, particularly with regards to infrastructure provision: as cities grow in size, less infrastructure is needed per person to provide necessary services. These are the benefits of high density and economies of scale. However, they show that many city processes, such as knowledge or wealth generation, do not slow down as it grows, but increase.

They present an equation:

$$Y(t) = Y_0 N(t)^{\beta}, \tag{1}$$

in which Y is the indicator to be understood (anything from resource consumption to city outputs, or social attributes) as a function of N, city size, at time t. Y_0 is the normalising coefficient (or the Y when N is at its smallest or initial value) and β is the scaling exponent which describes the relationship between Y and N.

Bettencourt et al. (2007) identify three types of scaling relationships and the indicators which are subject to each. First is a sublinear relationship (β<1), which demonstrates the benefits of a city's economy of scale: as it grows, a city may need less material infrastructure to support a larger population. Second is a linear relationship (β ≈ 1), which includes attributes related to individual human needs, such as housing, or household water or electricity consumption. Finally, superlinear relationships (β>1) are categorised by attributes which demonstrate the outcomes of urban agglomeration, such as increases of knowledge production, total energy consumption, cases of crime or disease, and affluence. Figure 2-14 shows different "regimes of city growth," dependent on each form of scaling relationship: (a) growth due to sublinear scaling leads to the convergence of the city to carrying capacity; (b) linear scaling results in exponential growth; (c) superlinear scaling results in divergent growth, which typically reaches a point of collapse, shown in (d) (Bettencourt *et al.*, 2007: 7305).

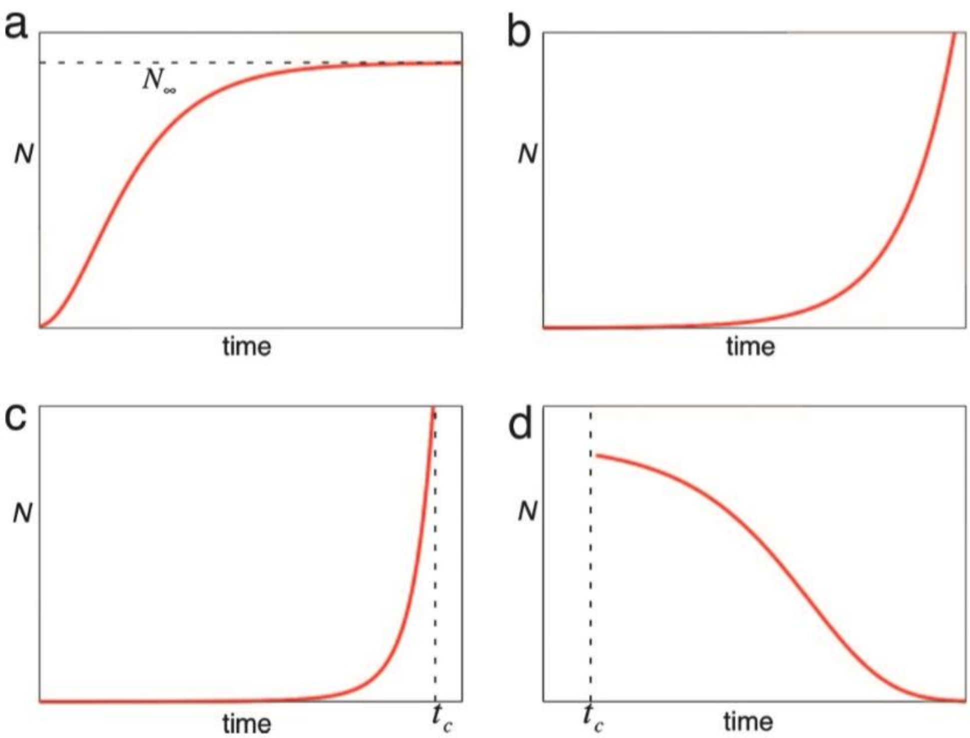


Figure 2-14: Regimes of growth as explained by Bettencourt et al. (2007: 7305)

Determining the average scaling coefficients and exponents which describe the relationship between city size and indicator, between population and resource consumption for this study, requires both size and indicator data from a large sample of cities for the same point in time. By plotting this information and fitting an average power line to the distribution, the scaling equation can be determined. In theory, this scaling relationship could be determined through the growth of one city over time. However, this would require data over a long time period and the resulting scaling exponent from a sample of one city may not be as empirically robust or transferable as one observed from multiple cities. This is particularly true if examining larger cities which deviate from the average rank-size distribution.

2.9. Summary

This chapter demonstrated the limited academic consensus surrounding urbanisation trends in Africa. This is partly due to the overwhelming number of social issues and partly from a lack of specific, empirical data with which to identify trends, or make decisions. A general overview of differential city definitions and approaches to understanding urban metabolism suggests that pathways towards sustainable cities are multiple and varied. There are no obvious or tested pathways to establishing equitable, economically productive and livable cities in Africa, partly due to a reliance on generalisations, enforced by mainstream agendas for urbanisation, economic growth, or sustainability, which are not relevant to many African spaces, let alone countries of the global south. To remedy this, more localised or context-specific information is necessary.

A survey of recent city typologies and rankings serves to demonstrate African cities' absence from most discussions and that only one global-level resource consumption analysis exists. The rationale for this study recognises the need for a more focused comparative study of African cities in order to demonstrate subtle differences more strongly, as opposed to the current comparisons with the vastly different cities of global north. The inclusion of more African cities would demonstrate material and energy efficiency baselines for cities not yet studied from resource perspectives; this would also provide insights into the relative sustainability of these cities, which may inform future focus of sustainability efforts.

The final section on scaling sought to demonstrate that estimated data may not be accurate enough to be useful. While more differential examination of African cities is desirable and necessary, limited data may hamper the usefulness of the resulting typology. The following chapter details the methods for building this much-needed reference tool.

Chapter 3: Research Methodology

3.1. Introduction

The primary objective of this study was to establish a typology of resource consumption in African cities. This involved categorising African cities by the types and quantity of resources they consume. The desired result was a typology consisting of 120 cities, separated into an appropriate number of clusters. The optimal number of clusters was a result in itself, as it was unknown how many unique forms of city exist on the continent. Such a typology has implications for how we understand (i) the global or national impact of these cities, (ii) the cities' relative sustainability and (iii) the current and future consequences of African urbanisation on resource consumption.

This chapter explains the study's overall research design and the methods utilised to achieve the above objective, organised by the five sub-objectives established in the introduction:

1. To identify and select representative cities for investigation that captures relevant attributes, such as demography, region, climate zone, income, poverty level, or function.
2. To demonstrate the scope of available resource consumption and socioeconomic data for selected African cities.
3. To establish and use robust statistical methods to estimate city-level data.
4. To group cities appropriately utilising available raw and estimated data.
5. To determine the predictor variables which influence resource consumption.

3.2. Research design

The process of categorising African cities by resource consumption primarily utilised secondary data analysis. The choice of this method was in line with the need for a typology: to circumvent the time consuming research demanded by analysis of urban metabolism of individual cities. The key strength of secondary data analysis is the timesaving benefit of using already-collected data. Much of this data also comes with some analysis already undertaken, which adds further perspective to the work. In data-rich environments, the researcher can be discriminating in the choice of data to work from. However, this choice can be challenging when building consistent datasets. Such inconsistencies include differing years of data-collection, discrepancy in units, differing methods for data estimation or collection, and a wide range of data sources. Here the researcher must also find a compromise between more accurate data (often of limited quantity) and more comprehensive or consistent data, which may be of lower reliability. Statistical analysis of data was completed in Microsoft Excel and R, an open source programming language available online at cran.r-project.org.

A typical workflow of research would ordinarily move from data acquisition, through data analysis to discussion. However, faced with data-scarcity, cycles of experimentation and informed speculation produced different estimations of required data. This study, thus shifted its primary focus from producing a singular typology to exploring the methods of data estimation and categorisation which would enable production of a typology. Figure 3-1 shows the stages of this study as *sample identification, data acquisition, data estimation, data analysis,* and *discussion.* The processes of identifying the correct sample and acquiring data were intertwined, as initially the scope of available data was unknown.

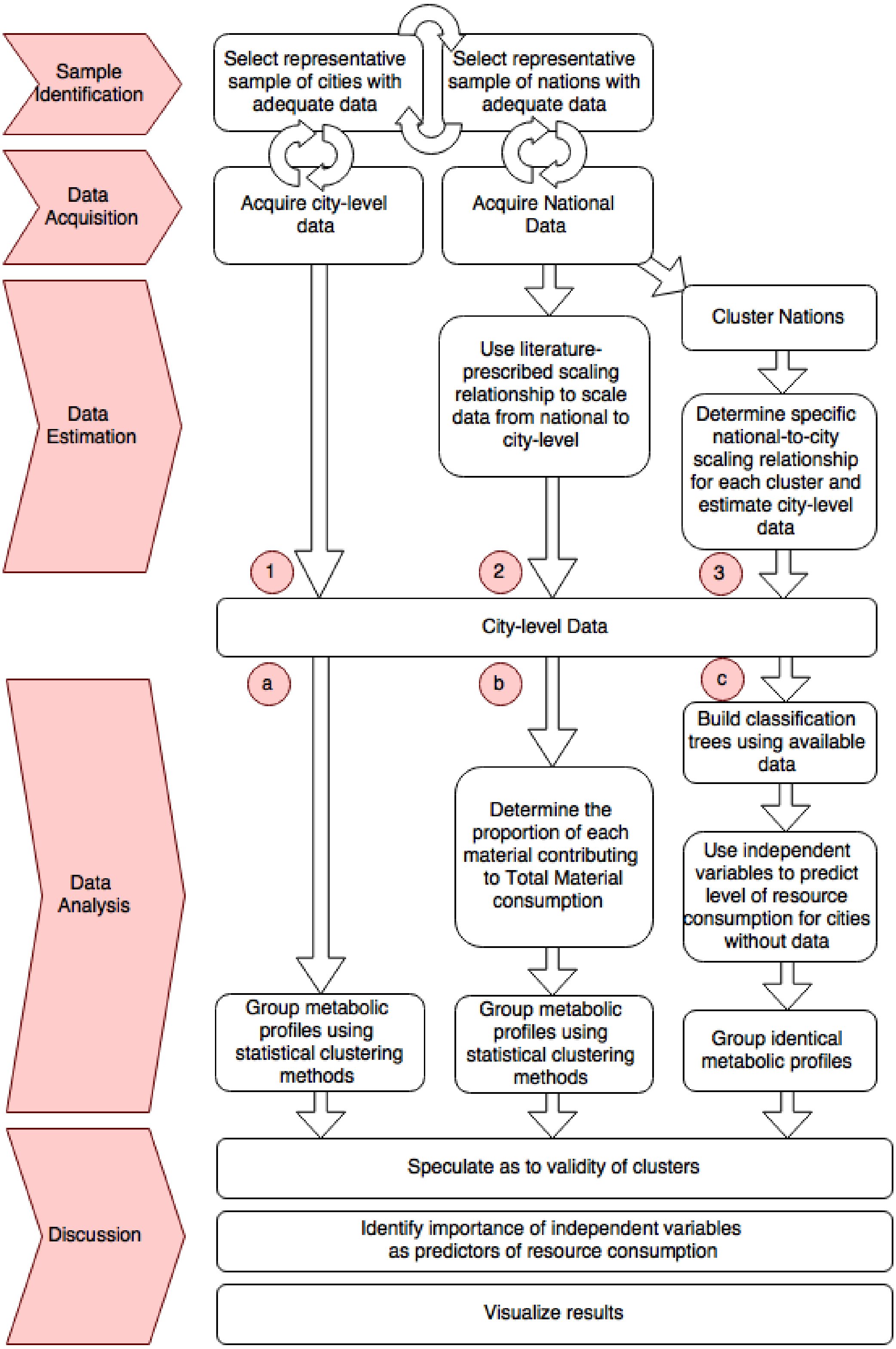


Figure 3-1: Five potential workflows for clustering cities by similar resource consumption.

Figure 3-1 shows two sets of pathways: one for gathering city-level data and another for clustering cities into a typology. The data estimation pathways are described below:

1. With a large enough sample of cities with enough raw city-level data, analysis could continue directly.
2. To scale city data from national data requires determining a scaling relationship between the two. Bettencourt et al. (2007) have identified several relationships which could be used as proxy. Saldivar-Sali (2010) used one scaling relationship as proxy for the global typology. This pathway makes use of scaling relationships chosen based on literature.
3. This pathway suggests that if nations can be clustered by similarity of socioeconomic variables, the differences between national- and city-level may be similar too. If scaling relationships could be determined for one country in each cluster, they could be used as proxy for the other members of the cluster. Ultimately, this requires very detailed data for that country, which were lacking for a member in most clusters.

The methods for developing and clustering metabolic profiles are described below:

a. City data could be clustered directly, normalising the data for comparison and using statistical clustering techniques. For this study, hierarchical clustering was chosen as most appropriate. This pathway preserves the relative magnitude of the resource indicator, instead of relying on a qualitative comparison.
b. Based on raw data, each resource indicator could be classed as high, medium or low intensity. Classification trees, explained fully in Section 3.6.1.1, could be built with independent variables to predict the dependent resource indicators, as was done for the global cities typology (Saldivar-Sali, 2010). Then one could predict the resource consumption for the cities lacking resource data, as long as the cities had data for predictor variables. However, only a small sample of cities had raw resource data, so this was not possible. Instead, a sample of cities was formed using the largest city from each country, and estimated data were used to build trees. The process of building classification trees identifies which variables are most useful in predicting the dependent variables, which was useful in approaching objective 5.
c. Pathways a and b compare the magnitude of each resource indicator between cities, as opposed to comparing the relative importance of that resource in the city system. This pathway would seek to compare cities as a whole, by examining each resource as a proportion of total material consumption. In doing so, it would effectively compare the shape of each metabolic profile instead of the magnitude, and therefore not require any

form of normalisation. This pathway was not included in the final analysis, but remains a possibility for future work.

After forming clusters, the validity of the clusters was examined, in both quantitative and qualitative manners, and if there were discrepancies, the process was repeated until the results were suitably consistent. For this study, pathway 2 was followed to estimate city-level data and pathways *a* and *b* were used to form resource typologies.

As limited city-level data was available, examination of predictors of resource consumption was limited to those outlined by multiple authors (Barles, 2009; Saldivar-Sali, 2010; Weisz & Steinberger, 2010; Fernández *et al.*, 2013; Creutzig *et al.*, 2015), namely population, population density, climate indicators, income and, to some degree, population growth.

Deciding how to normalise the data posed an interesting choice. Convention has relied on per capita baseline comparison of cities, but there is some dissatisfaction with this as such a measure overlooks differences in population distribution, social make-up or city function. Using per capita normalisation of resource data effectively shows the resource intensity of a population. However, Satterthwaite (2009) suggests that resource intensity is not necessarily a function of population but of consumption, a proxy for which is affluence or GDP. Normalising the resource data by GDP would effectively show the resource intensity of a nation or city's economy. For this study, the per-capita convention was followed, but an exploration of a per-unit-GDP measure was also undertaken.

3.3. Selecting cities for the typology – objective 1

The desired sample of cities aimed to include a variety of city types, showing differences in population size, population density, growth rate, climate, income, and function, such as administrative, industrial, transit hub, trade port or financial center. By inclusion of multiple indicators, such a sample enables determination of the contributors to resource consumption. The inclusion of smaller cities was also important, as these satellite cities will become more impactful as their populations grow. To be inclusive, and allow a larger scope of understanding, attempts were made to include multiple cities from all African countries. The final sample of cities was influenced by the presence of data.

From the initial dataset of 687 identified cities, a smaller list of cities was distilled by attempting to include three cities per country following the priority of (i) country capital, (ii) largest remaining city and (iii) remaining city with the most available data. Any remaining cities of over one million people were also included, resulting in a list of 161 cities. This sample was reduced to 120 cities, each of which had complete data for population, population density, and climate. Stellenbosch, South Africa, was included as this study was completed at Stellenbosch University, and its inclusion would be useful to reference in future local research. Not every country has three representative cities due to incomplete data or limited number of sizable cities.

3.4. Acquiring and estimating data – objective 2

3.4.1. Desired data

The desired dataset included a slew of demographic, socioeconomic and geographic indicators with the intention of understanding their relationship to resource consumption. Of particular interest were the predictor variables identified by Krausmann et al. (2008) and Barles (2009), and utilised in the global city typology (Saldivar-Sali, 2010), namely population, population density, climate and affluence, either in the form of gross domestic product or income.

Variables to describe the distribution of population or wealth within cities, such as the Gini coefficient, would have been useful for relating the effects of social inequality to resource consumption. However, the methods for forming the Gini coefficient are varied and include other raw variables, which may undermine the consistent use of first order indicators. Understanding the spatial distribution of cities within nations is relevant to data scaling, and offers an indication for where the impacts associated with unplanned urbanisation are likely to manifest. Urban primacy has been used in relation to governance and the prioritisation of cities which are central for development. It also provides insights into the regularity of population distribution in nations, and therefore what we can expect from scaling by population. Thus, an index for urban primacy was improved from the UN definition. The desired resource variables follow Eurostat guidelines (2001) for materials, and includes energy indicators and water, following the global typology of cities. The nine key variables include per capita consumption of water, electricity, fossil fuels, total energy, biomass, industrial minerals, construction materials, ores, total materials and emissions of carbon dioxide. Data for waste flows were limited and had no national equivalent from which to scale.

3.4.2. Sources of city-level data

Sources of demographic data were numerous, offering differences in scope and method. Thomas Brinkhoff's population statistics website, *citypopulation.de*, provided population data curated from international and national statistical institutes. Using geographical information, Brinkhoff made efforts to merge data of smaller administrative areas to demonstrate the full population of cities and urban agglomerations. As the most abundant source of population data, the Brinkhoff's data was used to build a skeleton dataset of about 687 urban settlements ranging in size from 26,450 people (Victoria, Seychelles) to 17,921,542 people (Cairo, Egypt). This skeleton was fleshed out with more variables and data-points detailed hereafter. UNData, with the release of the 2014 revision of World Urbanization Prospects (UN-DESA, 2014) provided annual population estimates rounded to the nearest thousand for cities over 300,000 people. The World Bank (2014) offered population, population growth rate, as well as some information detailing access to resource services, for 31 key cities. The tenth edition of Demographia World Urban Areas (Demographia, 2014), an annually published inventory of global urban areas over 500,000 people, included estimates of population, population density and built area, based on satellite image analysis. The Lincoln Institute of Land Policy (2000) hosts 'a universe of cities' on their website which offered estimates of city population, built-up area, compactness, and distance from the ocean for the year 2000. Much of the population data was validated by national census data, with additions or corrections made to city data for Algeria, Botswana, Malawi, Morocco, Mozambique, Nigeria, Rwanda, Somalia, and South Africa.

Climate zones were determined for all cities using Koppen-Geiger classification, the most frequently used mapping of climate types (Kottek, Grieser, Beck, Rudolf & Rubel, 2006). The classification by Wladimir Koppen in 1900 demarcated areas based on the distribution of vegetation types which are specific to certain climates. This produced a mapping of five climate zones: equatorial, arid, warm temperate, snowy and polar. Kottek et al. (2006) extended the original classification into a three-part designation of climate zone, temperature and precipitation. What emerged from their updates are 31 unique climactic zones, as displayed in Figure 3-2. African cities exhibit 14 of these.

The importance of including climate indicators in the typology relates to how climate impacts the energy needed for thermal regulation in buildings. With this in mind, further climate data were sought from BizEE software Limited’s website, *degreedays.net*, which catalogues data from local weather stations. Heating Degree Days (HDD) count the number of degrees below a base temperature over an amount of time. This allows calculation of the number of degrees of heating, and associated energy, required to ensure thermal comfort. Cooling Degree Days (CDD) count the number of degrees above a base temperature over an amount of time. This allows calculation of the number of degrees of cooling, and associated energy, required to ensure thermal comfort. The average annual HDD and CDD were each collected using a base temperature of 20 degrees Celsius, with the average ranging over two to five years.

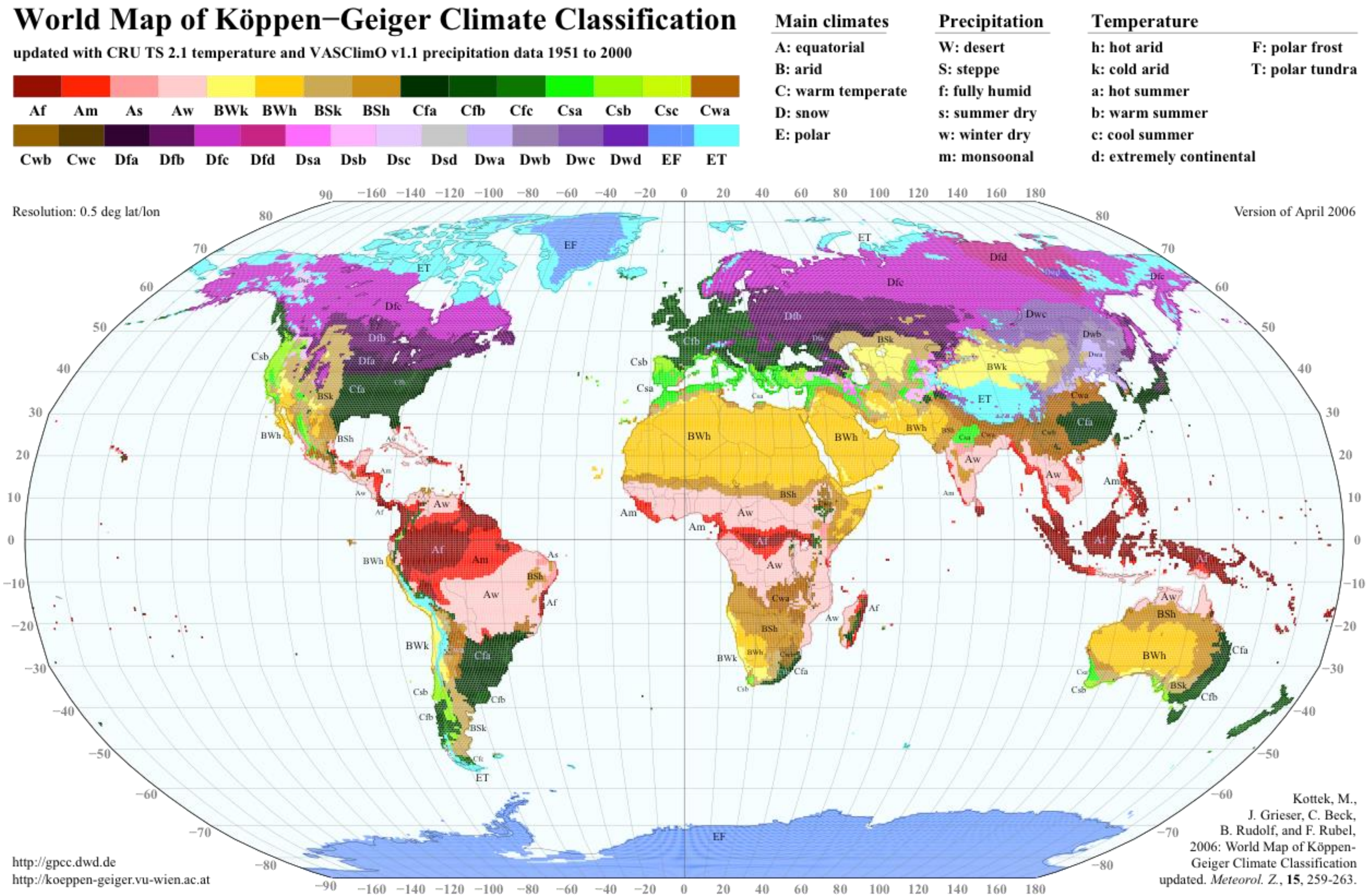


Figure 3-2: The updated Koppen Geiger climate map courtesy of Kottek et al. (2006)

City-level economic data were quite rare to find, with PricewaterhouseCoopers (2009) having estimated urban GDP for 15 African cities using UN population estimates and determined national to urban ratios. UNData provided Gini coefficients of inequality for 39 cities. In a seemingly singular effort, UN-Habitat (UN Habitat, 1999) used a qualitative method to identify the city development index for 29 cities, with rankings for city product, education, health infrastructure, education and waste. Unfortunately the index pre-dates 2000 and has not been re-evaluated.

Resource input and output data were rarer still, with most information detailing the percentages of the population with access to services such as electricity, improved sanitation, improved water, waste collection, and sufficient living area (2014). The only comprehensive collection of magnitudes of resource use was found in the Economist Intelligence Unit's (2011) African Green City Index, which detailed electricity and water consumption, carbon emissions and municipal waste production, and infrastructure rollout for 15 cities. Water data was sourced from The International Benchmarking Network for Water and Sanitation Utilities (IBNET, 2015). While not necessarily a complete accounting of the water consumed in a city, it included data for local utilities and the population they serve. More detailed data were found for individual cities in Egypt, South Africa, Nigeria, Angola, Kenya and Ghana. The final dataset used in this study includes a varying degree of data for 687 African cities from 2000 to 2014 for the variables described in Table 3-1.

Table 3-1: Discovered city-level data by variable

Variable	Number of cities for which data is available	Source
Name of City	687	Various
Population	653	citypopulation.de, United Nations (2014)
Administrative Area	101 – data for 122 is calculable from density	UN Habitat (2014)
Built Area	112	Demographia (2014), Lincoln Institute of Land Policy (2000)
Population Density	122 – data for 168 is calculable from area	Demographia (2014), Lincoln Institute of Land Policy (2000)
Climate Zone	653	Kottek et al. (2006)
Cooling Degree Days	110	degreedays.net
Heating Degree Days	110	degreedays.net
Urban GDP	20	PWC (2009), various national documents
City Development Index	29	UN Habitat (1999)

Urban Gini Index	By income – 24, by consumption -17	UN Data (2014)
Percentage of Slums	4	World Bank (2014)
Access to Electricity	57	UN Data (2014)
Access to Improved Water	45, 30, 80	IBNET (2014), UN Data (2014), World Bank (2014)
Water Consumption	15	Economist Intelligence Unit (2011)
Electricity Consumption	15	Economist Intelligence Unit (2011)
Waste Production	15	Economist Intelligence Unit (2011)
Carbon Emissions	15	Economist Intelligence Unit (2011)

3.4.3. National data

There is relatively consistent data for demographics, economics and resource production or consumption in African nations. The following sources were used to gather national data. Demographic, geographic and economic data, such as population, area, population density, degree of urbanism, occurrence of poverty, or gross national income were sourced from the World Bank (2014). Water consumption was also sourced from the World Bank (2014), using freshwater withdrawals as a proxy for consumption. Energy production and consumption data, as well as emission outputs were sourced from the US Energy Information Agency (2014), and material consumption data, based on trade information, was sourced from a new online portal, *materialflows.net*, administered by the Sustainable Europe Research Institute (SERI) and Vienna University of Economics and Business (WU) (2014). However, disaggregated data for biomass, construction materials, industrial minerals and ores were only available as ‘used extraction,’ and no import data for these variables were available. This gives only a partial picture of consumption for these resources as material consumption includes used local extraction as well as imports. Climate data was approximated from the Koppen climate classification (Kottek *et al.*, 2006). As most countries demonstrate multiple climate types, the climate associated with the largest area of land was chosen.

Minimal data was found for the nations or territories of Mayotte, Reunion, Saint Helena Ascension and Tristan da Cunha, and Western Sahara, which were omitted from the final dataset. Due to its recent independence, limited resource data exists for South Sudan, so data from Sudan was used as a proxy for understanding cities in South Sudan. The final dataset has complete data for 53 Nations, as described in Table 3-2.

Table 3-2: Discovered national data by variable

Data category	Indicator	Units	Source
Geography	Climate zone	none	Kottek et al. (2006)
	Area	sqkm	World Bank (2014)
Demographic	Population	Person	World Bank (2014)
	Population density	Person/sqkm	
	Urban population	%	
	Rural population	%	
	Annual population growth	%	
Socioeconomic	Gross domestic product (GDP)	Billion USD	World Bank (2014)
	Contribution of sectors to GDP: Agriculture, Fisheries and Forestry Mining (& Oil) Manufacturing Electricity, Gas and Water Construction Wholesale and Retail Trade Transport, Storage and Communication Finance, Real Estate, Business Public Administration & Social Services	%	
	Gross National Income (GNI)	Billion USD	
	GNI per capita	USD/person	
	Urban poverty	%	
	Rural poverty	%	
	Inequality (Gini Index)	Dimensionless (0-100)	
	Human Development Index	Dimensionless (0-1)	UN Data (2014)
Energy	Total primary energy consumption	ktoe	Energy Information Administration (2014)
	Total net electricity consumption	Billion kWh	
	Total petroleum consumption	ktoe	
	Dry natural gas consumption	ktoe	
	Total coal consumption	kt	
	Electricity access	%	World Bank (2014)
Materials	Direct material consumption	kt	SERI & WU (2014)
	Biomass (used extraction)	kt	
	Industrial and construction minerals (used extraction)	kt	
	Ores (used extraction)	kt	
	Imports	USD	World Bank (2014)
	Exports	USD	
	Water consumption (Freshwater withdrawals)	Billion cubic meters	
Wastes	Total CO_2 emission from consumption of energy	Million metric tons CO_2	World Bank (2014)
	Total methane emissions	Million metric tons CO_2	

3.4.4. Data scope, strengths and weaknesses

The first round of data sourcing yielded barely any resource data at the city level. The two key weaknesses of the city-level data were inconsistencies between data sources in each variable and differing dates of data collection. Often, any distinction between urban agglomerations and cities was not made apparent in the data, suggesting that some city populations or areas may have been misrepresented. However, these were not large problems as the typology was already acknowledged to be an estimate of relative magnitudes of resource consumption. Complete data for population, population density and climate existed for 120 cities, with affluence remaining the final predictor variable to acquire. Income would prove to be estimable using national data.

The national data were much more robust, with each variable having relatively complete data from a single source, a single year, and with consistent units. The two desired variables of average urban income and urban primacy were estimated from these data. Used extraction, though only partially accounting for consumption, was used as a proxy for consumption for biomass, construction minerals, industrial minerals and ores. However, due to only partial data on industrial minerals and ores, and commentary as to their lack of importance in shaping the global typology (Fernández *et al.*, 2013), these indicators were excluded from the typology, leaving only 8 resource indicators, namely consumption of biomass, fossil fuels, total energy, electricity, construction materials, total materials and water, and emissions of carbon. Industrial minerals and ores were included in the scaling efforts out of interest.

3.5. Data estimation – objective 3

3.5.1. Urban primacy and city size distributions

In order to discover if a relationship between urban primacy (Chapter 2, Section 2.5.3) and resource consumption exists, an indicator of urban primacy was created. UN-Habitat builds their primacy indicator by dividing the population of the largest city by the population of the second largest (UN Habitat, 2010). This was a good starting point, yet it overlooks countries with two or three apex cities, as well as the percentage of the country's population inhabiting these prime centers. To form a more revealing indicator, urban primacy was calculated as the population of the largest city divided by the average population of the 2nd and 3rd largest cities, and multiplied by the per cent of the urban population residing in the largest city. In order to visualise city-size distributions in each nation, rank-size distributions were completed for each nation, as described in Chapter 2, Section 2.8.

3.5.2. Urban income and economic production

A key aspect of predicting urban resource consumption is the affluence of the population, understood by the average urban income. Two processes were followed to determine the urban income:

1. Income was estimated by comparing the relative poverty in urban and rural spaces. This method used World Bank data of national population, urban and rural population

proportions, GNI and proportions of both urban poverty and rural poverty. Using the World Bank prescribed poverty line of $1.25 per day (World Bank, 2014), it was stated that each person 'in poverty' made $1.25 per day, or $456.25 per year. This offered a concrete number for total income of the urban and rural poor. Subtracting this amount from nations' produced a *total affluent income* which could be split by affluent populations in urban and rural spaces. Finally, the *urban affluent income* and *urban poor income* were summed to provide national urban income. This method does not account for any difference in the amount earned by affluent members of rural and urban populations. The key steps are outlined as follows:

$$AIUP = UP * \ UPV * USD456.25 \tag{2}$$

$$AIRP = RP * RPV * USD456.25 \tag{3}$$

$$AIUA = \%UP * \big(GNI - (AIUP + AIRP)\big) \tag{4}$$

$$AUI = \frac{AIUP+AIUA}{UP} \tag{5}$$

where AIUP is the annual income of the urban poor, AIRP is the annual income of the rural poor, AIUA is the annual income of the urban affluent, and AUI is the average urban income. UP is the urban population, %UP is the urban population as a proportion of nation population, RP is the rural population, UPV is the percentage of urban population living in poverty, RPV is the percentage of rural poverty.

2. Income was estimated by calculating the proportion of income from non-extractive industry in the nation. This was adapted from a methodology developed in 1980 by the Office of Housing in the US Agency of International Development (1980). They suggest that urban income may be determined from the proportion of non-agricultural domestic production. As many African nations' economies include a large proportion of mineral extraction, this activity was important to include. For their urban income estimation method, the Indian Ministry of Statistics and Programme Implementation (MOSPI, 2007) suggests that above ground mining predominantly takes place in urban areas, while underground mining takes place away from large settlements. For this method, unclear as to the different forms of mining in many countries, mining activities were stated to be rural. MOSPI further suggests that the oil industry is a predominantly urban one. With a stated assertion that all non-extractive economic production takes place in the city, the per cent of GDP derived from urban activities is stated as the total GDP minus the proportion of GDP from agriculture and mining

activities, excluding those related to oil refining. This assertion produces the following equations:

$$Average\ urban\ income = \frac{GNI * UA}{UP} \tag{6}$$

$$Average\ urban\ GDP = \frac{National\ GDP * UA}{UP} \tag{7}$$

where UA is the proportion of GDP derived from urban activities and UP is the urban population of a nation.

In order to ensure different per capita values for urban GDP and income in each city of the same nation, as has been observed in multiple cities (Bettencourt *et al.*, 2007), both the urban GDP and urban income were distributed using the city scaling method steps ii and iii described in Section 3.5.3, below. Urban GDP and urban income used scaling exponents of 1.15 and 1.12 respectively, which were observed by Bettencourt et al. (2007). Based on results, the second method for estimating urban GDP and income was used in further analyses.

Determining the urban and rural GDPs enabled quantification of the economic productivity of both urban and rural populations. This was calculated as follows:

$$Urban\ Productivity = \frac{Urban\ GDP}{UP}, \tag{8}$$

$$Rural\ Productivity = \frac{Rural\ GDP}{RP}, \tag{9}$$

Dividing urban productivity by rural productivity showed how much more, or less, productive urban spaces are than rural spaces.

3.5.3. City scaling

The following procedure was used for each resource indicator to determine their value at city level:

i. The first step was to establish the average urban consumption for the indicator. Consumption of total energy, fossil fuels, electricity, total materials, and construction materials, as well as carbon emissions showed positive linear relationships to GDP, so the proportion of urban consumption was determined similarly to urban income and urban GDP:

$$UR = \frac{NR * \mathrm{UA}}{UP}, \tag{10}$$

where UR is the average urban resource consumption or emission, NR is the national resource consumption or emission, UA is the per cent of GDP derived from urban activities and UP is the urban population.

For fossil fuels, coal was excluded from urban consumption, as it would primarily be used for thermal electricity generation away from cities. Industrial minerals and ores were stated to be wholly consumed in cities, so the urban average was determined as the total national consumption of industrial minerals and ores divided by urban population. For biomass and water consumption, which showed no clear relationship to GDP or other indicators, the national average was utilised as the urban average.

ii. Distributing this average between the cities of each nation utilised the Bettencourt et al. (2007) equation. A scaling exponent (β) was assigned for each resource based on whether they were superlinear or sublinear. Using the population of the largest city in each nation, the normalisation constant (Y_0) for each nation was determined with this equation:

$$Y_0 = \frac{UR * CPi}{\mathrm{CP}i^{\beta}} * \beta \,, \tag{11}$$

where CP is the largest city's population. The additional multiplication by the scaling exponent, though not part of Equation (1), was used to increase or decrease the Y_0 by a factor, as the consumption in the largest city would tend to be higher or lower than the urban average. Without this extra multiplication, the total resource consumption would not be fully distributed to cities, and the total urban consumption would come up short. This is an imperfect way to solve the problem, but it returns more complete values for total urban consumption. Without it, total consumption is not accounted for by resulting city-level resource indicators. A more apt equation could be formulated by use of an integral. However, further analysis for this study had been completed before this was determined, so the more accurate equation will be part of future work.

iii. Deriving the value for resource consumption for each city then becomes a matter of returning to the original equation:

$$CRj = Y_0 * \mathrm{CP}j^{\beta} \,, \tag{12}$$

where CPj is the city population and CRj is the city resource indicator.

The values utilised for each step of the scaling method are shown in Table 3-3. Step i determines the initial urban average of the indicator and steps ii and iii distribute this to cities based on their population and scaling exponent associated with the resource.
The energy variables scale superlinearly, so the scaling exponent of 1.07 was utilised. It is stated that industrial minerals and ores, and construction materials would scale sublinearly, due to the benefits of economic scale and increased opportunities for material or industrial efficiency found in larger cities. These materials each used an exponent of 0.9. Total Materials used an exponent of 1.05, determined as the weighted average of the exponents of its components: Fossil Fuels, Biomass, Construction Materials and Industrial Minerals and Ores.

Biomass and water seem to be universal requirements across urban and rural borders, so they scale linearly with population. However, to allow some distinction between cities of the same nation, they were scaled slightly superlinearly. With the derived city resource consumption data, it was possible to form resource consumption profiles for use in clustering the African cities.

Table 3-3: Assigned values for scaling to city level, by resource type

Resource	**Step i**	**Step ii & Step iii**	
	Initial resource value	Type of power relationship	β
Total Energy Consumption (TE)	$\frac{NR * \mathrm{UA}}{UP}$	Superlinear	1.07
Electricity Consumption (EL)	$\frac{NR * \mathrm{UA}}{UP}$	Superlinear	1.07
Fossil Fuel Consumption (FF)	$\frac{NR * \mathrm{UA}}{UP}$	Superlinear	1.07
Carbon Dioxide Emissions (CO2)	$\frac{NR * \mathrm{UA}}{UP}$	Superlinear	1.07
Total Material Consumption (TM)	$\frac{NR * \mathrm{UA}}{UP}$	Superlinear	1.05
Construction Material Consumption (Con)	$\frac{NR * \mathrm{UA}}{UP}$	Sublinear	.9
Industrial Mineral Consumption (Ind)	$\frac{NR}{UP}$	Sublinear	.9

Biomass Consumption (Bio)	National Average	Linear to Superlinear	1.02
Water Consumption (H2O)	National Average	Linear to Superlinear	1.01

3.6. Categorising cities – objective 4

3.6.1. Clustering techniques

This section describes the two main clustering techniques utilised in this study, namely classification trees and hierarchical clustering.

3.6.1.1. Classification trees

Classification trees are intuitive tools for sorting data into discrete categories based on a set of predictor variables (Breiman, 1984). This is done by splitting data in a binary manner which provides the clearest delineation of a specific category. This is repeated for each resulting group until a stopping criterion, such as a minimum size desired for the category, is reached. Each split has a clear decision rule which determines the path for each element to follow. The resulting tree would tend to be too large, over-fitting the data, and is pruned back using cross validation. Classification trees are flexible, graphical, easily upgradable, and allow for the inclusion of both continuous and categorical variables. Additionally, they are open tools, with each classification step visible. Classification trees allow for data to be plugged in as it changes, or for new data, not included in the study to be examined if desired.

Making classification trees requires a *training* dataset, which has a full complement of independent and dependent variables, with which to build the decision rules. The rpart function in R was used to build trees for each resource, and the prune.tree function was used to trim them. However, raw data were too limited to form robust trees. This study used estimated city-level data as the training dataset to build classification trees. This also helped to identify the most important independent variables which predicted resource consumption, as described in the research design (Section 3.2). Selected cities were sorted into high, medium and low consumption for each of the eight resource indicators using the resulting classification trees.

3.6.1.2. Hierarchical clustering

Hierarchical clustering presented itself as a simple choice for clustering technique. Agglomerative hierarchical clustering measures the relative ‘distance’ between elements to be clustered, based on chosen variables. It builds a dendrogram starting with the two closest elements and adding the next closest until all elements are accounted for. The resulting tree is then cut into the appropriate number of clusters. K-means clustering lends itself as a potential alternative form of clustering, particularly as it us useful for visual analysis and demonstration of the distribution of elements by chosen variables. However, this technique requires stating the number of desired groups before clustering, something that is somewhat unclear in this analysis. In addition elements may belong to multiple clusters. While this may be true, it is not helpful to forming a distinct typology.

Hierarchical clustering of nations and cities was completed in R using the ward.D method of hclust and euclidian method of dist. Options for the number of unique clusters were determined using a scree test, which provides a qualitative visualisation of how many groups may be optimum. The final number of groups was chosen qualitatively based on how closely the cities fit when the groups were analysed. The data were normalised for comparison using median normalisation: similar to log normalisation, except retaining a 0-100 index. Normalisation of this manner is important so that the clustering determines how different each individual is from each other, and not from the highest value. Zero was used for any missing data points.

Redundant variables were removed from the datasets to be clustered. This is important so as not to skew the clusters in favor of certain variables. For example the national proportion of urban population is simply the inverse of the proportion of rural population, so only one was included. This process produced multiple stages of clustering, and was calibrated based on scrutiny of each result. Informed speculation played a key role in validating the results as no previous studies existed with which to compare, and it was important to frequently ask the question: ‘does this make sense?’ Theories to explain certain clusters were recorded, however, it became apparent that local experience of a city is required. Thus the typology can serve as a discussion point for future work in validating scaled data and city clusters.

3.6.2. National clusters

Two forms of national clustering were undertaken, first using only socioeconomic variables, and secondly using only resource variables. Initially, these clusters were meant to enable the use of scaling exponents more specific to each cluster. However the lack of even minimal city data within each group ruled this method out. The national clusters remain of interest for what they might suggest about how cities will cluster. Classification trees were used to determine the relative importance of the predictor variables in determining resource consumption.

3.6.3. City clusters

The sample of 120 cities were clustered in four ways:

- hierarchical clustering of the predictor variables of population, income, affluence and two climate indicators of heating degree days and cooling degree days.
- hierarchical clustering of scaled data for carbon emissions and consumption of fossil fuels, electricity, biomass, water and construction materials. The data were normalised to per capita measures and normalised using median normalisation.
- hierarchical clustering of scaled data for carbon emissions and consumption of fossil fuels, electricity, biomass, water and construction materials. The data were normalised to per unit GDP measures and normalised using median normalisation.
- scaled resource data for the largest city of each country were organised into resource consumption classes as delineated in Table 3-4. The resource indicators used were carbon emissions and consumption of total energy, fossil fuels, electricity, total materials, construction materials, and water. The 54 cities were used to build a training classification tree for each resource indicator. Due to the sample size being low and the variation among individuals, it was desired that the classification trees be as accurate as possible. Therefore, the classification trees had a stopping criterion which required that non-homogenous groups of 4, at minimum, be split. The resource classes for the remaining 66 cities were determined using these trees. The cities were then hierarchically clustered by similarity of resource profile. As this was a qualitative method, industrial minerals and ores could have been included, with missing data noted as low consumption. However, so as to allow for comparison with other typologies, industrial minerals and ores were excluded.

All typologies were compared, with discussion as to their relative value in the results section (Chapter 4) of the study.

Table 3-4: Delineations of per capita resource classes

Per capita resource indicator	Low	Medium-Low	Medium	Medium-High	High	Units
TE	0-100	101-500	501-1000	1001-2000	Greater than 2000	kgoe/person
FF	0-100	101-500	501-1000	1001-2000	Greater than 2000	kgoe/person
EL	0-25	25-50	50-100	100-300	Greater than 300	kgoe/person
CO2	0-250	250-750	750-2500	2500-5000	Greater than 5000	kg CO_2/person
TM	0-1250	1250-2500	2500-5000	5000-10000	Greater than 10000	kg/person
Bio	0-1250	1250-2500	2500-5000	5000-10000	Greater than 10000	kg/person
Con	0-1250	1250-2500	2500-5000	5000-10000	Greater than 10000	kg/person
Ind	0-1250	1250-2500	2500-5000	5000-10000	Greater than 10000	kg/person
H2O	0-50	50-100	100-250	250-500	Greater than 500	m^3/person

3.7. Determining variable importance – objective 5

Throughout the analysis of the developed typologies, connections were drawn between levels of resource consumption and various socioeconomic or geographical indicators. This was limited to population, population density, climate indicators, income and, to some degree, population growth.

To enrich the qualitative assessment, a more systematic approach was used, guided by the classification tree building process. As classification trees are built, independent variables are utilised to differing degrees to sort dependent variables. For the case of resources, each indicator is ranked by its importance in developing each resource tree. Comparing this information allows the determination of which indicators are most useful in predicting levels of resource consumption.

The robustness of each group is also dependent on specific resource indicators, as shown in Fernandez (2013). Removing one resource indicator at a time from the typology demonstrated the importance of each resource in shaping the final clusters. This is quantified by the number of cities moving from their final groupings.

3.8. Summary

This chapter described the research design and multiple pathway options for estimating city data and clustering cities in this study. Pathway 2 was chosen to estimate city-level data using literature-guided scaling relationships. Pathway A and C were chosen to cluster cities, as quantitative and qualitative methods respectively. The chapter presented the equations used to determine an indicator of urban primacy and to estimate urban GDP and income. It presented a three-step method for scaling national data to city level. Finally it explained the chosen ways to cluster cities and nations.

Chapter 4 presents a discussion of the results.

Chapter 4: Results

This chapter presents a progression of results organised into four sections: the first offers a visualisation of the most resource intense cities in the Africa. The second examines what the national data showed and how it was scaled to city level, the third analyses how the nations and cities were clustered and the fourth offers insights into the importance of various variables in predicting resource consumption. As this study used an exploratory method, the analysis of these results was two-fold; firstly, the robustness of the scaling and clustering methods was examined, and secondly, insights were drawn from the resultant clusters.

4.1. The most resource intense African cities

In examining the resource consequences of rapid African urbanisation, this study provides a baseline for resource consumption intensity for 120 cities as of 2011, listed in Appendix 6.1. Figure 4-1 compares 20 cities for each the largest total annual consumption and the largest per capita annual consumption. This visualisation, and the process of creating it, has shown the following five insights:

i. The two maps show the distinction between aggregate resource intensity and per capita resource intensity. All of the largest cities in Africa are shown in Figure 4.1a, as they have the largest populations and, as expected, the largest aggregate resource intensity. Many of them do not show up as high per capita consumers in Figure 4.1b due to their large population. For instance, Lagos, is the 8th largest resource consumption on the continent, while Cairo, the largest aggregate resource consumer, is the 10th largest per capita consumer of materials. In fact, high per capita consumption seems to be found in cities of the northern and southern regions, which tend to have the greater per capita GDPs and the highest HDI ratings. This distinction highlights the differing priorities of resource efficiency and resource access. Those cities appearing in both maps may benefit from efficiency strategies to ensure maximal output from their resources. However, those missing from the per capita consumption map would find their priorities in improving resource access and their resource intensity is expected to grow as they develop more industry.

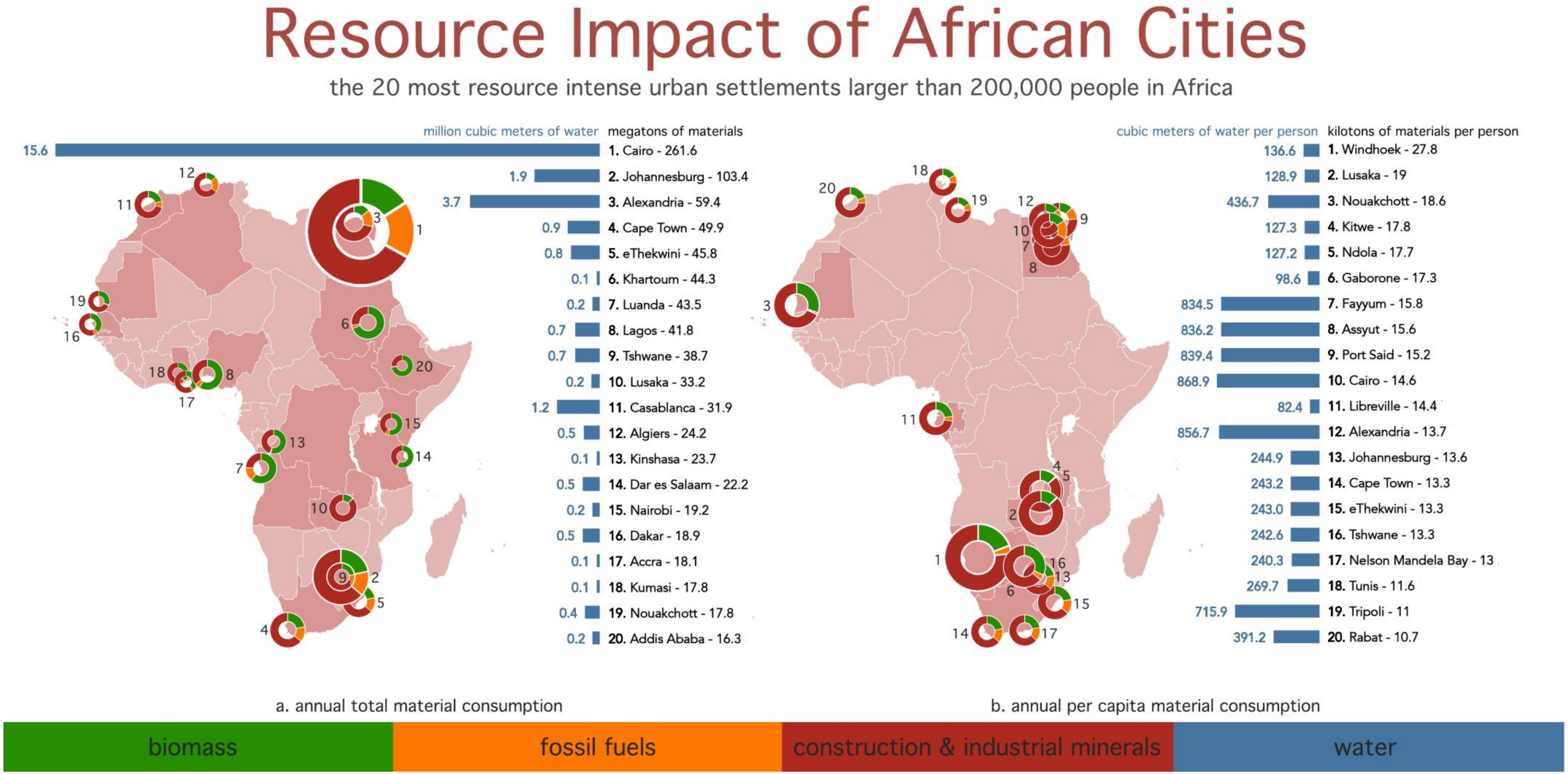


Figure 4-1: Resource impact of African cities

i. Many of the cities noted to be the fastest growing cities in Figure 2-7, located in eastern and western regions, are conspicuously absent from these maps. This is where greater resource intensity is expected to occur in the future. At the moment, those with highest per capita consumption, have the slowest population growth rates.

ii. The resource profiles, demonstrated as a distinction between biomass, fossil fuels, and construction and industrial minerals, show the city's overall position in the global socio-metabolic transition. For example, Johannesburg and Casablanca show large proportions of construction and industrial materials, suggesting a large industry presence, potentially around extraction or manufacturing. They also show a reduced consumption of biomass, and a larger use of fossil fuels, as expected in the sociometabolic transition. Cities like Khartoum, Dar es Salaam, Luanda and Kinshasa demonstrate majority biomass consumption for their resource profiles, suggesting that they are still in the agrarian regime. Dakar and Accra seem to be shifting towards more construction and industrial materials, and increased fossil fuels. However, it is unclear whether all these cities are subject to conventional expectations of industrialisation, as discussed in Chapter 2, Section 2.6.2. Instead, pockets of industry may be more prevalent than a holistic shift.

iii. Water is included in Figure 4.1 as a demonstration that there are no clear trends surrounding it. An interesting distinction between the aggregate water consumption is observed in which Cairo, for example, shows almost 5 times greater water consumption than the next largest water consumer. Khartoum has incredibly low water consumption. This remains a curiosity through the remainder of this study as there is no defined trend between climate and water or GDP and water. One might expect to find large quantities of water consumed in predominantly agricultural spaces, but this was not explored in this study. Speculation as to this matter included suggestions that more water is consumed in hotter or dryer areas, or that it is tracked more carefully in water-scarce areas, where there are fewer extraction opportunities, as compared to water abundant areas, where it is harder to track extraction.

iv. Delimiting the chosen sample to cities with populations over 200,000 excluded some of the largest per capita consumers. Malabo, Victoria, Port Louis, Manzini and Walvis bay show very high per capita consumption and are included in later analysis. The high per capita consumption levels are potentially due to various reasons, namely: (i) the greater ease at providing resources to a smaller population; (ii) fewer benefits offered by economies of scale; (ii) smaller populations; (iv) distinct functions of island nations which may rely more on imported resources. The cities below 200,000 population were excluded from Figure 4.1 as their processes are likely different from larger cities.

4.2. Exploring the national data – objective 1, 2 & 3

This section defines the samples of nations that are used for analysis. It shows the process of developing an urban primacy indicator and estimating both urban income and urban GDP data. It draws connections between urbanisation, GDP and resource consumption at the national level to inform the process of scaling data from national- to city-level.

4.2.1. Sample of nations

Table 4-1 shows the final sample of nations selected for examination. It attaches the acronym associated with the country for later use in differentiating cities. The most urbanised region is Southern Africa, followed by Northern, Western, and Middle. The least urbanised region is Eastern Africa.

Table 4-1: Final Sample of African Nations, sorted by geographical region

Northern Africa	Western Africa	Eastern Africa	Middle Africa	Southern Africa
Total Population: 213 million	Total Population: 314 million	Total Population: 341 million	Total Population: 128 million	Total Population: 59 million
Urban Population: 106 million	Urban Population: 141 million	Urban Population: 80 million	Urban Population: 54 million	Urban Population: 35 million
Urban Proportion: 50 per cent	Urban Proportion: 45 per cent	Urban Proportion: 24 per cent	Urban Proportion: 42 per cent	Urban Proportion: 59 per cent
Algeria - AL Egypt - EG Libya - LY Morocco - MC South Sudan - SS Sudan - SU Tunisia - TU	Benin - BE Burkina Faso - BF Cape Verde - CV Cote D'Ivoire - CDI Gambia - GAM Ghana - GH Guinea - GU Guinea-Bissau - GB Liberia - LI Mali - MALI Mauritania - MN Niger - NI Nigeria - NG Senegal - SE Sierra Leone - SL Togo - TO	Burundi - BU Comoros - CO Djibouti - DJ Eritrea - ER Ethiopia - ETH Kenya - KE Madagascar - MAD Malawi - MAL Mauritius - MS Mozambique - MZ Rwanda - RW Seychelles - SY Somalia - SO Tanzania - TZ Uganda - UG Zambia - ZA Zimbabwe - ZI	Angola - AN Cameroon - CA Central African Republic - CAR Chad - CH Congo (Dem Rep) - DRC Congo (Rep) - RC Equatorial Guinea - EQG Gabon - GAB	Botswana - BO Lesotho - LE Namibia - NA South Africa - SA Swaziland - SW

4.2.2. Urban primacy and city-size distributions

Urban primacy poses a curious obstacle in African development, as it represents much of the legacy of centralised colonial rule or post-independence authoritarianism. In order to promote resilient, context-appropriate urban development, decentralisation of urban governance may be the most useful step. It has also been noted that the decentralisation, or privatisation, of resource provision services enables megacities not only to function, but to flourish (Chapter 2, Section 2.4.2). Decentralisation can relate to formal, regulated organisations in competition or show up as reactive informal businesses, which seek to fill the gap between demand and supply of resources. Informal service provision is typically to the benefit of citizens or industry, but may exacerbate environmental, economic or community health issues. The indicator of urban primacy, is useful in (i) understanding the national distribution of urban population, (ii) understanding the likely distribution of service delivery priorities, and (iii) identifying cities' degree of variance from average scaling relationships.

The indicator developed in this study, shown in Table 4-2, demonstrates the importance of the largest city in the country, in relation to other cities, but also in relation to the distribution of the nation's urban population. The UN method is included for comparison. The nations are also sorted into classes based on the likely distribution of urban population:

- Class A includes 14 nations with over 30 per cent of the urban population in the largest city, with no other cities over 100,000 people. These are countries with small areas or limited productive land. Attempting to shift some functions from the prime city would be difficult as there are few other cities of competitive size.
- Class B includes nations with dual apex cities and few other cities over 100,000. Malawi is the only member of this group, despite Ghana and Cameroon also having dual apex cities. Lilongwe and Blantyre make up 75 per cent of the urban population, so urban governance priorities revolve around these key spaces with lessons for other growing cities coming from here.
- Class C includes nine nations with over 30 per cent of the urban population in the largest city, and only a few secondary cities over 100,000. Shifting some responsibilities to other cities may help with their development, though many will follow innovations from the prime city.

- Class D includes 14 nations with over 30 per cent of the urban population in the largest city, yet with multiple cities over 100,000. This offers a great opportunity to diversify functions between cities and having unique development plans to encourage their growth, potentially with ways for cities to rely on each other's economic strengths.
- Class E includes nations with less than 30 per cent of the urban population in the largest city, and few other cities over 100,000 people. Botswana is the only member of this group. Here, the urban population is distributed into many small settlements, so general plans in the form of settlement type may be more beneficial than city specific plans.
- Class F includes 14 nations with less than 30 per cent of the urban population in the largest city, and multiple cities over 100,000. These countries already have multiple urban nodes which will benefit from separate development plans for each city to ensure context aware development strategies.

Table 4-2: Urban Primacy and its determinants, from most prime at top, to least prime at bottom

COUNTRY	Largest city as a percentage of urban population	Largest city	# of cities over 100,000	UN method	Urban primacy	Median normalised	Class
Liberia	51.4	1,010,970	1	24.6	13.80	100.0	a
Djibouti	54.2	353,801	1	15.6	9.14	83.1	a
Mauritania	55.1	846,871	2	11.7	7.70	77.9	c
Guinea-Bissau	45.5	203,000	1	11.3	6.71	74.3	a
Burundi	47.7	497,166	1	11.9	5.79	71.0	a
Mali	38.3	1,930,000	9	12.5	5.28	69.2	d
Eritrea	57.2	435,383	1	7.8	4.99	68.1	a
Rwanda	53.3	1,135,428	3	7.6	4.82	67.5	c
Guinea	41.7	1,650,000	3	6.9	3.95	64.3	c
Sao Tome & Principe	45.1	51,728	0	7.8	3.63	63.1	a
Senegal	51.6	2,930,000	9	4.7	3.37	62.2	d
Seychelles	56.4	26,450	0	5.6	3.17	61.5	a
Uganda	30.3	1,659,600	5	9.2	3.01	60.9	d
Togo	34.0	837,437	1	8.8	3.00	60.9	a
Chad	36.1	951,418	3	6.9	2.93	60.6	c
Cote d`Ivoire	47.9	4,765,000	>10	5.4	2.74	59.9	d
Madagascar	30.2	2,128,900	8	8.2	2.64	59.6	d
Angola	44.2	5,278,800	7	4.3	2.56	59.3	d
Tanzania	35.2	4,364,541	>10	6.2	2.54	59.2	d
Egypt	51.8	17,921,542	>10	4.1	2.52	59.1	d
Gabon	40.1	550,000	2	5.3	2.40	58.7	c
Niger	44.2	1,302,910	5	4.7	2.39	58.7	d
Gambia	38.5	382,096	2	4.0	2.33	58.4	c
Ethiopia	20.4	3,103,700	>10	10.8	2.28	58.3	f
Central African Republic	35.9	622,771	2	5.0	2.22	58.1	c
Dem. Rep. of Congo	38.4	8,415,000	>10	5.6	2.21	58.0	d
Republic of Congo	58.0	1,560,000	2	1.9	2.02	57.3	c
Namibia	38.3	325,858	1	5.1	1.99	49.5	a
Sierra Leone	41.1	945,423	4	4.1	1.82	45.3	c
Burkina Faso	34.8	1,475,223	2	3.0	1.78	44.3	c
Kenya	31.1	3,133,518	>10	3.4	1.62	40.4	d
Somalia	41.5	1,554,000	>7	2.3	1.39	34.6	d

Cape Verde	43.6	133,863	1	1.9	1.33	**33.2**	**a**
Sudan	38.3	4,632,000	>10	2.5	1.24	**30.9**	**d**
Zambia	32.7	1,747,152	9	3.5	1.20	**29.9**	**d**
South Sudan	26.7	500,000	5	4.2	1.15	**28.6**	**f**
Lesotho	31.9	178,345	1	2.9	1.04	**25.8**	**a**
Swaziland	38.3	98,874	0	1.3	0.89	**22.1**	**a**
Comoros	30.5	60,000	0	2.9	0.88	**21.9**	**a**
Zimbabwe	28.8	1,485,231	7	2.3	0.85	**21.1**	**f**
Malawi	40.3	978,800	5	1.2	0.75	**18.6**	**b**
Benin	19.6	862,445	5	3.0	0.70	**17.4**	**f**
Equatorial Guinea	35.3	100,000	1	1.7	0.59	**14.7**	**a**
Libya	23.4	1,110,000	>10	1.9	0.57	**14.3**	**f**
South Africa	23.8	7,613,297	>10	2.0	0.50	**12.6**	**f**
Botswana	18.6	227,333	2	2.3	0.50	**12.6**	**e**
Nigeria	13.8	11,223,000	>10	3.3	0.49	**12.2**	**f**
Morocco	16.9	3,083,000	>10	2.4	0.41	**10.3**	**f**
Algeria	10.4	2,851,000	>10	3.7	0.39	**9.8**	**f**
Cameroon	21.3	2,350,000	>10	1.0	0.39	**9.6**	**f**
Tunisia	10.3	728,453	7	2.7	0.34	**8.5**	**f**
Mauritius	25.6	137,608	3	1.3	0.34	**8.4**	**f**
Ghana	16.1	2,070,463	>10	1.0	0.28	**6.9**	**f**
Mozambique	16.0	1,225,900	>10	1.4	0.26	**6.5**	**f**

The degree to which urban primacy, notable for being more pronounced in nations under authoritarian rule, may affect economic production is worth exploring. However, using GDP and HDI as indicators of development, no direct relationships are found. As an indicator of decentralised governance, primacy may be more indicative of resource access, via the quality of service delivery, than of overall resource consumption.

Urban primacy is well visualised in the city-size distributions shown in Figure 4-2. The Figure shows the rank-size relationship of cities in a number of African countries. The slope of the distribution is expected to be close to -1. Typically, the upper parts of the distribution show this slope, while the lower part, formed of larger cities, tends to deviate. Variance is expected as part of Zipf's law and is primarily due to the deviation of larger and prime cities from this linear pattern. Nigeria is an interesting exception, as, despite the large size of Lagos, Nigeria's urban population seems well distributed through other cities. This shows concord with a low urban primacy rating. This does not hold true for Kinshasa, Cairo and Nairobi, which remain quite prime cities in their respective countries. Angola's overall slope may indicate a poor accuracy of available population data which has not been updated recently. In addition, Rosen and Resnick (1980) explain that city-proper data, more readily available than agglomeration data, yields higher Zipf's exponents that skew the relationships. As such, more correct relationships are visible when using data for urban agglomerations, the commonly applied criterion for comparing urban economies.

The rank-size relationships are potentially predictive of the accuracy of the outcomes of step ii and step iii in scaling resource data for cities, as discussed in Chapter 3, Section 3.5.3. Any deviations of larger cities from the average relationship between population and the city attribute were ignored when making use of Bettencourt et al's (2007) relationships to estimate data: the outcomes showed only average values. Qualitative insights from the behavior of cities in the rank-size relationship might have helped to inform more correct differences between cities, once data had been scaled. For example, the deviation from average of the five largest cities in South Africa could inform their degree of deviation from the average resource consumption that is calculated for them.

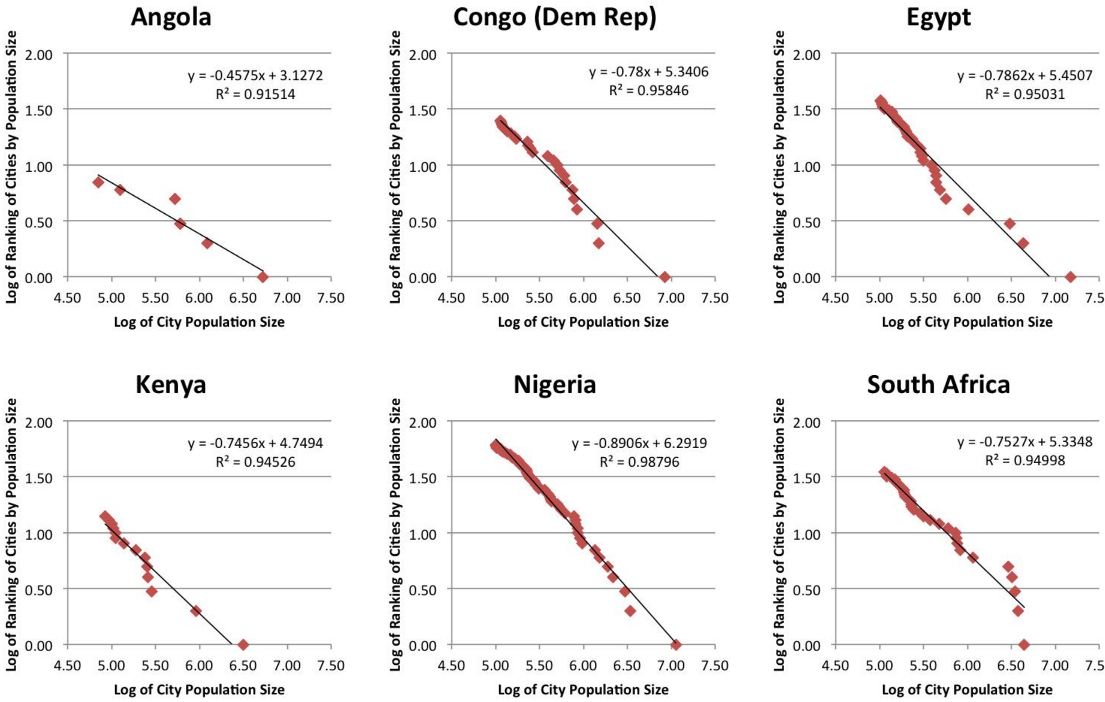


Figure 4-2: Individual Rank-Size relationships for six African nations

4.2.3. Average urban income and GDP

The utilised variables and results of both methods for determining urban income are shown in Table 4-3. For both methods, average urban income was decidedly higher than the national average. However, the method of using relative poverty was flawed. Stating a poverty threshold of $1.25 per day, or $456.25 per year, did not take into account that this amount was higher than many of the nations' average annual incomes. For example, Burundi's average annual income is $220, which suggests that on average, Burundi's population is in poverty. This is a global absolute poverty measure and overlooks specific incarnations of poverty in each country, seen through differences in lifestyle and cost of living. Identifying a lower threshold would be insightful, particularly if it were possible to utilise a unique poverty threshold in each country. However, the various manifestations of poverty make a threshold difficult to determine. In addition, this method states that affluent populations in rural and urban spaces have equivalent incomes. An inability to measure the distribution of wealth within the poor populations, and between the urban and rural affluent populations is the key flaws with this method.

Calculating average income using the proportion of GDP derived from urban economic activities proved to be a more effective method. Most nations showed higher urban incomes than the national averages. Where the urban average income is below national level, such as for Liberia and Sierra Leone, it seems that extractive industries, stated as rural activities, are the most predominant contributors to GDP. This is at odds to the nations' relatively large proportion of urban population and very high levels of urban poverty. This contradiction may speak either to a larger proportion of agriculture taking place in the cities, suggesting more peri-urban forms, or to a high proportion of poverty reducing the average urban income. The results of this method suggest that, on aggregate, African cities produce 79 per cent of Africa's total GDP. This proportion is in agreement with UN Habitat (2010) estimate of 80 per cent. However, it is likely that these figures are elevated as certain activities like trade, construction and administration surely exist to some degree in rural areas, even if the contribution to GDP is lower than from cities. The highest proportion of GDP derived from cities is in Cote d'Ivoire, at 95.5 per cent, and the least in Liberia, at 24.3 per cent.

The results of the second method were used in determining average income and average GDP at the city level. Where income data were not calculable, GDP data were used as proxy.

Table 4-3: Estimations of average urban income and their determinants

Country	% Urban Population	% Rural Population	% Urban Poverty	% Rural Poverty	% GDP from Urban Activities	Annual per capita national income (USD)	Annual per capita urban income by % Poverty (USD)	Annual per capita urban income by Urban Economic Activity (USD)	Annual per capita urban GDP by Urban Economic Activity (USD)	Urban productivity as a factor of rural productivity
Algeria	72.87	27.14	14.83	44.91	90.2	4,460	**4,884**	**5,521**	**6,697**	**343**
Angola	59.14	40.86	18.70	58.30	88.8	4,070	**4,968**	**6,111**	**8,581**	**548**
Benin	44.91	55.09	31.40	39.70	63.9	720	**739**	**1,024**	**1,098**	**217**
Botswana	61.61	38.39	19.40	44.80	75.2	6,940	**7,832**	**8,470**	**8,862**	**189**
Burkina Faso	26.51	73.49	25.20	52.80	52.6	620	**681**	**1,230**	**1,368**	**308**
Burundi	10.93	89.07	34.00	68.90	60.0	220	**10**	**1,208**	**1,445**	**1,223**
Cameroon	52.09	47.92	12.20	55.00	77.4	1,150	**1,361**	**1,709**	**1,780**	**315**
Cape Verde	62.58	37.42	13.20	44.30	90.4	3,570	**4,052**	**5,157**	**5,286**	**563**
Central African Republic	39.10	60.90	49.60	69.40	45.0	490	**501**	**564**	**563**	**127**
Chad	21.83	78.17	20.90	52.50	80.2	900	**1,102**	**3,307**	**3,921**	**1,450**
Comoros	28.07	71.93	34.50	48.70	64.1	830	**899**	**1,895**	**1,944**	**458**
Congo (Republic)	63.65	36.35	25.70	83.00	74.8	2,200	**2,879**	**3,301**	**938**	**569**
Cote d`Ivoire	51.28	48.72	29.40	54.20	95.5	1,140	**1,281**	**1,471**	**4,857**	**1,212**
Dem. Republic of Congo	34.28	65.72	61.50	75.70	66.2	330	**290**	**720**	**1,644**	**186**
Djibouti	77.08	22.92	25.79	96.50	95.9	999	**1,151**	**1,243**	**1,990**	**696**
Egypt	43.54	56.46	15.30	32.30	85.1	2,720	**3,009**	**5,316**	**6,457**	**741**
Equatorial Guinea	39.51	60.49	31.50	79.90	89.3	13,440	**23,131**	**30,375**	**52,042**	**1,278**
Eritrea	21.36	78.64	62.00	70.19	83.1	390	**376**	**1,517**	**2,027**	**1,810**
Ethiopia	17.02	82.98	25.70	30.40	52.9	390	**386**	**1,212**	**1,478**	**548**
Gabon	86.15	13.85	29.80	44.60	94.2	8,850	**9,103**	**9,677**	**12,253**	**261**
Gambia	57.21	42.79	32.70	73.90	72.0	510	**529**	**642**	**659**	**192**
Ghana	51.87	48.13	10.80	39.20	76.9	1,420	**1,594**	**2,105**	**2,415**	**309**
Guinea	35.46	64.54	35.40	64.70	57.2	410	**391**	**661**	**814**	**243**
Guinea-Bissau	43.90	56.10	51.00	75.60	50.9	570	**615**	**661**	**588**	**132**
Kenya	23.98	76.02	33.70	49.10	69.3	820	**898**	**2,369**	**2,798**	**715**
Lesotho	27.57	72.43	41.50	60.50	84.3	1,230	**1,468**	**3,760**	**3,578**	**1,410**
Liberia	48.18	51.82	55.10	67.70	24.3	330	**309**	**166**	**214**	**35**
Libya	77.74	22.27			33.6	10,156	**Missing Data**	**Missing Data**	**5,801**	**14**
Madagascar	32.57	67.43	51.10	81.50	73.3	420	**394**	**945**	**1,026**	**568**

Malawi	15.70	84.30	17.30	56.60	64.0	340	**262**	**1,386**	**1,101**	**955**
Mali	34.93	65.07	18.90	50.60	50.0	670	**743**	**959**	**1,037**	**186**
Mauritania	41.51	58.49	20.80	59.40	56.1	970	**1,175**	**1,311**	**1,445**	**180**
Mauritius	41.80	58.20	12.40	8.00	96.3	8,100	**7,883**	**18,662**	**21,058**	**3,624**
Morocco	57.04	42.96	4.80	14.40	80.3	2,940	**3,052**	**4,139**	**4,215**	**307**
Mozambique	31.22	68.78	49.60	56.90	65.0	450	**449**	**937**	**1,211**	**409**
Namibia	38.39	61.61	14.60	37.40	78.1	4,980	**5,871**	**10,131**	**11,992**	**572**
Niger	17.87	82.13	36.70	63.90	47.7	370	**323**	**988**	**1,082**	**419**
Nigeria	49.62	50.38	34.10	52.80	77.9	1,710	**1,919**	**2,685**	**2,526**	**358**
Rwanda	19.12	80.88	22.10	48.70	62.1	550	**586**	**1,786**	**2,070**	**693**
Sao Tome & Principe	62.65	37.35	63.80	59.40	76.8	1,240	**1,206**	**1,520**	**1,760**	**197**
Senegal	42.56	57.44	33.10	57.10	81.1	1,030	**1,179**	**1,963**	**2,009**	**579**
Seychelles	53.62	46.38			97.7	11,080	**Missing Data**	**20,187**	**23,524**	**3,674**
Sierra Leone	39.26	60.74	31.20	66.10	35.7	500	**519**	**455**	**587**	**86**
Somalia	37.76	62.24	26.53	53.00	No Data	107	**6**	**Missing Data**	**245**	**Missing Data**
South Africa	61.99	38.01	52.90	60.80	87.9	6,850	**7,285**	**9,714**	**10,517**	**445**
South Sudan	18.05	81.95	24.40	55.40	No Data	1,360	**1,817**	**Missing Data**	**7,363**	**Missing Data**
Sudan	33.24	66.76	26.50	57.60	63.5	1,340	**1,688**	**2,560**	**3,306**	**349**
Swaziland	21.28	78.72	31.10	73.10	92.5	2,890	**5,135**	**12,562**	**13,849**	**4,562**
Tanzania	26.74	73.26	15.50	33.30	67.5	540	**555**	**1,363**	**1,549**	**569**
Togo	38.02	61.98	34.60	73.40	48.2	470	**478**	**596**	**767**	**152**
Tunisia	66.31	33.69	11.30	4.10	90.0	4,050	**3,954**	**5,497**	**5,776**	**457**
Uganda	15.58	84.42	9.10	27.20	75.5	460	**461**	**2,229**	**2,929**	**1,670**
Zambia	39.17	60.83	27.50	77.90	80.1	1,180	**1,710**	**2,413**	**3,089**	**625**
Zimbabwe	38.62	61.38	46.50	84.30	76.8	730	**940**	**1,452**	**1,857**	**526**

The highest per capita urban income is estimated to be from Equatorial Guinea, followed by Seychelles, Mauritius, Swaziland, Namibia and South Africa. It is notable that the highest per capita incomes are from countries with small populations. Equatorial guinea has a large oil industry and very high poverty, which is suggestive of large funds bypassing the poor and supporting an elite few, as described by Hendrick-Wong and Angelopulo's (2014) exclusive urbanisation. Swaziland has a large manufacturing-based economy with similar poverty profile to Equatorial Guinea. Mauritius and Seychelles offer tertiary economic industries and large external funds are brought into the country through banking or tourism. This may inflate the estimated average income and not reflect the cost of living experienced by locals. The incomes of Namibia and South Africa fit with a diversity of tertiary economic activities: a modest GDP spread over a small population for Namibia and a large GDP spread over large population for South Africa. These estimates suggest that urban spaces in Mauritius are 3624 times more productive than its rural spaces or 445 times more productive for South Africa.

The lowest per capita urban income is estimated for Liberia, followed by Sierra Leone, Central African Republic, Togo, Gambia, Guinea and Guinea Bissau. This is expected as they display some of the lowest average national incomes and have majority primary sector economies. Cities in these countries remain relatively unproductive spaces, showing only 35 times more productivity in Liberian cities than rural areas, or 132 times for Guinea-Bissau's urban areas. This is an interesting juxtaposition to Burundi, the nation with the lowest average national income. The urban spaces in Burundi are 1223 times more productive than its rural areas, showing how cities can truly be the machines of a nation's economy.

4.2.4. Variable relationships – energy, GDP, HDI

Mapping the national data shows simple deviations from popular conceptions of the continents' economic growth and degree of urbanisation. This section demonstrates general correlations between the presence of cities, a stronger economy, and the social benefit this affords. It then ties energy and material consumption to economic production.

Figure 4-3 shows the relationship between urbanism and economic development for African nations. Three observations may be drawn from this graph:

- It is not useful to rely on continental generalisations to understand African urbanism. The oft-cited statistic that Africa is only 40 per cent urban is somewhat insubstantial when it is observed that 25 African nations are already over 40 per cent urban, 17 are over 50 per cent 11 of which are over 60 per cent. Regionally, only the Eastern region shows average urbanisation below 40 per cent. This means that as governing entities, multiple countries are already in need of strong urban policies to make full use of the benefits of economic agglomeration, while minimising the potential agglomeration diseconomies.

- While the relationship displays variance, there is a clear positive relationship between urbanism and per capita GDP. In general, the nations with higher proportions of urban population show higher per capita GDPs. However, it also confirms that this relationship is not definite for each nation, and it is understandable how the ‘urbanisation without growth’ debate has been propagated. For example, Equatorial Guinea has the highest per capita GDP, while Somalia has the lowest, despite each being about 40 per cent urban. Driving the urbanisation debate is the query as to the pace of economic growth in relation to urban growth, which has been observed to be slower in sub-Saharan Africa than in the rest of the world.
- Visualising the Gini coefficient on this graph shows that inequality is not particularly correlated to urbanism or per capita GDP. It does provide some insight into how equally the GDP may or may not be distributed within the population, which may a have similar bearing on the equality of resource access.

Figure 4-3: GDP as a function of urbanism, with the indicator of the Gini coefficient

Figure 4-4 shows a slightly more coherent relationship between urbanism and human development index. It suggests that there are benefits to urbanising, yet at what stage these benefits become apparent is questionable. Past 50 per cent urban, there are quick increases in HDI. One can speculate that cities falling between 30 and 50 per cent urban are either experiencing agglomeration diseconomies, such as in Liberia, Guinea-Bissau or Democratic Republic of Congo, which show high instances of urban poverty, or that stronger detriments to HDI are occurring outside of urban areas. Djibouti is an interesting outlier here as it is 77 per cent urban, yet shows low HDI. This may indicate the form of government or social services available in Djibouti City.

Figure 4-4: Human Development Index as a function of urbanism, with indications of urban poverty

Figure 4-5 shows a tight, positive, linear correlation between per capita GDP and HDI, suggesting that social welfare is quite reliant on the country's ability to generate wealth. Minimal deviations occur, except by some countries with predominant mineral extraction industries, such as Equatorial Guinea and Angola. Seychelles is the pinnacle of HDI, with very high per capita GDP. It has low urban poverty if one uses the $1.25 threshold. However, this contrasts heavily with a high Gini rating of 0.657, suggesting high inequality. Perhaps even if most of the population is over the monetary poverty thresholds, relative poverty may still exist, once again offering a reminder that poverty must be understood as more than a financial measure. To be expected, urban poverty is generally higher in the lower HDI and economically productive countries.

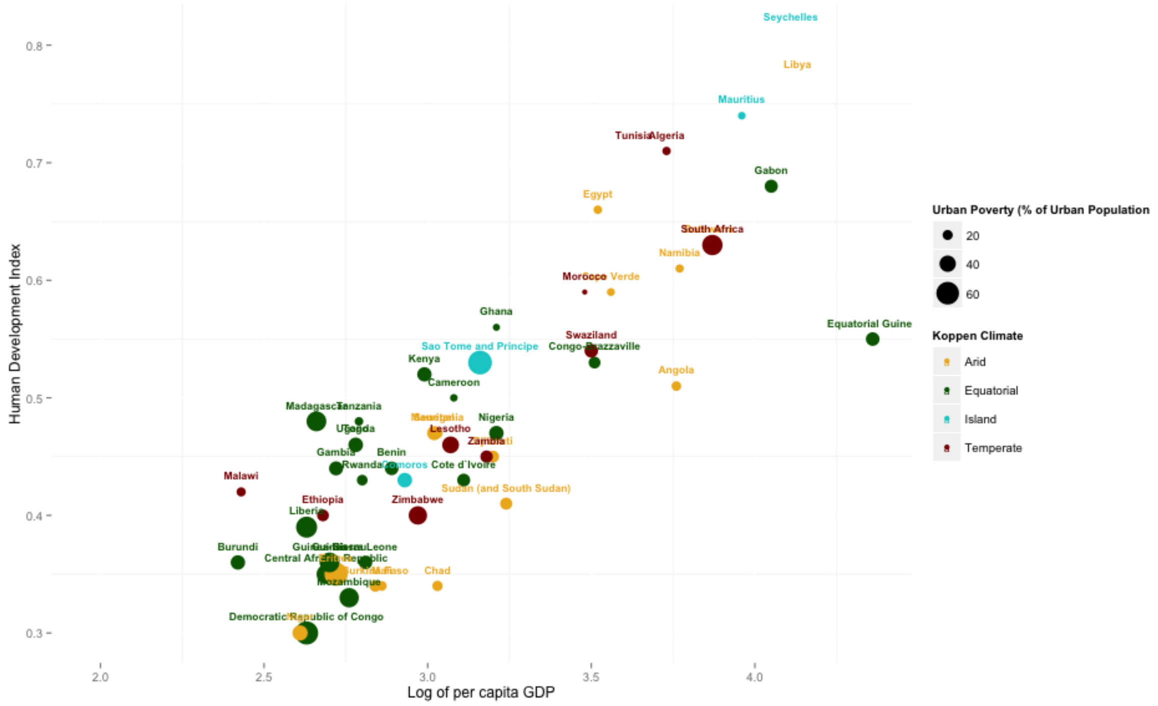


Figure 4-5: Human Development Index as a function of GDP per capita, with indications of urban poverty

In examining how resource consumption is related to economic production and social upliftment, correlations were sought between multiple socioeconomic and geographic factors, yet GDP was the most clearly correlated indicator.

Figure 4-6 shows a direct linear relationship between GDP and energy consumption. More energy is consumed by more industrialised or service oriented countries, whose activities contribute to higher GDP output. The largest economies are noted to be South Africa, Nigeria, Egypt, Algeria and Angola, yet large populations reduce their per capita output behind nations with smaller populations such as Seychelles, Equatorial Guinea, Mauritius and Libya. Somalia and Chad are outliers with low GDP and low energy consumption respectively.

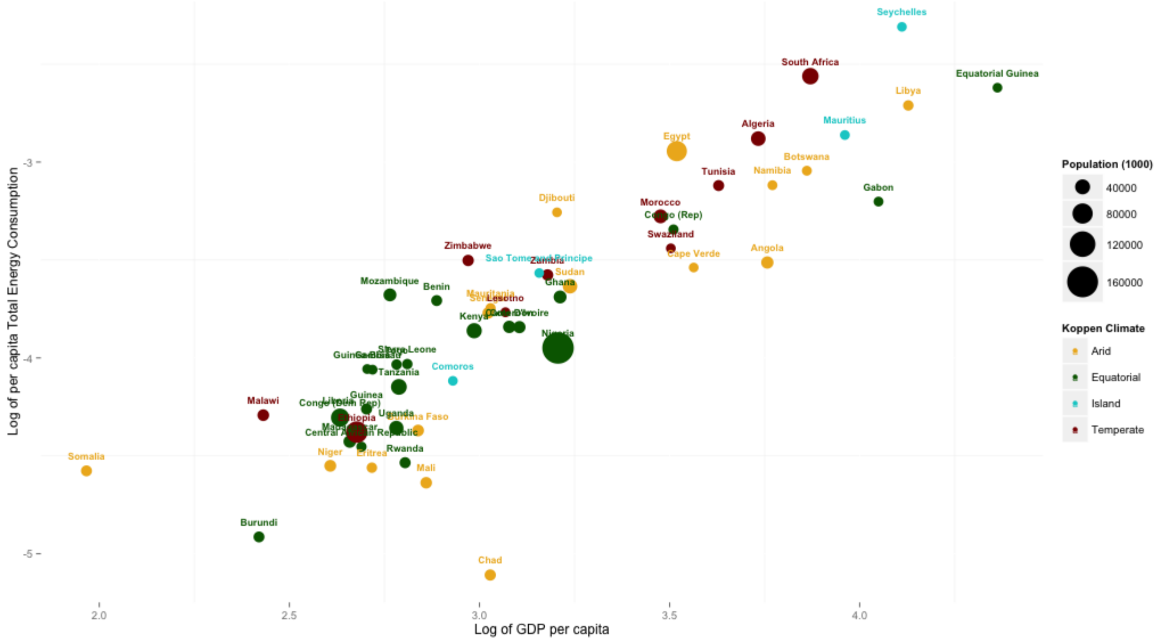


Figure 4-6: Total energy consumption as a function of GDP

Figure 4-7 shows the proportion of GDP derived from different economic sectors, organised from lowest economic production, and low energy consumption, on the left to highest economic production, and high energy consumption, on the right. The colors denote the location of these activities, with the green hues as rural activities and the orange hues as urban activities. As nations industrialise, agriculture becomes less impactful to the GDP and more urban activities increase in importance. It is interesting to note that manufacturing, finance, trade or administration do not show obvious increases individually, but the combination of these activities increases as a whole. The mining and oil contributions to GDP vary throughout the distribution as they are reliant on the availability of minerals in the country and their degree of exploitation.

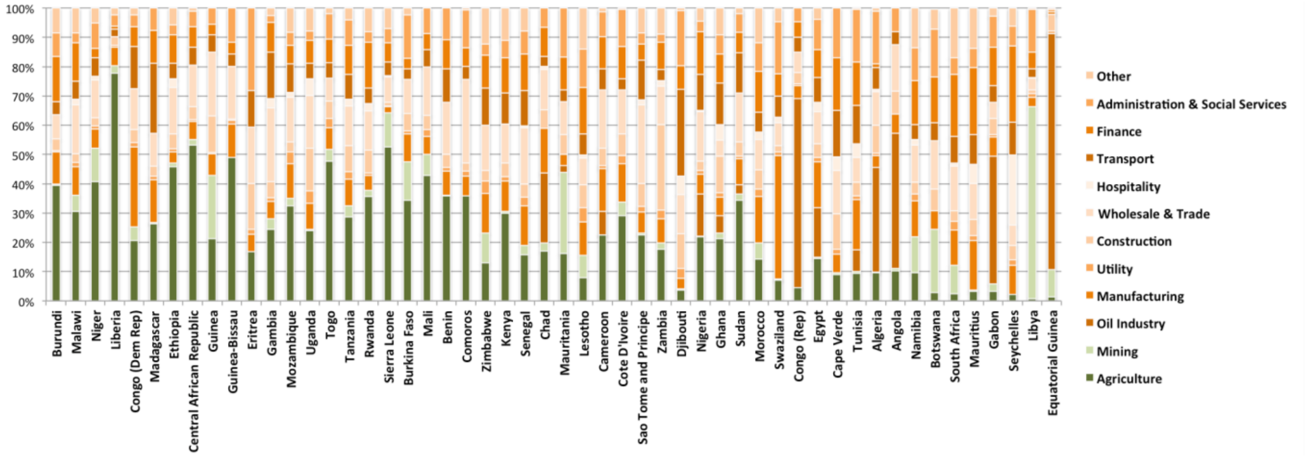


Figure 4-7: Proportional contributions to GDP by economic sector, divided by rural and urban activity and ranging from lowest per capita GDP on the left to highest per capita GDP on the right.

Figure 4-8 shows that the relationship between total material consumption and GDP is also a positive one, but less clearly defined. This is particularly due to biomass consumption, which shows no correlation to GDP. Figure 4-9 shows the material profiles of African nations ranging from lowest per capita GDP on the left to highest on the right. One can see that although the proportions of materials change as countries get richer, per capita biomass consumption remains somewhat stable, suggesting that it is a consistent need for people across countries. As per capita GDP increases, it is possible to observe overall increases in material intensity, and changes in the proportions of material consumed, including more consumption of ores, industrial minerals, and construction materials.

Figure 4-8: Total material consumption as a function of GDP

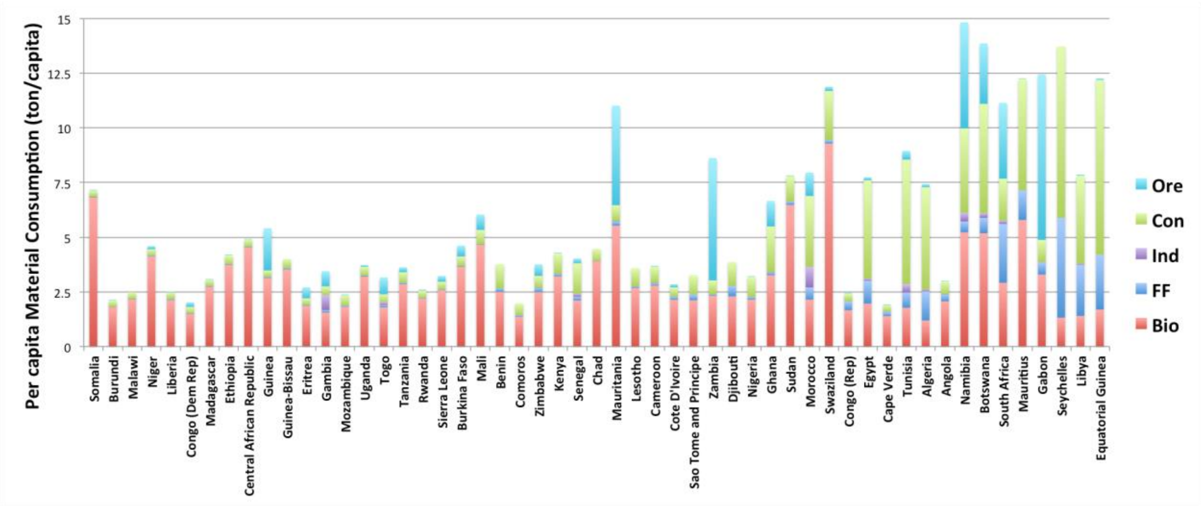


Figure 4-9: Material profiles of African nations by per capita material consumption, ranked from low per capita GDP on the left, to high on the right.

4.3. Exploring the city data – objectives 1, 2 & 3

This section defines the sample of African cities used in the typology and details the insights gleaned about cities from raw demographic data, and scaled economic and resource data.

4.3.1. Sample of cities

Table 4-4: Selected cities for categorisation

Northern Africa	**Western Africa**	**Eastern Africa**	**Middle Africa**	**Southern Africa**
Total Population: 213 million Urban Population: 106 million Urban Proportion: 50 per cent	Total Population: 314 million Urban Population: 141 million Urban Proportion: 45 per cent	Total Population: 341 million Urban Population: 80 million Urban Proportion: 24 per cent	Total Population: 128 million Urban Population: 54 million Urban Proportion: 42 per cent	Total Population: 59 million Urban Population: 35 million Urban Proportion: 59 per cent
Algiers - Algeria	Cotonou - Benin	Bujumbura - Burundi	Huambo - Angola	Francistown - Botswana
Constantine - Algeria	Porto Novo - Benin	Gitega - Burundi	Luanda - Angola	Gaborone - Botswana
Oran - Algeria	Bobo Dioulasso - Burkina Faso	Moroni - Comoros	Douala - Cameroon	Maseru - Lesotho
Alexandria - Egypt	Ouagadougou - Burkina Faso	Djibouti - Djibouti	Yaounde - Cameroon	Walvis Bay - Namibia
Asyut - Egypt	Praia - Cape Verde	Asmara - Eritrea	Bangui - Central African Republic	Windhoek - Namibia
Cairo - Egypt	Abidjan - Cote D'Ivoire	Addis Ababa - Ethiopia	Moundou - Chad	Cape Town - South Africa
Fayum - Egypt	Yamoussoukro - Cote D'Ivoire	Mek'ele - Ethiopia	N'Djamena - Chad	eThekwini - South Africa
Port Said - Egypt	Banjui - Gambia	Kisumu - Kenya	Bandundu - Congo (Dem Rep)	Johannesburg - South Africa
Benghazi - Libya	Accra - Ghana	Mombasa - Kenya	Kinshasa - Congo (Dem Rep)	Mangaung - South Africa
Tripoli - Libya	Kumasi - Ghana	Nairobi - Kenya	Lubumbashi - Congo (Dem Rep)	Nelson Mandela Bay – S. Africa
Casablanca - Morocco	Sekondi-Takoradi - Ghana	Antananarivo - Madagascar	Brazzaville - Congo (Rep)	Stellenbosch - South Africa
Fes - Morocco	Conakry - Guinea	Mahajanga - Madagascar	Pointe-Noire - Congo (Rep)	Tshwane - South Africa
Kenitra - Morocco	Bissau - Guinea-Bissau	Blantyre - Malawi	Malabo - Equatorial Guinea	Manzini - Swaziland
Marrakesh - Morocco	Monrovia - Liberia	Lilongwe - Malawi	Libreville - Gabon	Mbabane - Swaziland
Rabat - Morocco	Bamako - Mali	Port Louis - Mauritius	Port-Gentil - Gabon	
Tangier - Morocco	Gao - Mali	Maputo - Mozambique	Sao Tome - Sao Tome & Principe	
Juba - South Sudan	Nouadhibou - Mauritania	Nampula - Mozambique		
Khartoum - Sudan	Nouakchott - Mauritania	Gisenyi - Rwanda		
Nyala - Sudan	Maradi - Niger	Kigali - Rwanda		
Sfax - Tunisia	Niamey - Niger	Victoria - Seychelles		
Sousse - Tunisia	Abuja - Nigeria	Hargeisa - Somalia		
Tunis - Tunisia	Benin City - Nigeria	Mogadishu - Somalia		
	Ibadan - Nigeria	Dar es Salaam - Tanzania		
	Ilorin - Nigeria	Dodoma - Tanzania		
	Kaduna - Nigeria	Mwanza - Tanzania		
	Kano - Nigeria	Zanzibar - Tanzania		
	Lagos - Nigeria	Kampala - Uganda		
	Ogbomosho - Nigeria	Kitwe - Zambia		
	Port Harcourt - Nigeria	Lusaka - Zambia		
	Zaria - Nigeria	Ndola - Zambia		
	Dakar - Senegal	Bulawayo - Zimbabwe		
	Thies - Senegal	Gweru - Zimbabwe		
	Freetown - Sierra Leone	Harare - Zimbabwe		
	Lomé - Togo			
	Sokode - Togo			

Table 4-4 shows the selected sample of cities by region. Though no efforts were made to do this, the number of cities sampled from each region is somewhat proportional to the total and urban populations in each region. The sample includes 120 cities, of which 56 are capital cities (South Africa has three), 44 are the single prime city in their country, 43 are coastal cities, 38 of which are described as international ports by World Port Source (www.worldportsource.com), and five of which are island cities.

The aggregate material and energy intensities for the sampled cities are ranked in Appendix 6.1. The scaling process produced results both above, on par with and below the limited raw data available. Looking at raw electricity consumption data for 15 cities (EIU, 2011), scaled data underestimated four cities, overestimated seven, and was within reasonable range of four cities. This demonstrates the variability of the scaling process, and the need for more specific ways to delineate urban and rural consumption, or more appropriately distribute consumption between cities.

Based on scaled resource data, the sampled cities with the highest energy consumption were Cairo, Johannesburg, Alexandria, Cape Town and eThekwini. Those with the highest material consumption were Cairo, Johannesburg, Alexandria, Cape Town and Luanda. These cities show large populations and quite strong economies. Those with the lowest energy consumption were Gitega, Moundou, Gao, Bandundu and Moroni, and the lowest materially consumptive cities were Gitega, Moroni, Sao Tome, Sokode and Bandundu.

4.3.2. Identifying relationships between city attributes

Many of the relationships described nationally hold true in this examination of cities, particularly as much of the data is scaled from national level. However, it is beneficial to confirm these relationships and observe the main shifts. The figures below explore some of the key attributes of the sample of cities and attempt to tease out any correlations.

Selected African cities fell within the upper-middle to low HDI and low to high population density categories determined by Saldivar-Sali (2010). This study has effectively zoomed in on this bracket of cities and populated it with a larger sample. Figure 4-10 shows the distribution of cities by the national HDI rating and city population density. Simple observation suggests that, in general, equatorial nations have lower HDIs, temperate and island cities tend to show lower population density and arid cities are found across the whole distribution.

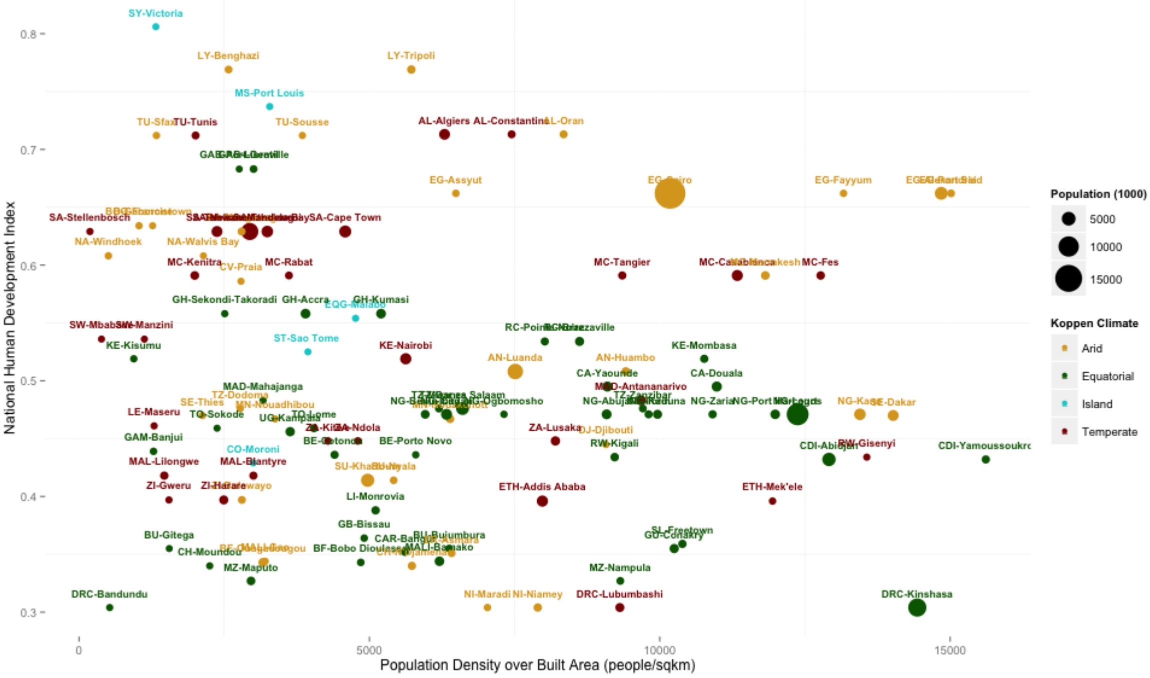


Figure 4-10: Distribution of cities by national Human Development Index and city population density

Figure 4-11 shows the distribution of cities by temperature using the variables of heating degree days and cooling degree days. The Koppen climate zones inform the placement of these cities: cities in temperate areas occupy the left side of this graph, showing annual variation between warm and cool temperatures. Equatorial cities are grouped tightly, with warm to hot temperatures all year round, and rarely dipping below 20 degrees Celsius. Cities in Arid regions occupy the whole distribution, demonstrating both the coolest and hottest temperatures. This makes sense because the delineation of arid zones is more to do with the level of precipitation than with temperature.

Should this graph be of cities of the global north, it would be indicative of the energy intensity of these cities. As thermal regulation is typically the largest consumer of energy in cities (Weisz & Steinberger, 2010), one would expect that cities in high temperature regions would expend more energy on cooling their buildings, while cities in cooler regions would expend energy on heating. Temperate cities would expend energy on both heating and cooling. For example, one would hypothesize that Constantine, Algeria would expend the most energy per capita on heating, that Khartoum, Sudan, would expend the most energy per capita on cooling, and potentially that Port Louis, Mauritius, would expend the least energy per capita on thermal regulation. However, the prioritisation of thermal regulation in many African cities is questionable, and in many cities, it certainly occupies a lower proportion of energy consumption than in the global north. This is not to say that air conditioning is not used in African cities, but rather a comment about how widespread its use is. Air conditioning, as a remedy for heat or cold may be more reliant on the affluence of the city, with cheaper, less energy-intensive options, like fans or gas heaters predominating.

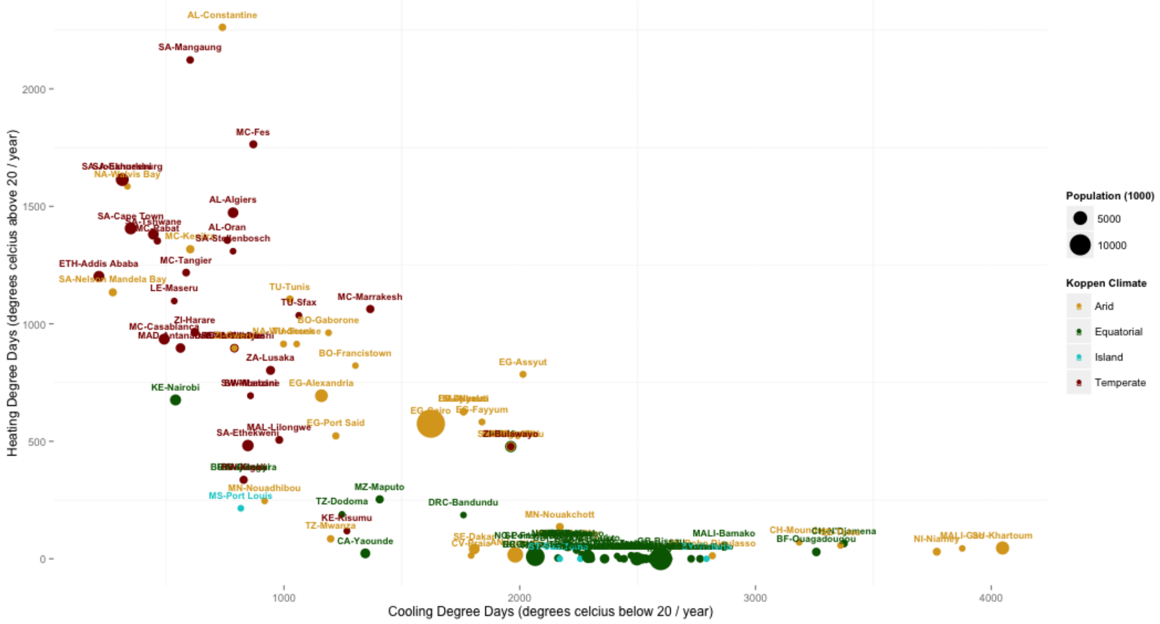


Figure 4-11: Climate distribution of cities using heating and cooling degree days

Kessides (2007) suggested that cities in areas of lush vegetation would face greater difficulties in spreading out, and thus have higher densities. Figure 4-12 does not demonstrate this conclusively, though cities in equatorial areas do tend to have higher densities than those in arid and temperate areas. The median density for equatorial cities is 6201 people per square kilometer, and 5700 and 3950 for arid and temperate cities respectively. Based on Krausmann et al. (2008), the denser cities either have grown quickly due to abundant local resources or are very old agrarian cities which have built up over time.

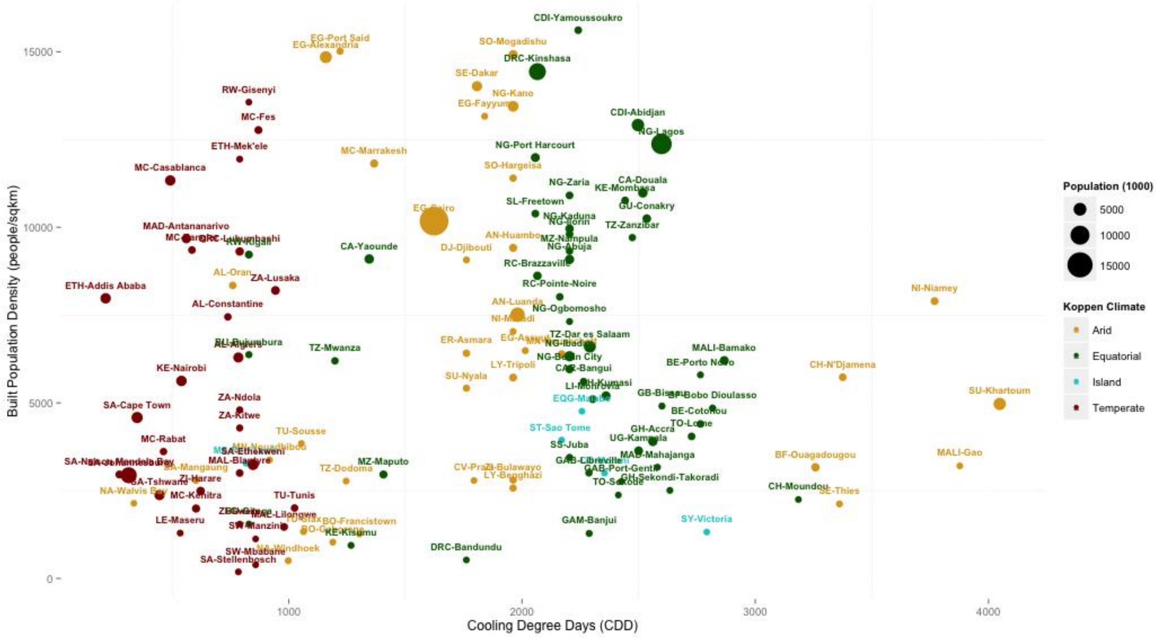


Figure 4-12: Distribution of cities by climate and population density

Figure 4-13 shows a distinction between the built urban area of a city and the administrative boundaries. Cities to the left of the line are underbound by the administrative areas, suggesting that decision makers are only engaged with a portion of the urban agglomeration, and might have minimal influence in managing the cities' hinterlands. They might benefit from extending city boundaries or forming administrative coalitions with neighbouring urban municipalities. Those to the right of the line are overbound by the administrative area and probably benefit from excess space to plan urban developments or protect as green infrastructure. It may be that these boundaries include secondary cities or towns which support the functioning of the major agglomeration, so having them under the same administrative systems would allow stronger coordination of the city bioregion.

Cairo and Johannesburg are examples of underbound cities. As large agglomerations, the cities are split into multiple administrative areas which might make cohesive decision-making difficult. Kinshasa is quite overbound and the administrative area includes smaller towns.

This is not to say that the administration will have control over how the city spreads out. Lagos megacity is overbound by Lagos State boundaries, which head east and west, but the commutershed sprawls north into Oyo State, which has resulted in complications around taxation of people who may work in Lagos State but live in Oyo State.

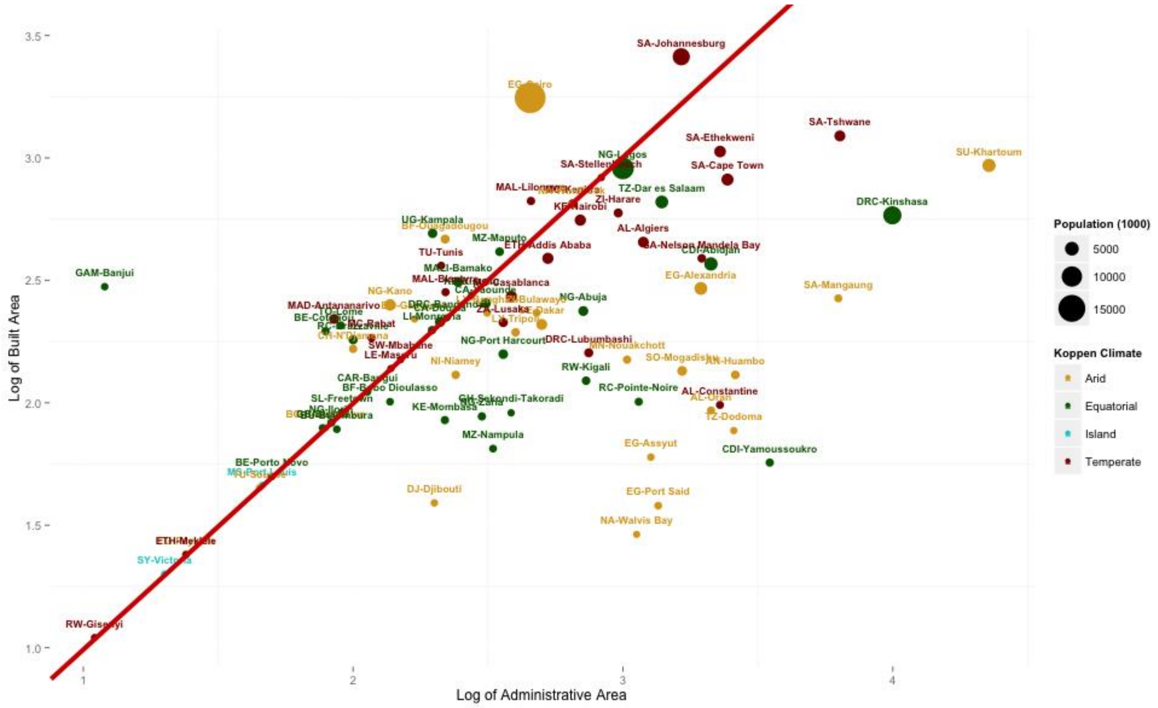


Figure 4-13: Cities overbound or underbound by administrative borders

Saldivar-Sali (2010) demonstrated that cities with lower densities tend to emit more carbon due to longer distances required for ground transit. The greater the area of the city, and the least compact it is, the more petrol is expended on transit. This can be measured by the carbon emissions of a city. Figure 4-14 shows the relationship between per capita carbon emissions and city density for African cities. It appears true for some cities, while others do not follow this pattern, suggesting that another factor is involved. In as much as carbon emissions are a function of transport, a large increase in CO2 emissions might be better understood as a sign of widespread private transportation, which is a function of affluence. Figure 4-14 likely shows the level of utilisation of private transportation, which, set as a function of density, shows higher carbon emissions. Low density, low-income equatorial cities are reliant primarily on public transportation, and show low carbon emissions. Low-density northern cities, such as those in Algeria, Tunisia and Libya show increased emissions. Cairo is an interesting outlier, as it has high carbon emissions, yet is a high-density city. By virtue of size, it still manages to sprawl over a large area, which may be one answer to the high emissions. South African and Swazi cities show very high carbon emissions, which are concordant with high incomes, more private transport and low-density cities. They might be skewed to a higher level by the coal-based energy sector which emits large amounts of CO2.

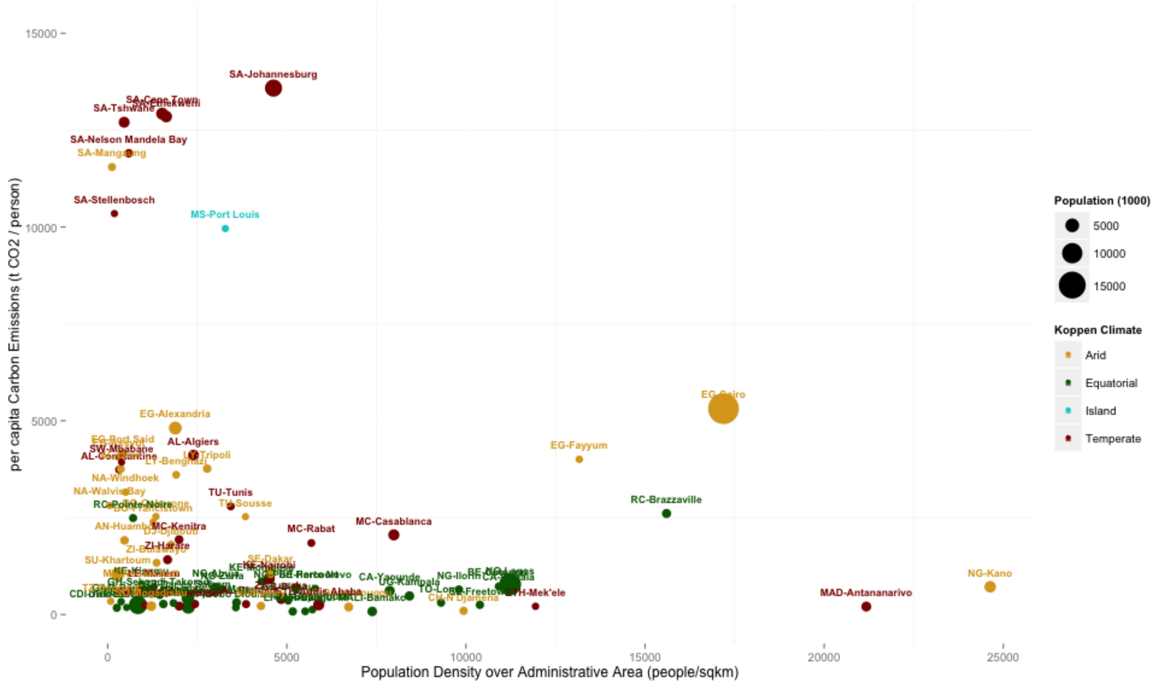


Figure 4-14: Carbon Emissions as a function of population density

Just as density is indicative of energy spent on transport, it is also suggestive of greater access to resources, as less cost is required to deliver networked infrastructures to smaller areas. Fewer, more directed pipes or wires can better supply a concentrated population than a sprawling one.

Figure 4-15 and Figure 4-16 show access to electricity and access to water, respectively, as functions of population density. A clear trend is visible: as density increases, so too does electricity access. However, the same is not true for water access, which shows no obvious correlation to density. This may relate to the configuration of resource systems in each city. Electricity requires more institutional involvement, for the generation of electricity and building of electric networks to deliver electricity to homes and businesses. On the other hand, water infrastructure is more varied and, while the ideal may be for piped networks to deliver treated water directly to consumers, alternative means of water delivery are widespread through African cities. Such alternatives include boreholes for water capture, water tankers, water bottles or water sachets for delivery, and plastic water tanks for storage. This decentralised system likely relies less on density, though transportation of water likely adds to the high carbon emissions expected from less dense cities.

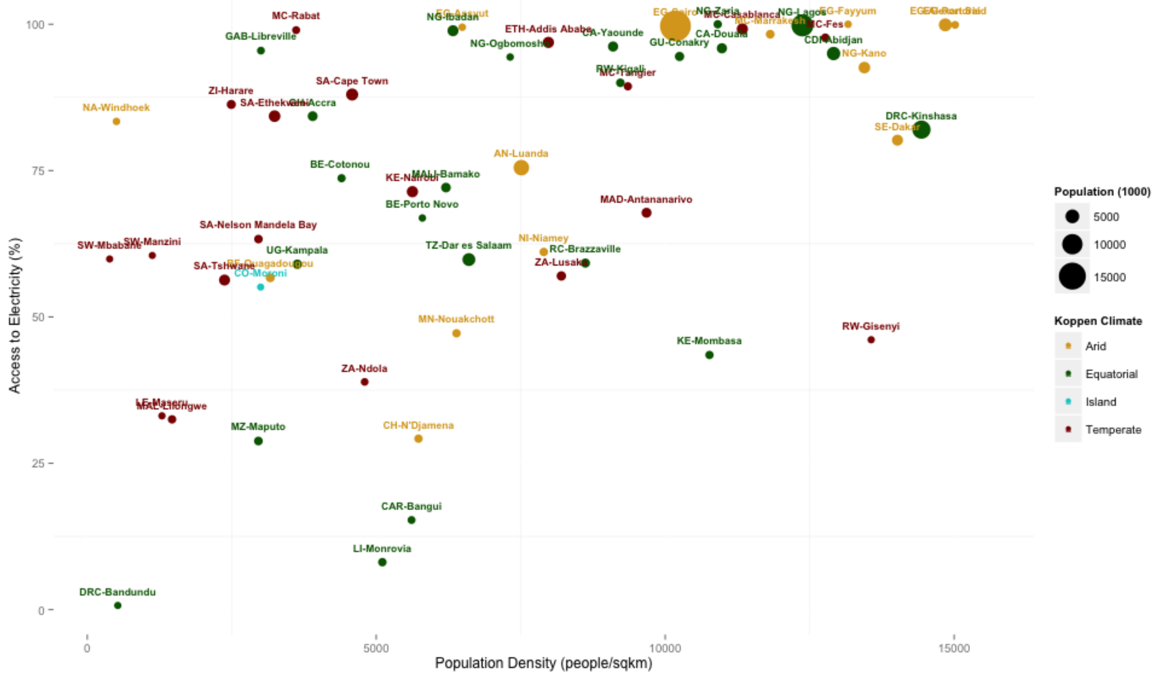


Figure 4-15: Access to electricity as a function of population density for 57 cities

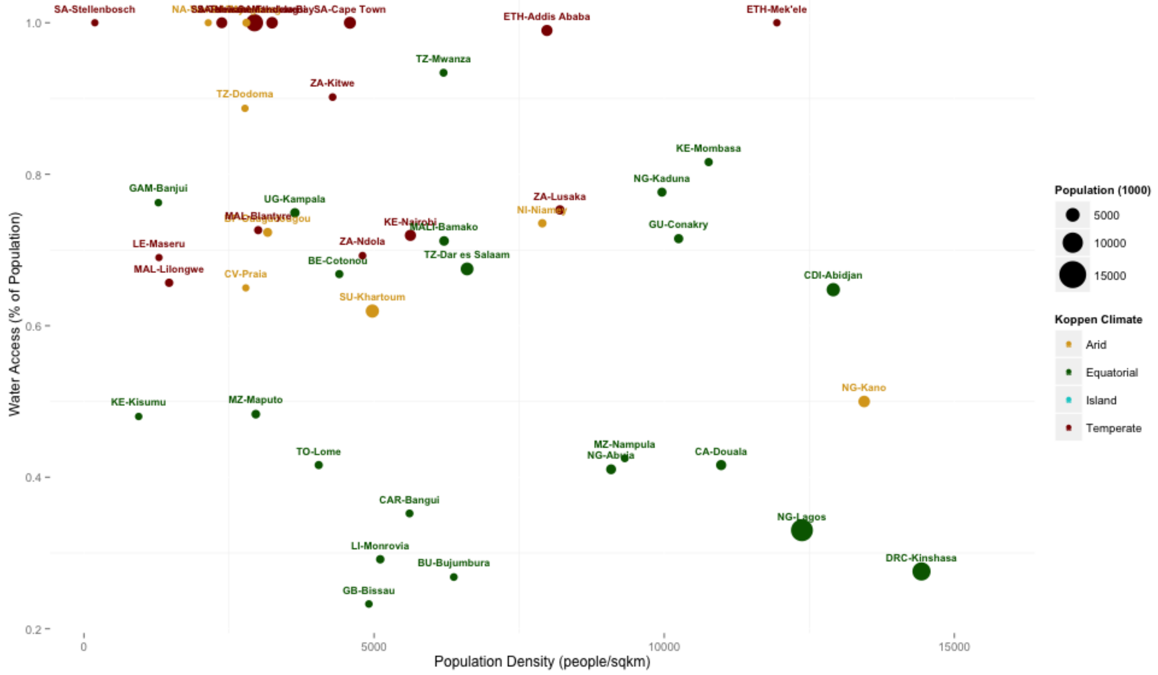


Figure 4-16: Water access as a function of population density for 45 cities

Resource consumption is purportedly limited by either availability of, or access to, the resource. With this being the case, increased access to the resource should lead to increased consumption.

Figure 4-17 and Figure 4-18 show electricity consumption and water consumption, respectively, as functions of access. Electricity consumption, while not linearly correlated, shows higher levels of consumption for cities over 50 per cent access. Water consumption is more linearly related to water access, suggesting that higher access leads to higher consumption. Other variables are likely at play, particularly as higher incomes will increase access.

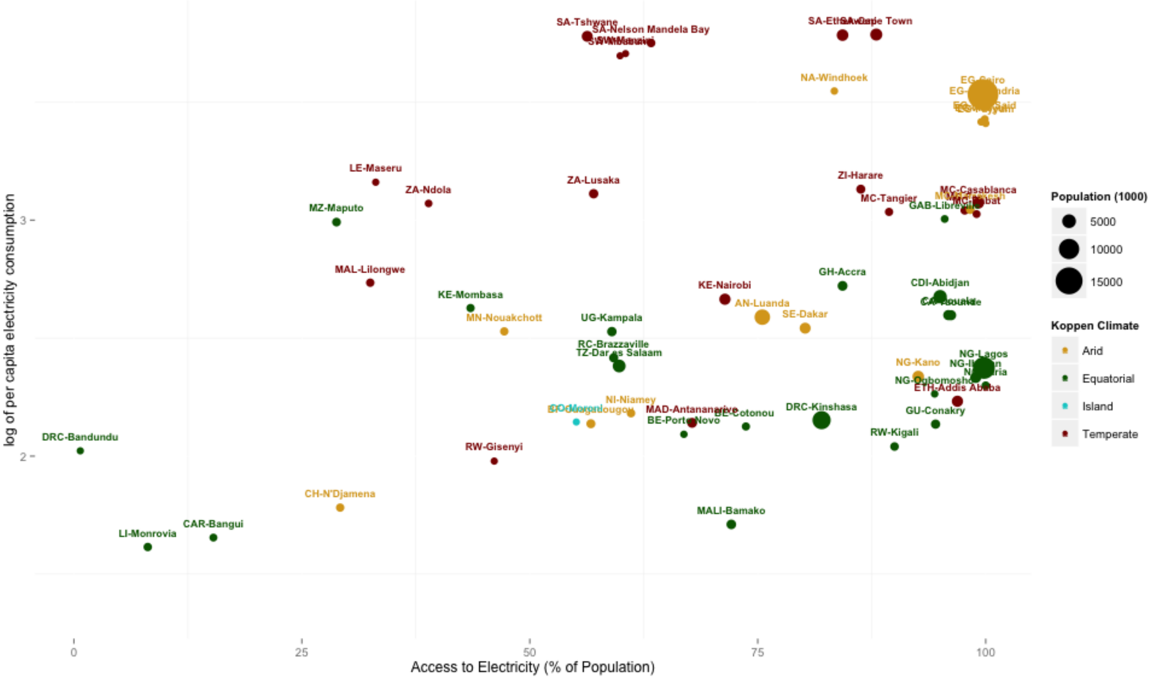


Figure 4-17: Per capita electricity consumption as a function of electricity access for 57 cities

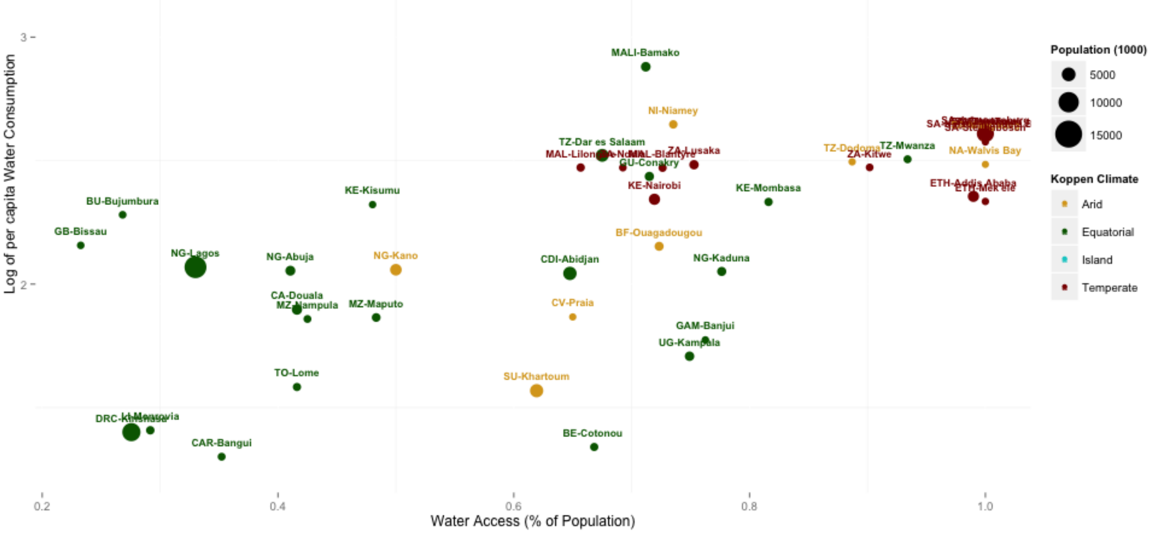


Figure 4-18: Per capita water consumption as a function of water access for 45 cities

4.4. Forming the typologies – objective 4

This section presents six typologies, summarised in Table 4-5 by scale and clustering pathways utilised. Most of the clustering outcomes are dependent on the simple choices of normalisation, either by using per capita or per unit GDP, or in standardising the data for comparison. Another choice involves whether to cluster by comparing the relative magnitude of resources between each city, as in pathway A and B, or by studying the relative proportions of resources utilised within each city. For example, a ranking of biomass consumption will return different results to a ranking of the proportion of biomass as a part of a city's total material consumption. The second option would more accurately group cities by similarity of 'shape' of their resource profile, while the first forms categories based on relative magnitudes of resource consumption. The outcomes tend to be similar, but results of pathway C may be easier to convey to others. Pathway C will be explored in future work.

Table 4-5: Different typologies completed in this study

	Indicators (form of normalisation)	Pathway A: Statistical Clustering of relative resource indicator magnitudes (Quantitative)	Pathway B: Classifying relative resource magnitudes with Classification Trees (Qualitative)	Pathway C: Statistical Clustering relative proportions of resource indicators within each city
National	Socioeconomic	Section 0		
	Resource (per capita)	Section 4.4.2		Future Work
City-Level	Socioeconomic	Section 4.4.3		
	Resource (per capita)	Section 4.4.4	Section 4.4.6	Future Work
	Resource (per unit GDP)	Section 4.4.5		Future Work

4.4.1. National typology by socioeconomic indicators

Nations were clustered by similarity of climate zone, population, population density, population growth, urban population, HDI, Gini coefficient, per capita GDP, and degree of urban primacy. The resultant groups are listed in Table 4-6, with a description of the typical socioeconomic features of the group. To understand the typical attributes of each group, the median value for each indicator was assessed and assigned a class of high, medium or low. These are relative values, only useful in comparing this sample of African nations.

Figure 4-19 displays the groups graphically on the African continent, with the lowest average HDI rating in red and the highest average HDI rating in green.

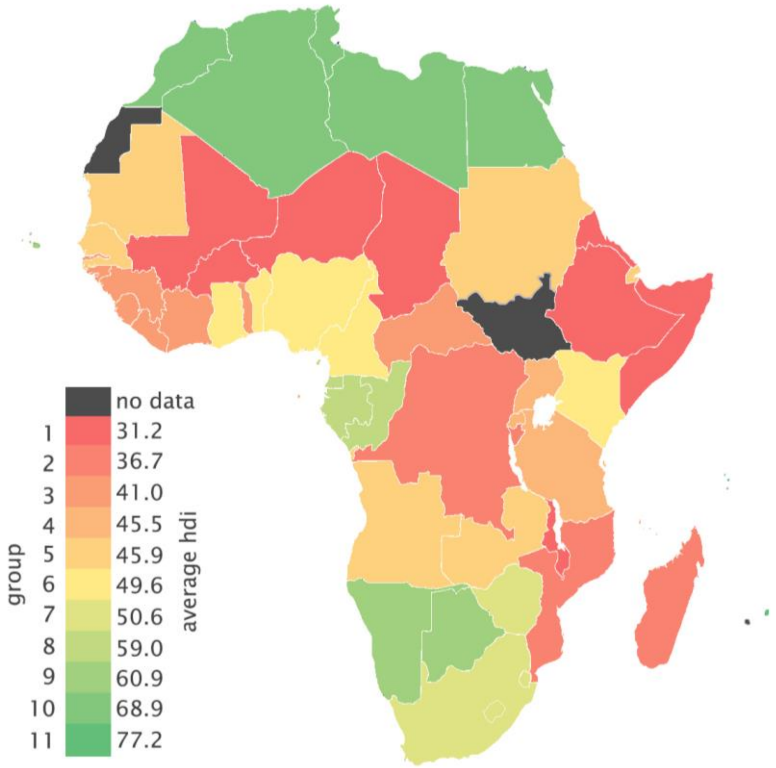


Figure 4-19: Clusters of Nations by socioeconomic and geographic variables, visualized by average HDI

Table 4-6: Typology of African nations by similarity of socioeconomic and geographic indicators

Group	Member Countries	Average HDI	Summary of group's typical socioeconomic attributes
1	Burkina Faso, Chad, Eritrea, Ethiopia, Malawi, Mali, Niger, Somalia	31.2	On average, members of group 1 fall in an arid climate. They have medium-sized national populations of low to medium population density, and show high annual growth. Each of their low urban populations is concentrated in one major city, with medium levels of urban poverty. These countries show medium levels of rural poverty and a middle rating on the Gini coefficient suggests a modest income gap between rich and poor. They have low per capita GDPs and equivalently low ratings on the human development index.
2	Burundi, Democratic Republic of the Congo, Madagascar, Mozambique	36.7	Members of group 2 show similar demographic attributes to group 1 except for an equatorial climate. They have medium urban populations, which, except for Mozambique, are concentrated in single major cities. The key differences are the high levels of urban poverty. These countries also show high levels of rural poverty and a middle Gini rating suggests only a moderate income gap. They have low per capita GDPs and low ratings on the human development index.
3	Central African Republic, Comoros, Cote D'Ivoire, Gambia, Guinea, Guinea-Bissau, Liberia, Sao Tome & Principe, Sierra Leone, Togo	41.0	On average, members of group 3 fall in an equatorial climate. They have small national populations of medium population density, and show medium to high annual growth. They have medium to high urban populations, concentrated in one major city, with high levels of urban poverty. These countries show medium to high levels of rural poverty, yet as with group 2, the Gini rating suggests that there is not a large gap between rich and poor. This group includes some of the poorest countries in Africa and the world, but with a medium HDI rating on average, the quality of life may be better than others.
4	Rwanda, Tanzania, Uganda	45.5	On average, members of group 4 fall in an equatorial climate. They have small- to medium-sized national populations of medium to high population density, and show medium to high annual growth. They have low urban populations, concentrated in one major city, with low levels of urban and rural poverty. A middle ranking on the Gini index suggests only a moderate income gap. They have low per capita GDPs and medium ratings on the human development index.
5	Angola, Djibouti, Mauritania, Senegal, Sudan, Zambia	45.9	On average, members of group 5 fall in an arid climate. They have small- to medium-sized national populations of low population density, and show medium to high annual growth. They have medium to high urban populations, concentrated in one major city, with medium levels of urban poverty. These countries show high levels of rural poverty and middle to high ratings on the Gini coefficient suggest a large income gap. They have medium per capita GDPs, from moderate mineral extraction industries, and medium ratings on the human development index.
6	Benin, Cameroon, Ghana, Kenya, Nigeria	49.6	On average, members of group 6 fall in an equatorial climate. They have large national populations of medium population density, and show medium to high annual growth. They have medium to high urban populations, distributed over many cities, with medium levels of urban poverty. These countries show medium levels of rural poverty and only a moderate income gap is suggested by the Gini coefficient. They have medium per capita GDPs and medium to high ratings on the human development index.

7	Lesotho, South Africa, Swaziland, Zimbabwe	50.6	On average, members of group 7 fall in a temperate climate. They have low to medium national populations of medium population density, and show low annual growth. They have medium to high urban populations, distributed over multiple key cities, with high levels of urban poverty. These countries show medium levels of rural poverty and high ratings on the Gini coefficient suggest large income gaps between rich and poor. They have medium to high per capita GDPs and medium to high ratings on the human development index.
8	Republic of Congo, Equatorial Guinea, Gabon	59.0	On average, members of group 8 fall in an equatorial climate. They have small national populations of low population density, and show medium annual growth. They have high urban populations, concentrated in one major city, with medium to high levels of urban poverty. These countries show medium to high levels of rural poverty with a moderate income gap suggested by the Gini coefficient. They have high per capita GDPs and, despite the high poverty indicators, have high ratings on the human development index.
9	Botswana, Cape Verde, Namibia	60.9	On average, members of group 9 fall in an arid to temperate climate. They have small national populations of low population density, and show low annual growth. They have high urban populations, distributed over a few key cities, with low levels of urban poverty. These countries also show low levels of rural poverty, yet the income gap is quite large. They have medium to high per capita GDPs and overall high ratings on the human development index.
10	Algeria, Egypt, Libya, Morocco, Tunisia	68.9	On average, members of group 10 fall in an arid climate. They have medium to large national populations of low to medium population density, and show low annual growth. They have high urban populations, distributed over many cities, with low levels of urban poverty. These countries show low levels of rural poverty and are a unique group in showing low Gini ratings, or a small income gap. They have high per capita GDPs, from oil and mining, and equivalently high ratings on the human development index.
11	Mauritius, Seychelles	77.2	The members of group 11 are Mauritius and Seychelles, two island states. They fall in an equatorial climate. They have very small national populations of high population density, and show low annual growth. They have medium urban populations, distributed over some key cities, with low levels of urban poverty and low levels of rural poverty. Middle to high ratings on the Gini coefficient suggests high income gaps, probably due to large foreign presence, increasing the cost of living. Both countries have high GDPs from established tertiary sectors, mostly revolving around finance and hospitality. Despite high inequality, they show the highest HDIs in Africa.

4.4.2. National typology by resource indicators

Nations were clustered by similarity of consumption of electricity, fossil fuels, biomass, construction materials and water, and emissions of carbon dioxide. The resultant groups are listed in Table 4-7, with the average total energy consumption and total material consumption of the group.

Figure 4-20 displays the groups graphically on the African continent, with the lowest average consumption of materials and energy in yellow and the highest average consumption rating in green. The complete resource profiles are visualised in Appendix 0.

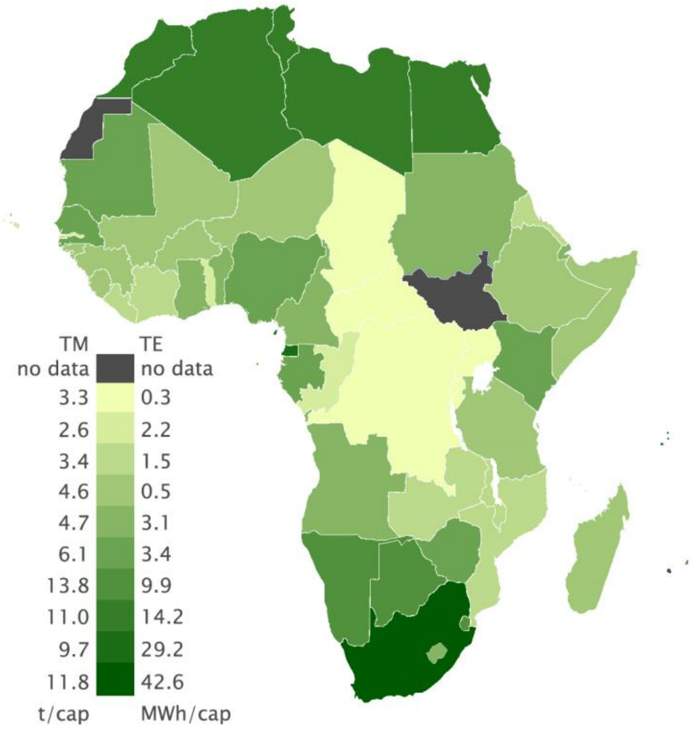


Figure 4-20: Resource clusters displayed graphically and by per capita resource intensity.

Table 4-7: Typology of African nations by similarity of resource indicators

Group	Members Countries	Average Material Consumption (t/cap)	Average Energy Consumption (MWh/cap)	Typical levels of resource consumption
1	Burundi, Central African Republic, Chad, Democratic Republic of the Congo, Rwanda, Uganda	3.1	0.4	Group 1 is made up predominantly of low density, rural countries with small populations, except for the Democratic Republic of Congo. All are landlocked countries and are net exporters. They are the lowest per capita material and energy consumers with primary sector making up between 25 and 55 per cent of their economies. Some manufacturing and construction is present with between 35 and 40 per cent tertiary sector. The resource profile is a material intensive one, with medium to high biomass consumption, medium to low construction material consumption and low energy consumption. the group has medium-low water consumption, making them the lowest of water consumers, along with group 5.
2	Cape Verde, Comoros, Republic of Congo, Gambia, Togo	4.4	0.5	Group 2 is made up of small countries by area and population. They are all coastal countries with Cape Verde and Comoros as island nations. All are net material importers except for the Republic of Congo and Togo, who are net exporters. Except for Cape Verde, which has a predominantly tertiary sector economy, the members have over 30 per cent extractive industry. This manifests as a resource profile with medium-low material consumption and medium-low to medium fossil fuel and electricity consumption. Members have medium-low to medium consumption of water.
3	Cote D'Ivoire, Eritrea, Liberia, Malawi, Mozambique, Zambia	2.5	1.3	Group 3 has similar resource profile shape of consistent levels of consumption all round, but is more material intense than energy intensive. Medium consumption of biomass, medium-low to medium consumption of construction materials, medium-low consumption of fossil fuels and medium-low emissions of carbon dioxide, yet medium-low to medium consumption of electricity, which suggests utilisation of hydroelectric electricity generation. These countries show middling levels of water consumption. This resource profile concords with primary sectors between 18 and 35 per cent and secondary sector between 15 and 40 per cent. Liberia is the outlier with 80 per cent extractive industry and very small secondary sector industry. Malawi and Zambia are two of only three net exporters in landlocked situations.
4	Burkina Faso, Ethiopia, Guinea, Guinea Bissau, Madagascar, Mali, Niger, Sierra Leone, Somalia, Tanzania	2.4	1.3	Group 4 is made of mostly low density countries with low to medium per capita GDPs. These nations' economies are characterised as about 50 per cent extractive with an average of 10 per cent from mining, except for Madagascar and Guinea-Bissau, which have minimal mining, and agricultural extraction accounting for 35 per cent and 50 per cent of their economies respectively. These countries show small manufacturing and construction contributions of between 10 and 20 per cent. This manifests as a resource profile of medium-low energy consumption across the board, with medium-high biomass consumption, medium-low to medium consumption of construction materials and medium-high water consumption.
5	Angola, Benin, Cameroon, Djibouti, Ghana, Lesotho, Sao Tome & Principe, Sudan	4.0	2.4	Group 5 shows effectively the same resource profile as group 1 but at a higher magnitude. These countries show medium consumption of all resources except water, which is medium-low, and biomass which is medium-high. Except for Angola and Sudan, these countries are all net importers of materials. An average of 20 per cent of the economy is derived from secondary sector activities and nations show biomass extractive industries of between 8 and 45 per cent. Angola and Djibouti are outliers, showing 45 per cent oil industry and 78 per cent tertiary industries respectively.

6	Gabon, Kenya, Mauritania, Nigeria, Senegal, Zimbabwe	4.5	2.2	Group 6 includes countries with large proportions of mineral or oil extraction, except for Kenya. Secondary sector activity ranges between 10 and 20 per cent contribution to GDP and tertiary sectors are between 40 and 60 per cent. The resource profile shows almost equal levels of consumption of each resource at medium to medium-high level. This suggests a population with balanced material and energy needs.
7	Botswana, Mauritius, Namibia, Swaziland	13.8	9.7	Group 7 is made of mostly southern countries with high GDPs and low-density populations. Primary sector contributions to GDP are between 10 and 25 per cent. Swaziland is a curious outlier with 40 per cent of its GDP reliant on manufacturing. All countries in the group have a well-developed tertiary sector. The resource profile shows a higher material intensity than energy intensity. It shows medium to medium-high consumption of fossil fuels and electricity, with associated carbon emissions. They show medium high consumption of construction materials and medium-high to high consumption of biomass and medium to high consumption of water. Swaziland is the largest per capita consumer of biomass in the continent, suggesting a relationship between its manufacturing and biomass. All these countries are linked to South Africa’s electricity infrastructure, which may account for the large consumption of energy
8	Algeria, Egypt, Libya, Morocco, Tunisia	8.3	12.6	Group 8 is made up of all northern-region countries except Sudan. It is unique in that it is the only group whose members are also the most similar by socioeconomic profile. Except for Libya, whose economy is 65 per cent natural gas dependent, these countries show balanced contributions to GDP from each economic sector. Agricultural contribution to GDP is between 1 and 14 per cent, which is reflected in proportionally lower biomass consumption. These countries show materially intensive resource profiles with medium-high to high consumption of construction materials, but medium-low to medium biomass consumption. energy consumption is medium to medium-high. Water consumption is medium-high, except for Egypt which shows high consumption, the highest in the continent.
9	Equatorial Guinea	9.7	29.2	Group 9 is the outlier of Equatorial Guinea, which is unique in deriving 90 per cent of its GDP from oil and mining. Its profile shows medium-low consumption of biomass and water, medium-high consumption of fossil fuels, which shows a similar level of carbon emissions, yet medium-low to medium electricity consumption, suggests its lack of use as an energy carrier. Construction material consumption is the highest on the continent.
10	Seychelles, South Africa	11.8	42.6	Group 10 is made up of two outliers who show more energy intensity than material intensity. Both South Africa and Seychelles show medium-high total material consumption, with Seychelles using a high proportion of construction materials and medium-low biomass, while South Africa shows medium-high biomass and medium construction material consumption. Both countries show high carbon emissions, with medium-high to high fossil fuel consumption and high electricity consumption. South Africa shows the highest electricity consumption on the continent, derived predominantly from coal. This grouping is a curious one due to the difference in population sizes and country areas. Ignoring any skewing of per capita results due to Seychelles small size, the countries show remarkable similarity in their proportions of agricultural, secondary sector and financial sector contributions to GDP, at 2, 8 and 22 per cent respectively. These two countries show success in development strategies, both for large country and small one.

The key observations to be made from the clusters in Table 4-7 are listed below:

- Some countries with small populations, such as Botswana, Equatorial Guinea, Mauritius, Namibia, Seychelles and Swaziland, show higher levels of consumption. This may reflect reduced efficiency or economy of scale experienced by smaller nations as compared to large nations. Alternatively, it may be due to the use of a per capita measure, which may have elevated resource intensity levels in these nations.
- While no direct correlations were found between climate and water, it is curious that higher per capita water consumption occurs in purportedly water scarce areas. Figure 4-21 suggests that in general, temperate countries consume more than arid ones, which consume more than equatorial ones. This could suggest that water consumption is not tracked as effectively in water-abundant countries or potentially that the populace must consume more water in hotter or dryer climates. There were no direct correlations between water consumption and the proportion that agriculture contributes to GDP, but biomass production may show a relationship to water availability.
- Biomass typically is a level of consumption above each other resource, yet for group six to 10 the reduced importance of agriculture to the economy shows a reduction of per capita consumption of this resource. This follows Krausmann et al's (2008) socio-metabolic transition, which identifies industrialisation as the shift from biomass to fossil fuel dominated economies. While all nations are at some stage of this transition, those in groups 6 and 7 seem to be on the cusp of transitioning from biomass to fossil fuel predominant industry, while those in 8 and 10 have already made this transition.
- To qualify these groupings, it is worth establishing that no African nations are fully resource affluent. Groups 7, 8 and 10 may occupy a level of resource sufficiency, suggesting that there is enough to allow industry to function with moderate success. However, within each of these nations there are surely pockets of resource affluence and resource deficiency. The term resource deficiency is meant as an alternative conclusion to resource efficiency, despite their similar presentation. Lack of resources may indicate a detriment to industry and social services, as opposed to a resource efficiency of industrial and social systems. Groups 1 through 6, and likely 9 due to high inequality, are designated resource deficient. However, this category of 41 countries warrants further distinction, as groups 5 and 6 are perhaps better off, while groups 1 to 4 are resource poor.

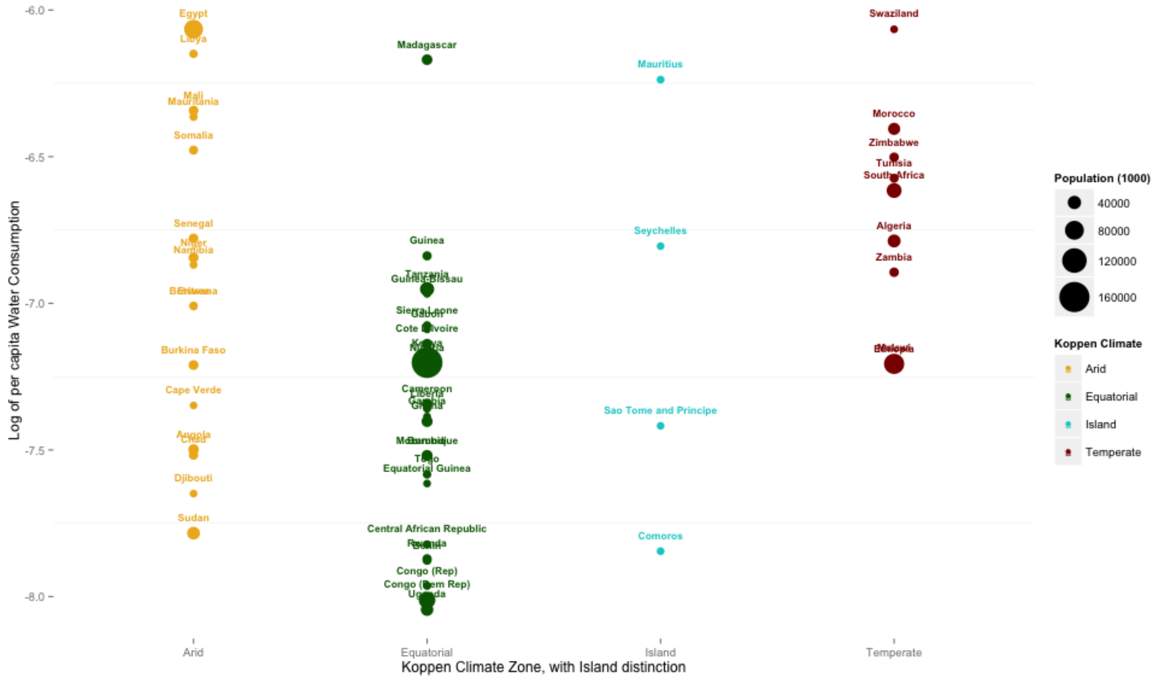


Figure 4-21: Water consumption by climate zone, with island nations separated

4.4.3. City typology by socioeconomic indicators

One hundred and twenty (120) cities were clustered by similarity of population, population density, cooling degree days, heating degree days and per capita GDP. Based on lessons from the global resource typology of cities (Saldivar-Sali, 2010; Fernández *et al.*, 2013), as well as arguments from Krausmann et al. (2008), Barles (2009), Satterthwaite (2009) and Weisz and Steinberger (2010), these variables give strong indications as to the likely level of resource consumption. Table 4-8 shows the 10 resultant groupings of cities along with brief descriptions.

Table 4-8: Typology of African cities by similarity of predictor variables

Group	Members	Description of Attributes
Group 1	BO-Francistown, BO-Gaborone, LE-Maseru, NA-Walvis Bay, SA-Stellenbosch, SW-Manzini, SW-Mbabane, TU-Sousse, ZI-Gweru	This group contains very small- to small-sized cities of low density, with low population growth. The cities are in quite variable temperatures and show medium to very high incomes
Group 2	CH-Moundou, CO-Moroni, CV-Praia, EQG-Malabo, GAB-Port-Gentil, MS-Port Louis, ST-Sao Tome , SY-Victoria	This group contains very small to small cities of low density, with low population growth. The cities are in constantly hot temperatures and show medium to very high incomes
Group 3	BU-Gitega, DRC-Bandundu, KE-Kisumu, MAD-Mahajanga, MALI-Gao, MN-Nouadhibou, SE-Thies, TO-Sokode, TZ-Dodoma, ZI-Bulawayo	This group contains small cities of low density, with low population growth. The cities are in somewhat variable temperatures and show low incomes
Group 4	BF-Bobo Dioulasso, BF-Ouagadougou, GAM-Banjui, GB-Bissau, MAL-Blantyre, MAL-Lilongwe, MZ-Maputo, SS-Juba, SU-Khartoum, ZI-Harare	This group contains medium cities of low density, with medium population growth. The cities are in somewhat variable temperatures and show low incomes
Group 5	AL-Algiers, AL-Constantine, AL-Oran, DJ-Djibouti, DRC-Lubumbashi, EG-Alexandria, EG-Asyut, EG-Cairo, EG-Fayum, EG-Port Said, ER-Asmara, ETH-Addis Ababa, ETH-Mek'ele, KE-Nairobi, MAD-Antananarivo, MC-Casablanca, MC-Fes, MC-Marrakesh, MC-Tangier, SU-Nyala, ZA-Lusaka	This group contains mostly medium to large cities of medium to high density, with medium population growth. The cities are in quite variable temperatures and show low to medium incomes
Group 6	AN-Luanda, CAR-Bangui, CH-N'Djamena, LY-Tripoli, MN-Nouakchott, MZ-Nampula, NG-Benin City, NG-Ibadan, NG-Ilorin, NG-Kaduna, NG-Ogbomosho, NI-Niamey, RC-Brazzaville, RC-Pointe-Noire, RW-Kigali, TZ-Zanzibar	This group contains mostly medium or large cities of medium density, with medium population growth. The cities are in somewhat variable temperatures and show low incomes
Group 7	AN-Huambo, BU-Bujumbura, CA-Yaounde, MALI-Bamako, NG-Abuja, TZ-Dar es Salaam, TZ-Mwanza	This group contains medium to large cities of medium density, with high population growth. The cities are in somewhat variable temperatures and show low incomes
Group 8	BE-Cotonou , GAB-Libreville, GH-Accra, GH-Kumasi, GH-Sekondi-Takoradi, LI-Monrovia, TO-Lome, UG-Kampala	This group contains medium to large cities of low density, with medium to high population growth. The cities are in constantly hot temperatures and show low to medium incomes
Group 9	LY-Benghazi, MC-Kenitra, MC-Rabat, NA-Windhoek, SA-Cape Town, SA-eThekwini, SA-Johannesburg, SA-Mangaung, SA-Nelson Mandela Bay, SA-Tshwane, TU-Sfax, TU-Tunis, ZA-Kitwe, ZA-Ndola	This group contains medium to large cities of low density, with medium population growth. The cities are in quite variable temperatures and show medium to very high incomes
Group 10	BE-Porto Novo, CA-Douala, CDI-Abidjan, CDI-Yamoussoukro, DRC-Kinshasa, GU-Conakry, KE-Mombasa, NG-Kano, NG-Lagos, NG-Port Harcourt, NG-Zaria, NI-Maradi, RW-Gisenyi, SE-Dakar, SL-Freetown, SO-Hargeisa, SO-Mogadishu	This group contains medium to very large cities of high density, with medium population growth. The cities are in somewhat variable temperatures and show low incomes

Based on the typical predictor variables elucidated in the literature, the following resource profiles are expected from each group.

Group 1. With medium to very high incomes and low density, it is expected that such cities will show high fossil fuel consumption in the form of transportation, and a large proportion of electricity as energy carrier. Low population growth suggests that there will be less reliance on construction materials for building new stock. Due to climate, this group of cities is likely to spend energy on both heating and cooling.

Group 2. This group is similar to group 1, except that its climate indicators suggest it will spend more energy in cooling.

Group 3. Low incomes in small cities suggest higher reliance on biomass as the primary resource. As they are smaller cities, they may not reap large benefits of scale, so may show higher per capita consumption of materials than their larger counterparts. Variable temperatures suggest expenditure of energy on both heating and cooling.

Group 4. These cities should show a similar profile to group 3 but at slightly larger magnitude, due to larger city sizes and increased population growth.

Group 5. These cities show low to medium incomes, suggesting that fossil energy may be becoming competitive with biomass. Their mid to high density suggests that energy will be spent more on industry than transport, and very variable temperatures suggest a large proportion used for thermal regulation. Medium population growth and medium income suggests more need for construction materials for formal building developments.

Group 6. Like group 5, these cities will expend more energy on industry than transit, yet the low incomes suggest that industry is still agricultural or extractive, and yet to fully diversify. Biomass will still be the predominant resource consumed, though medium growth rates suggest the occurrence of more construction to accommodate new people, whether formally or informally.

Group 7. These cities will show the same profile as group 6, but with higher growth, they should show higher consumption of construction materials. Low incomes may mean that more informal construction is taking place.

Group 8. Low to medium incomes suggests a transition from biomass reliance to fossil fuel industry, and low density suggests large proportions of fossil fuels used in transit. However, this may be reduced by less widespread reliance on private transport. In Benin and Burkina Faso, for example, motorbikes are the predominating vehicles and minibus taxis are common in all these cities. As income increases, occurrence of more private vehicles will push up fossil fuel consumption and carbon emissions. High population growth suggests high construction needs, though this will be more pronounced in the higher income cities. Consistent heat suggests more energy expended on cooling, though this is also tied to income.

Group 9. Like group 8, these cities will expend more energy on transit, though higher incomes suggest more private transportation, so higher fossil fuel consumption. This group will likely use more construction materials too, despite only medium growth. This is because higher incomes indicate more formal types of construction. Variable temperatures and high income suggest large amounts of electricity spent on thermal regulation.

Group 10. These cities show larger high-density cities, which suggest that benefits of economic agglomeration will reduce per capita material consumption and low income means that less energy will likely be expended on transportation. These cities will show high biomass consumption and, despite high construction needs due to medium population growth, low to medium formal construction material consumption is expected. Consistent heat suggests that some energy is expended on cooling.

Very little can be predicted about water consumption. Water is a consistent requirement for human existence, so if settlements continue to exist, water is clearly consumed to some degree. Informal systems for acquiring water may not be tracked, and undermine accurate estimations of consumption. This may be more true for water abundant areas, as it would be easier to track limited supplies of water. With stronger economies, governments can invest in stronger water infrastructures. This will ensure greater water access, which may in turn lead to higher consumption, or at least, higher recorded consumption. If these infrastructures extend to water-based sanitation, the magnitude of water consumption increases more strongly. Cities in hotter climates may require more water for human needs or industrial cooling systems, such as for cooling thermal power stations.

Construction in many African cities may not follow expected patterns because in each country and city, governments and corporations are involved to very different degrees in meeting the demographic shifts and associated housing and employment needs. Many cities' governments will show active involvement, while some will leave it to corporate or informal interests, which may result in poor estimates of construction material consumption and lead to sprawling informal settlements. As construction materials are expected to be locally sourced, tracking them may still prove tricky, even where formal construction industries are involved.

4.4.4. City typology by hierarchical clustering of per-capita resource indicators

This typology of cities by resource indicator was formed using hierarchical clustering of per capita resource indicators and resulted in 10 resource profiles. Cities were clustered by levels of fossil fuel, electricity, construction material, biomass and water consumption, and carbon emissions. A limitation of the scaling technique is that cities of the same nation were placed within the same group. The scaling process meant that, while cities have different per capita consumption from others in the same nation, for the most part, their consumption levels are still quite similar. In addition, the overall resource profile is effectively the same ‘shape’ for all cities in one nation. This can be seen in Group 3 and Group 9, Nigerian cities and South African cities, respectively. Should the cities be clustered by only one or two resource indicators, cities of the same nation would be found in different clusters. This meant that this method of clustering effectively produced a national typology of urban resource consumption. It could be argued that for some cities this national grouping is appropriate. For example, the clustering of cities by socioeconomic attributes showed that all sampled South African cities, except for Stellenbosch, were more similar to each other than to others in Africa. This is an insightful clustering as the members of each group differ from the national groupings.

Table 4-9 shows the resource profiles for the 10 clusters of cities, organised by speculated progression along the socio-metabolic transition, with median total material consumption displayed. Groups 1 to 3 are deemed resource poor, groups 4 to 7 are in transition and groups 8 to 10 are resource sufficient. The red lines demonstrate the median or most typical level of consumption by members of each group. The pink area shows the range of consumption levels, which demonstrates the robustness of each group. In other words, large ranges suggest that the cities may be less similar in resource profile, such as in Group 10, than those with low ranges, such as group 3 or 9. Country abbreviations are introduced in Table 4-1.
Descriptions of each profile follows here below:

Group 1. These cities show low consumption of all materials except biomass and water. This suggests limited industry and low incomes in these cities. The range for construction materials and fossil fuels suggests that these cities are growing fast.

Group 2. This group of cities shows the same resource profile as group 1 but with low water consumption.

Group 3. This group is made up of exclusively Nigerian cities, still primarily biomass dependent, yet with medium fossil fuel consumption and medium construction materials to suggest a faster growing economy. The sheer size of these cities' populations shows low per capita magnitude, despite these cities being some of the most resource intense cities on the continent.

Group 4. These cities show medium consumption of biomass, water and electricity, and low to medium consumption of construction materials and fossil fuels, with medium-low carbon emissions. This suggests these cities re making use of electricity, most likely from hydroelectric generation.

Group 5. This group shows medium all-round energy consumption and medium consumption of construction materials, with medium-high biomass consumption and medium-low water consumption

Group 6. Like group 5, these cities show medium energy consumption, medium-high biomass consumption, yet with medium-low construction materials and medium high water consumption.

Group 7. This group shows medium consumption of biomass, electricity, fossil fuels and medium-low consumption of water and construction materials.

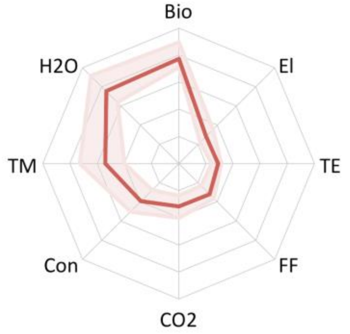
Group 8. This group is almost the same shape as the national resource group 8, and includes cities from the same countries, with the addition of Senegalese cities. It shows medium-low to medium consumption of biomass, medium to medium-high electricity consumption, medium fossil fuel, medium to medium-high construction material, and medium-high water consumption.

Group 9. This group is made up of South African cities, which show medium to medium-high biomass consumption, high electricity consumption, medium to medium-high fossil fuel consumption, medium-high carbon emissions, due to coal produced electricity and abundant private transport in less dense cities, medium to medium-high construction materials and medium to medium-high water consumption.

Group 10. This group is made up of outliers who, between them all, account for the largest consumption of all resources. Swazi cities show the highest consumption of water and biomass, Victoria, in Seychelles, consumes the most energy, and Malabo, in Equatorial Guinea, consumes the most construction materials.

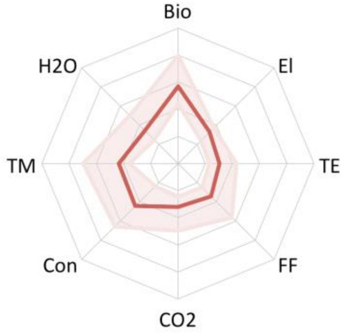
Table 4-9: Typology of African cities, produced using hierarchical clustering of resource indicators per capita

Group 1: 4.9 ton per cap



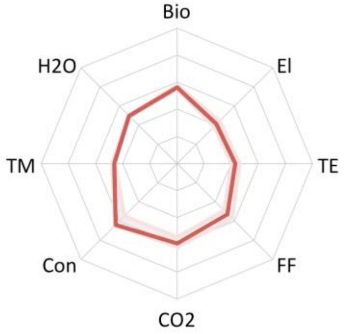
GB-Bissau, GU-Conakry, MAD-Antananarivo, MAD-Mahajanga, MALI-Bamako, MALI-Gao, NI-Maradi, NI-Niamey, SL-Freetown, SO-Hargeisa, SO-Mogadishu

Group 2: 3.5 ton per cap



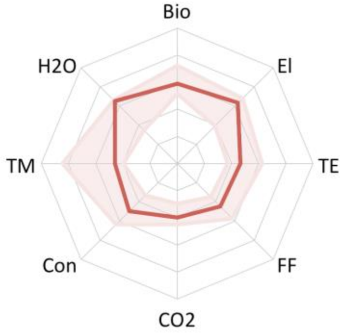
BF-Bobo Dioulasso, BF-Ouagadougou, BU-Bujumbura, BU-Gitega, CAR-Bangui, CH-Moundou, CH-N'Djamena, CO-Moroni, DRC-Bandundu, DRC-Kinshasa, DRC-Lubumbashi, ETH-Addis Ababa, ETH-Mek'ele, GAM-Banjui, LI-Monrovia, RW-Gisenyi, RW-Kigali, TO-Lome, TO-Sokode

Group 3: 3.9 ton per cap



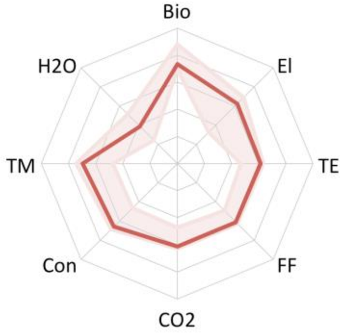
NG-Abuja, NG-Benin City, NG-Ibadan, NG-Ilorin, NG-Kaduna, NG-Kano, NG-Lagos, NG-Ogbomosho, NG-Port Harcourt, NG-Zaria

Group 4: 3.8 ton per cap



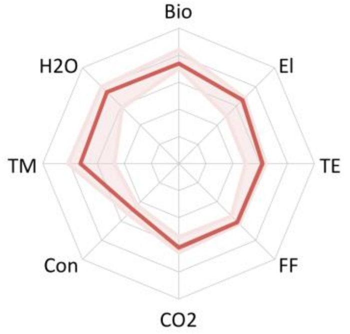
CDI-Abidjan, CDI-Yamoussoukro, ER-Asmara, MAL-Blantyre, MAL-Lilongwe, MZ-Maputo, MZ-Nampula, TZ-Dar es Salaam, TZ-Dodoma, TZ-Mwanza, TZ-Zanzibar, ZA-Kitwe, ZA-Lusaka, ZA-Ndola

Group 5: 6.2 ton per cap



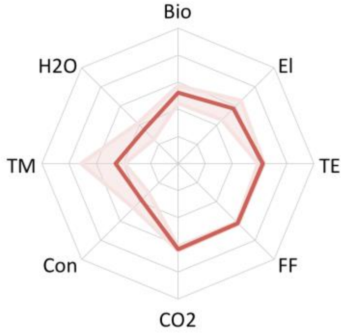
BE-Cotonou , BE-Porto Novo, CA-Douala, CA-Yaounde, DJ-Djibouti, GH-Accra, GH-Kumasi, GH-Sekondi-Takoradi, KE-Kisumu, KE-Mombasa, KE-Nairobi, LE-Maseru, SS-Juba, SU-Khartoum, SU-Nyala, UG-Kampala

Group 6: 7.9 ton per cap



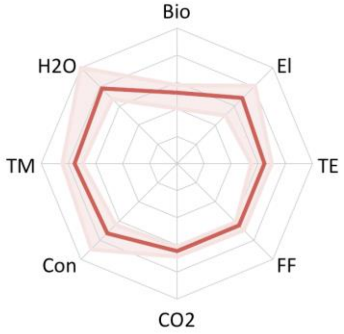
GAB-Libreville, GAB-Port-Gentil, MN-Nouadhibou, MN-Nouakchott, ZI-Bulawayo, ZI-Gweru, ZI-Harare

Group 7: 3.8 ton per cap



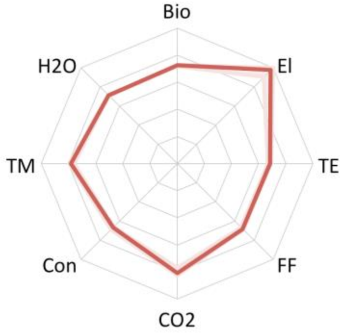
AN-Huambo, AN-Luanda, CV-Praia, RC-Brazzaville, RC-Pointe-Noire, ST-Sao Tome

Group 8: 9.7 ton per cap



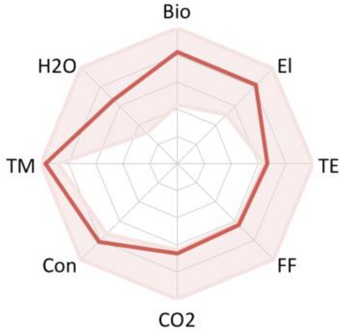
AL-Algiers, AL-Constantine, AL-Oran, EG-Alexandria, EG-Asyut, EG-Cairo, EG-Fayum, EG-Port Said, LY-Benghazi, LY-Tripoli, MC-Casablanca, MC-Fes, MC-Kenitra, MC-Marrakesh, MC-Rabat, MC-Tangier, SE-Dakar, SE-Thies, TU-Sfax, TU-Sousse, TU-Tunis

Group 9: 11.6 ton per cap



SA-Cape Town, SA-eThekwini, SA-Johannesburg, SA-Mangaung, SA-Nelson Mandela Bay, SA-Stellenbosch, SA-Tshwane

Group 10: 23.2 ton per cap



BO-Francistown, BO-Gaborone, EQG-Malabo, MS-Port Louis, NA-Walvis Bay, NA-Windhoek, SW-Manzini, SW-Mbabane, SY-Victoria

4.4.5. City typology by hierarchical clustering of per-unit-GDP resource indicators

One hundred and twenty (120) cities were again clustered using hierarchical clustering of the same variables as in Section 4.4.4. However, while the previous typology demonstrated the relative resource impacts of a city's population, this one demonstrates the resource intensity of a city's economy. The resource profiles are visualised in Appendix 0 and show the level of resource intensity per-unit-GDP.

The resource profiles are organised from lowest to highest energy intensity of GDP, based on the global metabolic transition concept (Krausmann *et al.*, 2008), in which high energy consumption is indicative of more service oriented industries, while lower energy intensity is indicative of primary or secondary sector, and high material intensity is more indicative of primary sector activities. However, as GDP grows, it may take less consumption to produce more, as already witnessed in resource decoupling (Robinson *et al.*, 2012). Thus, these profiles could show either the intensity or efficiency of each resource indicator.

In this typology, two cities deviate from others in the same nation. These are Dar es Salaam, in group 5 and Khartoum, in group 4. The other cities from Tanzania and Sudan are in group 7. This suggests that the larger cities have greater resource efficiency as they produce larger proportions of GDP from less consumption. This is encouraging as a result, and is why a more effective scaling method, which better differentiates cities, is needed. As urban GDP was estimated in this study using population, among other variables, it is still a function of population. Thus, normalising data that was scaled using population size by GDP still produces similar values. Raw GDP data would circumvent this issue, and show a more diverse mix of same-nation cities per group.

Utilising a per-unit-GDP measure may be a more appropriate way to understand resource consumption, especially as resource decoupling is a desirable outcome. However, a dual typology, which compares the resource intensity of the population as a whole, and the resource intensity of the economy, showing how resources are concentrated in each city, is recommended. As an initial exploration, Figure 4-22 compares resource profiles normalised by per-capita and per-unit-GDP measures. The overall shape of the profiles demonstrates which resources are more important for the population and which are more important for economic production. Biomass and water seem most important for the population, with construction materials becoming more important within an affluent city, such as Johannesburg. A more directed investigation as to the sector-specific consumption of each resource would be useful for qualifying such profiles.

Monrovia's economy is shown to be more resource intense or less resource efficient than its population. The city's population makes more use of biomass and water than the other resources, while the economy shows medium to medium-high consumption of all resources, tending to be slightly more materially intense than energy intense. Dar es Salaam shows similar resource intensity per capita and per-unit-GDP, except for more biomass consumption per capita and more consumption of total materials per-unit-GDP. Johannesburg shows higher intensity per capita for electricity, biomass, water and construction material consumption and almost equal intensities for energy indicators.

The differences in resource intensity between population and economy may indicate the affluence of the city, essentially based on the share of economic production enjoyed by the population. It may also indicate the level of inequality within the population. For example, it could be speculated that if lower intensity is shown by the population, as with Monrovia, then either the economy is not particularly strong, or few people are participating in it. This may represent differences between formal and informal economy activities. The difference between CO2 intensities could suggest that the city demonstrates exclusive urbanisation, in which, on average, the population consumes few goods, while an elite few consume at high levels. This is in concord with the observed levels of poverty and estimated incomes of Liberia. The similarity of shape for Dar es Salaam might suggest an equally involved population in economic production. Johannesburg's profile, showing typically higher resource intensity for the population for than for the economy, could suggest that biomass, water, construction materials and electricity are more strongly related to the needs of the population and that Johannesburg's economy has decoupled from these resources. The energy intensity suggests a tertiary sector economy. High CO2 suggests high consumption by the population. However, this does not suggest that inequality may not exist in these spaces. This one again shows the limitation of using averaged data to describe a whole city.

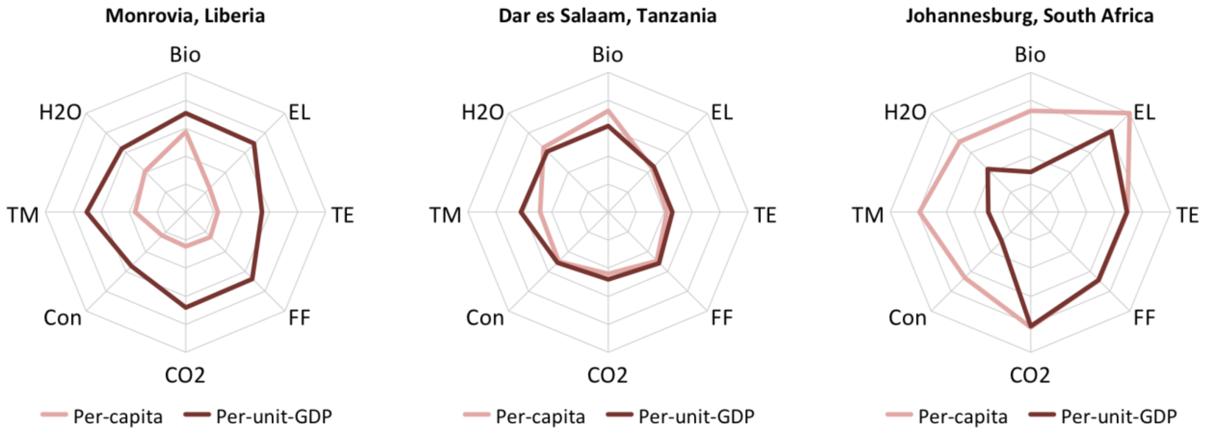
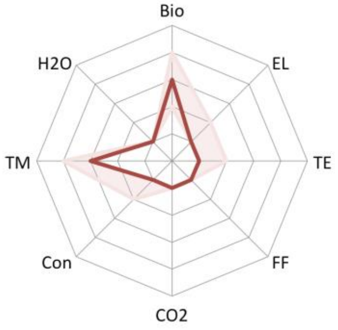


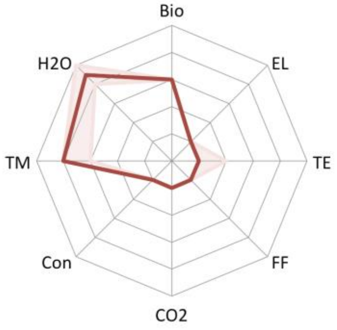
Figure 4-22: Comparison of per-capita and per-unit-GDP resource intensity for three cities

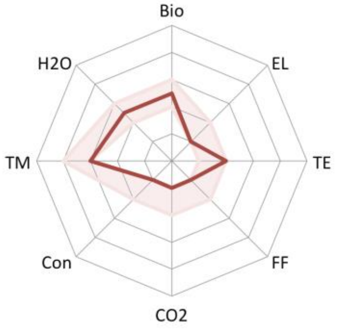
4.4.6. City typology using classification trees

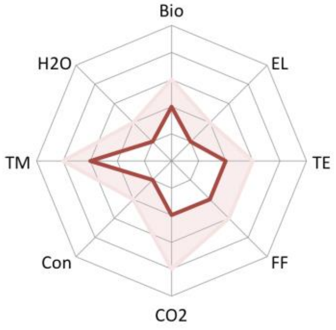
This method assigned a resource class of 1 through 5 to the resource variables of the largest city in each country, 1 being low and 5 being high. The resource indicators used were consumption of total materials, fossil fuels, electricity, biomass, construction materials and water, and carbon emissions. Industrial materials were excluded from this typology to enable comparison with other typologies, but, as this was a qualitative analysis, it could be included. A version of this typology was completed with industrial minerals, and is in Appendix 6.4. Classification trees were built from 54 cities, using these designations and the four independent variables of population, population density, climate, and income. The levels of resource consumption or emission for the remaining 66 cities were determined using the resultant decision trees. The resulting resource profiles were then clustered using hierarchical clustering. This produced 13 distinct groups, shown in Table 4-10. The table shows the group’s resource profile, city members and a box-plot of the relative levels of population size, population density, heating degree days, cooling degree days, per capita GDP and population growth. These levels provide insights into the cause of city groupings.

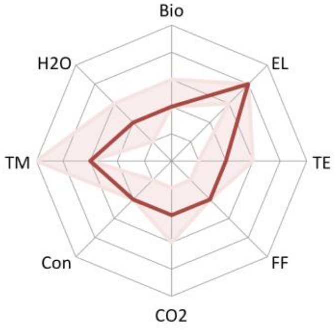
Table 4-10: Typology of African cities, produced using classification trees and resource indicators per capita



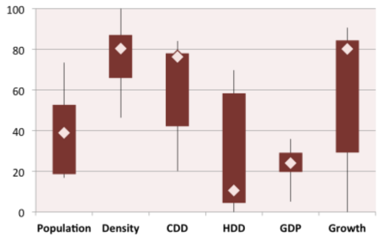


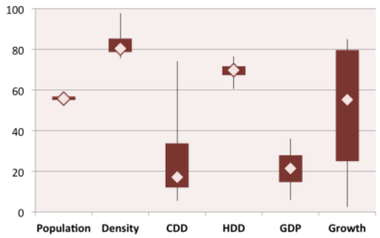


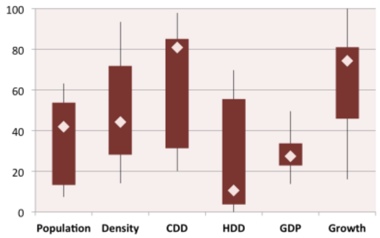


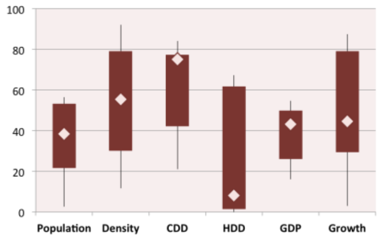


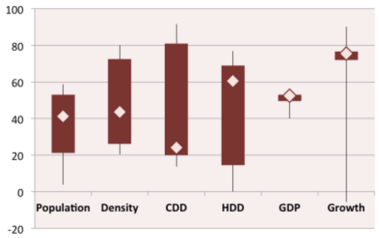
Group 1	Group 2	Group 3	Group 4	Group 5
BE-Porto Novo BU-Bujumbura CDI-Yamoussoukro DRC-Kinshasa ETH-Mek'ele LI-Monrovia MZ-Nampula NG-Ogbomosho NI-Maradi SL-Freetown SO-Hargeisa TZ-Zanzibar	DRC-Lubumbashi ETH-Addis Ababa MAD-Antananarivo SO-Mogadishu	BF-Bobo Dioulasso BF-Ouagadougou CA-Douala CAR-Bangui CDI-Abidjan ER-Asmara GB-Bissau GU-Conakry MAD-Mahajanga MAL-Blantyre MALI-Bamako MALI-Gao MN-Nouadhibou MZ-Maputo NI-Niamey RW-Gisenyi SE-Thies TZ-Dodoma TZ-Mwanza ZI-Gweru	BE-Cotonou BU-Gitega CA-Yaounde DJ-Djibouti EG-Asyut EG-Fayum GAM-Banjui MAL-Lilongwe NG-Port Harcourt RC-Brazzaville ST-Sao Tome TO-Lome	CH-Moundou CH-N'Djamena CO-Moroni GH-Sekondi-Takoradi KE-Nairobi MC-Tangier RW-Kigali ZA-Kitwe ZA-Lusaka ZA-Ndola ZI-Bulawayo



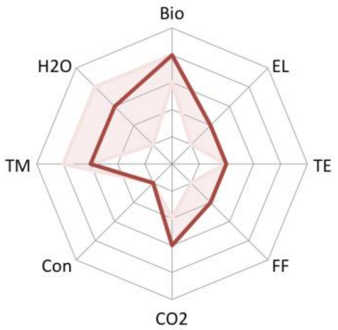




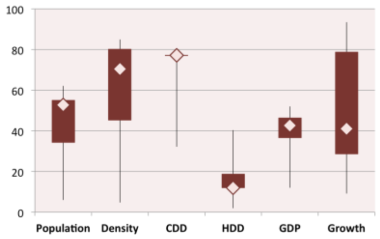




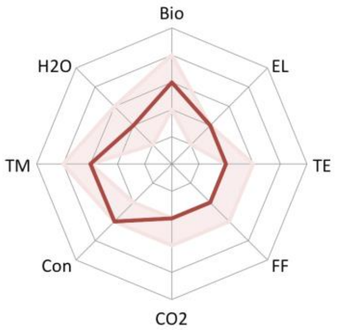
Group 6



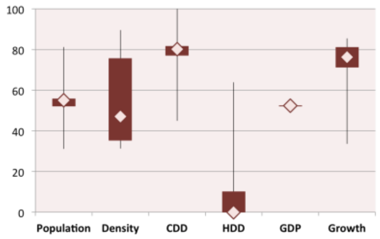
DRC-Bandundu
KE-Kisumu
MN-Nouakchott
NG-Abuja
NG-Benin City
NG-Ibadan
NG-Ilorin
NG-Kaduna
NG-Zaria
TO-Sokode
TZ-Dar es Salaam



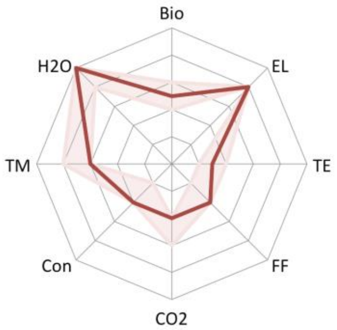
Group 7



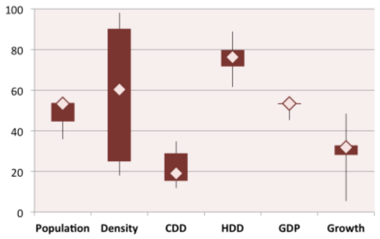
GH-Accra
GH-Kumasi
KE-Mombasa
NG-Lagos
RC-Pointe-Noire
SS-Juba
SU-Khartoum
SU-Nyala
UG-Kampala



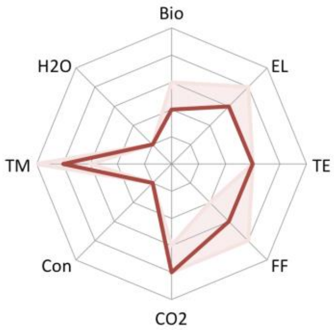
Group 8



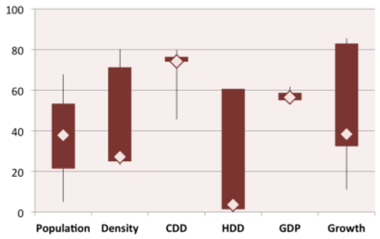
EG-Port Said
MC-Fes
MC-Kenitra
MC-Marrakesh
MC-Rabat
ZI-Harare



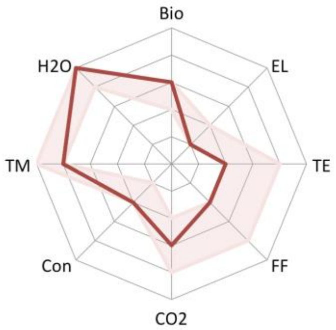
Group 9



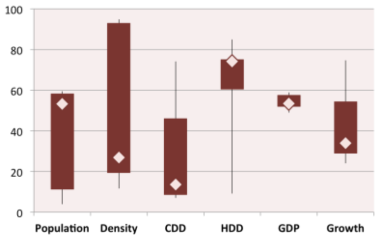
AN-Huambo
AN-Luanda
CV-Praia
GAB-Libreville
GAB-Port-Gentil
LY-Benghazi
LY-Tripoli



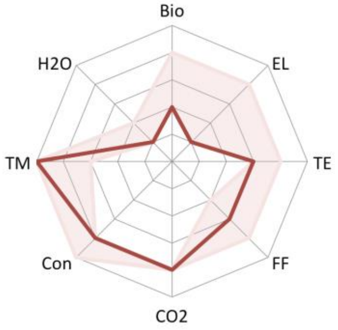
Group 10



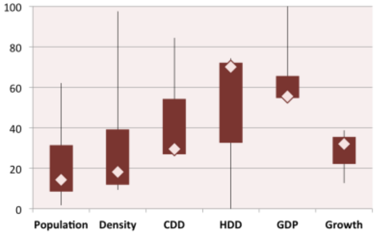
LE-Maseru
NA-Walvis Bay
NG-Kano
SA-Nelson Mandela Bay
SE-Dakar



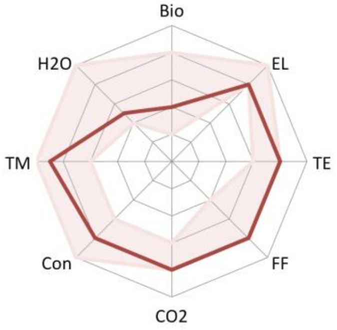
Group 11



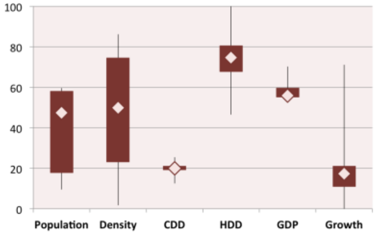
BO-Gaborone
EG-Alexandria
EQG-Malabo
SY-Victoria
TU-Sfax
TU-Sousse
TU-Tunis



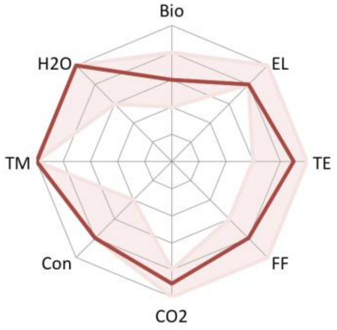
Group 12



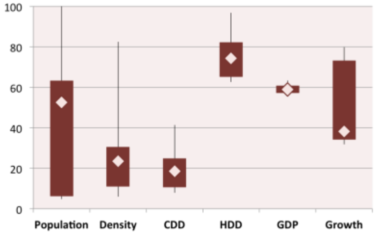
AL-Algiers
AL-Constantine
AL-Oran
MC-Casablanca
MS-Port Louis
NA-Windhoek
SA-eThekwini
SA-Stellenbosch



Group 13



BO-Francistown
EG-Cairo
SA-Cape Town
SA-Johannesburg
SA-Mangaung
SA-Tshwane
SW-Manzini
SW-Mbabane



Notably, cities from the same nation were found in separate groups. For example, Dar es Salaam, Zanzibar, and Dodoma and Mwanza are in different groups, displaying variations in consumption of biomass, construction materials and water, and carbon emissions. A positive outcome is that even if cities are in different groups from their nation's largest cities, those used to form training trees, large cities are also in groups with other members of their nation, as with Johannesburg in South Africa, Accra in Ghana and Lusaka in Zambia. This suggests the method is robust, and simply requires confirmation of whether the initial sample size was large or diverse enough to ensure proper sorting of the remaining cities. The use of classification trees means that errors in sorting cities are expected, and that analysis of this method must question membership of each city while still attempting to understand the resource profile. This is a difficult task for a researcher whose knowledge about each city will be easily exceeded by the everyday experiences of the people actually living there. As part of future work, further quantitative and qualitative investigation into each city would be invaluable to validating this method.

Speculation as to the member's participation in this group will follow a brief description:

Group 1. These cities show medium consumption of biomass and low consumption of each other resource. These cities are still heavily in the agrarian regime. This is further supported by relatively low incomes. It is curious to see Kinshasa in this group. Despite being a city with large aggregate resource impact, its large population lowers its per capita resource intensity.

Group 2. This group of cities also has biomass as its primary resource, at medium consumption. Medium-high total material consumption suggests that industrial minerals are consumed in a moderate way in these cities.

Group 3. This group has medium consumption of biomass, water and total materials. It shows medium-low energy consumption, which is concordant with lower density and slightly higher income than groups 1 and 2.

Group 4. These cities show medium-low biomass consumption and medium-low fossil fuel consumption, suggesting more industry occurring in these cities. Low electricity consumption suggests that fossil energy is primarily in industry and minimally in electricity generation. Only medium density and medium-low CO2 emissions suggests a decent proportion of fossil fuels used in transit.

Group 5. This group shows medium-low biomass consumption, medium-high electricity consumption, though medium-low fossil fuel consumption, suggesting this electricity is either imported or generated predominantly from renewable sources.

Zambia, Ghana and Malawi show high proportions of hydroelectric electricity generation. This higher electricity consumption may indicate a burgeoning manufacturing or services industry. Curiously, Secondi-Takoradi, a secondary city in Ghana shows higher electricity consumption than Accra and Kumasi (Group 7). This could be due to a smaller population skewing a per capita measure, or due to a high energy timber and technology industries in these spaces, while Kumasi and Accra are administrative and manufacturing cities. Medium-low construction material consumption is concurrent with a median high growth rate and middle income.

Group 6. This group of cities shows medium-high biomass consumption, which may relate to modest urban agriculture, fishing or forestry industry operating in the city. Medium-low electricity and fossil fuel consumption, with medium carbon emissions suggests moderate energy spent on transit and the presence of strong manufacturing industries. Low construction material consumption fits with a median medium population growth rate and medium-low income level. Medium levels of water consumption suggest a reliance on thermal electricity generation or reflect the needs of water in hotter climates.

Group 7. These cities show medium-high biomass consumption, again indicating strong primary industry. This is interesting, given that this group contains mostly medium- to large-sized cities, and less agriculture would be expected. The energy profile is similar to group 6, except with only medium-low carbon emissions. This is curious, as the cities are less dense than those in group 6, so more emissions from transit would be expected. However group 7’s slightly higher incomes may account for more administrative and service activities taking place in these cities. The energy profile shows medium-low consumption of electricity and fossil fuels, with a range of medium-low to medium for fossil fuels and carbon emissions, which corroborate the cities’ medium density and medium-high income. Medium construction material consumption agrees with a high growth rate and medium incomes. These cities show a range of water consumption levels, with a median at medium-low.

Group 8. This group shows medium-low to medium biomass consumption, possibly due to being in mostly arid locations. The energy profile shows medium-high electricity consumption with medium-low fossil fuel and carbon emissions, suggesting strong service economies with electricity generated elsewhere and imported.

Medium-low growth and medium income accounts for medium-low construction material consumption. High water consumption may be due to greater water demand in arid or temperate climate.

Group 9. This group shows medium-low biomass consumption, medium electricity and fossil fuel consumption, and high carbon dioxide emissions. In addition, total material consumption is medium-high, but construction material consumption is low. This all relates with oil and mining dominating the economy of medium-high GDP. Low water consumption is curious as, except for Libyan cities, these cities are in water rich areas. A predominant oil economy could mean that funds have not yet been expended on service delivery to the local populace. Praia, Cape Verde is an exception to this group. A large trade, transport and service economy explains the electricity use and may account for the carbon emissions.

Group 10. This group contains small- to medium-sized cities with medium biomass consumption, low electricity consumption, low fossil fuel reliance and medium-low carbon emissions. This, in concordance with medium income suggests biomass extraction and processing industries, with low energy intensity secondary sector activities. This is supported by medium-high total material consumption and medium-low construction materials, which show that other materials are being used to a large degree. High water consumption may link to temperate cities' need. Nelson Mandela Bay may fit the economic profile described, but it is likely out of place in this group, as it will enjoy high electricity consumption through South Africa's national grid. It may fit better in group 5 or 13, depending on its level of water consumption.

Group 11. These cities show medium-low biomass consumption, low electricity consumption, with medium fossil fuel consumption and medium-high carbon emissions. This relates to large secondary sector activities. The range of electricity consumption suggests some cities have a larger tertiary sector. For example, Victoria, Seychelles, is mostly service industry. High total material and medium-high construction material consumption is related to the mid-to high incomes and indicates some industrial mineral consumption in those cities. Overall, the group shows low water consumption.

Group 12. This group shows medium-high electricity and fossil fuel consumption, and medium-high carbon emissions, indicate large energy sectors, high transportation emissions and large industry. Large incomes show medium-high construction material consumption to address low to medium population growth. This suggests more institutional participation in construction. These cities show medium-low biomass and water consumption, perhaps due to arid location.

Group 13. These cities are similar to those of Group 12, but show but show high water consumption and total material consumption, with slightly more energy use and resultant carbon emissions than Group 12.

Group 1 and 2 are similar in profile except for water consumption which is higher for cities in temperate climates than for those in equatorial ones. Groups 1 and 3 show a range of construction materials which may relate to higher growth rates in some cities. Groups 10 to 13 show large ranges for some resources, which suggest a less than uniform city type. Consternation may be voiced in grouping these outwardly-different cities. However, these are the most similar when compared to the rest of the continent's cities. It may be more appropriate to isolate the outliers by their unique resource profiles, than to group them.

In comparing methods, it is interesting to note that the largest cities of each nation will show the same resource profile as it did when clustered hierarchically. This is because they were used to build the training set. This method has allowed the smaller cities to deviate from the resource shape of the larger city, instead of being scaled versions of the same shape.

4.5. Determinants of variable importance – objective 5

As the clusters were analysed, qualitative links were drawn between socioeconomic and climate attributes to suggest what the causes or outcomes of resource consumption in cities may be. Connections were then isolated in a systematic manner, using the outcomes of classification trees building to show the relative importance of independent variables in predicting the dependent variable. Table 4-11 shows the outcome for cities when building the classification trees using the largest cities of each country.

Table 4-11: Relative importance of independent variables in predicting levels of resource intensity

Resource consumption	**Independent Variables**						
	Population	*Density*	*Climate Zone*	*CDD*	*HDD*	*GDP per capita*	*Total*
Total energy (TE)	15	23	5	12	15	29	99
Electricity (EL)	12	21	2	17	13	34	99
Fossil fuel (FF)	15	16	9	13	18	29	100
Carbon emissions (CO_2)	23	19	3	13	10	31	99
Biomass (Bio)	23	20	6	18	19	14	100
Construction materials (Con)	20	19	4	12	16	30	101
Industrial Minerals and Ores (Ind)	39	17	12	17	-	15	99
Total materials (TM)	16	20	5	19	11	30	101
Water (H_2O)	24	12	6	14	21	22	99
Average Importance	**20.8**	**18.6**	**5.8**	**15**	**15.4**	**26**	**99.8**

As expected, per capita GDP was identified as the strongest predictor of energy consumption and resultant carbon emissions. Population density was the second most important variable in predicting energy consumption. For electricity consumption higher electricity access due to ease of infrastructure provision to dense areas might lead to higher consumption. Fossil fuel consumption may be reliant on transport distances. Population was the second most important indicator for carbon emissions, followed closely by density. This is suggestive of consistent human needs playing a role in carbon intensity.

Per capita GDP was also the strongest predictor of construction material consumption and total material consumption. Population was the next strongest predictor for construction materials, followed closely by density. This may be related to construction as a need for an expanding population, and density suggesting benefits of agglomeration reducing the amount of material need to build infrastructures or dense buildings.

Population was the key predictor of biomass consumption and water consumption, which agrees with the literature findings that they are tied to everyday human needs. Levels of biomass consumption were predicted next by density and climate indicators, with affluence the least important indicator. Density may determine the level of access, while climate indicators refer to the country's ability to grow crops or forest. The second strongest predictor of water consumption was per capita GDP, which may relate to the costs involved in improving water quality and distribution. It also demonstrates the degree of propagation of water based sanitation systems, which improve with affluence. Climate was next most important, though this indication does not give insight into why some arid countries demonstrate higher per capita consumption than water rich countries.

Curiously population was also the key predictor for Industrial Minerals and Ores. This may indicate the types of city sizes which have predominant industry. More likely it was an artifact of limited data. Distributing the same urban average consumption of industrial minerals to all cities in a nation incorrectly suggests homogenous levels of industry in all cities. As industry is tied to economic production, industrial minerals were expected to show stronger relationships with urban GDP.

4.6. Summary of findings

Comparing the aggreage and per capita resource intensity of cities offers insights into the priorities of improved efficiency or improved access to resources between cities. Cities of the northern and southern region demonstrate the largest resource intensity, though these are growing very slowly. The fastest growing cities do not yet show high resource intensity.

Identified linear trends between GDP and resource consumption allowed the estimation of city-level data for consumption of electricity, fossil fuels, construction materials, biomass and water and emissions of carbon dioxide. The inconsistent corroboration of scaled-data and limited raw data demonstrates the challenge of arriving at a generalised scaling technique for multiple cities. Limited data for industrial minerals and ores resulted in its exclusion from the typologies.

An indicator of urban primacy was developed and nations were classed by their distribution of urban settlements and population. 14 nations show high urban primacy with no other cities which immediately lend themselves as alternatives for development. 14 nations demonstrated very distributed urban populations and multiple key settlements. The remaining 25 cities showed a range of distributions. While showing no relationship with resource consumption, urban primacy, indicative of centralised governance, may be useful in understanding resource access, via the quality of service delivery.

Two methods for determining urban income were completed. The method making use of relative poverty was flawed as it required more specific monetary thresholds for delineating relative poverty within each country. It also could not distinguish between affluent populations in rural or urban spaces. The second method, making use of urban economic activity, was chosen for use in this study. It demonstrated larger average urban incomes than average national incomes and showed that urban spaces were between 14 and 4,562 times more productive than rural spaces, depending on the country.

Various relationships between socio-economic and resource indicators were explored, verifying the correlation between urbanisation, HDI, GDP and energy consumption. Inequality remains difficult to examine when utilising a single averaged observation to understand nations or cities. Key observations for African cities are below:

- Climate may not be as strong a contributor to energy consumption in most African cities, as with other international cities, due to typically stable temperatures and questionable distribution of energy-intensive thermal regulation technologies.
- Equatorial-region cities tended to be slightly more dense than arid-region cities which tended to be denser than temperate-region cities.
- Carbon emissions associated with the density of cities are also a function of affluence. Low-density, low affluent cities produce minimal carbon emissions, despite larger distances to travel. This may be related to the higher utilisation of public (or non-motorised) rather than private transportation in less affluent cities.
- Access to electricity increased with population density
- Access to water showed no clear correlation to population density
- Cities which demonstrated higher access to water and to electricity demonstrated higher consumption of both.

National clusters were developed by socioeconomic indicators and by resource indicators. These typologies served as a baseline for what might be expected from city level resource intensity, before four stages of clustering were completed for cities:

- First, the cities were grouped by predictor variables to allow speculation as to what would be expected in terms of their resource consumption. This produced groupings with members of different countries in different groups, though levels of resource consumption were all speculative.

- Secondly, they were clustered using quantitative per-capita resource consumption data scaled directly from national level. This may be the best clustering method, yet it was undermined by data which was not differentiated enough in the scaling method. This resulted in cities of the same nation remaining in the same resource profile groups.
- Thirdly cities were clustered using the same method, but utilising resource data normalised by per-unit-GDP. While the previous typology showed the resource intensity of cities' populations, this type of normalisation essentially allowed the comparison between the resource intensity of the cities' economies. As GDP was estimated by using population, among other indicators, its usefulness as normalising agent for this study is questionable. This typology may be utilised best in tandem with the per-capita normalised typology.
- Finally cities were clustered using a sample of one city per country to predict what resource consumption might be expected from cities based on their socioeconomic predictor variables. This showed a distribution of same-nation cities through multiple groups, a few of which may be errors in sorting by classification trees, but many of which might more accurately depict differences in consumption, especially given how urban primacy shifts priorities of service delivery to key cities. It is certainly the most useful typology for encouraging further exploration.

Assessing the importance of four variables in predicting resource consumption showed that GDP was the most important predictor of fossil fuel consumption, electricity consumption, carbon emissions, and construction material consumption. Population and density were the most important predictors of biomass consumption. Population was the strongest predictor of water consumption and industrial mineral consumption. However, it is speculated that due to 'used extraction' only showing a proportion of industrial mineral consumption, this outcome may likely have been an error.

Chapter 5 concludes this study and offers limitations and recommendations for future research.

Chapter 5: Conclusion

This study has presented insights into the benefit of examining the urban metabolism of cities to inform their growth and the allocation of their resource flows. It has suggested how African cities might be understood in similar ways and differentially, with some insights as to how urban metabolism studies may need to adapt their methods to encompass situations unique to contexts in cities of the global south and in Africa.

While the primary objective of this study was to produce a resource flow typology of African cities, limitations in data access transformed the work into an exploration of the ways a resource consumption typology could be generated using limited data. The sub-objectives of this study were:

1. To identify and select representative cities for investigation that captures relevant attributes, such as demography, region, climate zone, income, poverty level, or function
2. To demonstrate the scope of available resource consumption and socioeconomic data for selected African cities
3. To establish and use robust statistical methods to estimate city-level data
4. To group cities appropriately utilising available raw and estimated data
5. To determine the predictor variables which influence resource consumption

The achievement of these sub-objectives, within the scope of the study, was demonstrated in the development of a method and the production of results, as summarized in Chapter 3, Section 3.2 and Chapter 4, Section 4.5, respectively. To conclude this study, it may be apt to refer to the challenges in undertaking urban metabolism studies, particularly given data-scarcity and lack of standardized methods for analysis, and to the need for and limitations of a typology. This section offers a summary of key findings of the study, a discussion of limitations, and suggestions for future work.

5.1. Key findings

The literature speaks of great demographic shifts taking place in African urban settlements, of the importance in shaping infrastructures to guide efficient and equitable delivery of resources, and of the limitations faced by African city governments, both in terms of environmental protection constraints and social upliftment imperatives. However, the literature tends to reference Africa as a whole, and there are minimal studies of resource flows or infrastructure at the city-level.

Scientific studies into Africa each tell different stories, which propagate misunderstandings of urban systems or urban development on the continent. Those which differentiate between regions, countries or cities within the continent may offer more useful perspectives and recommendations for city governments to utilises. Something overlooked in the literature review was the repeated statistic that Africa is 40 per cent urban. While this may be true, the form of urban Africa becomes clearer when learning that only the Eastern Region shows an urban proportion less than 40 per cent, and that there are 17 countries over 50 per cent urban, 11 of which are over 60 per cent urban. Thus, a key recommendation of this study is the disaggregation of ‘urban Africa’ in future studies, referencing either smaller regions or types of city. While generalizations are useful and often necessary for far-reaching impact, they should be couched in something more meaningful than geographic association, such as socioeconomic similarities. In this way, the tool of a typology is highly useful for making nuanced scientific contributions.

The lack of focused studies relates, among other things, to the lack of city-level data required to undertake urban metabolism analysis. To address this, the typology was identified as a useful tool for categorizing cities, with minimal data. The typology was formed out of a need to (i) examine the global impact of cities, (ii) understand future urban growth and consumption trends, and (iii) determine the efficacy of sustainability initiatives. It also demands less research time and funding than individual city analysis and allows the comparison of cities’ relative consumption. These first two points are demonstrated simply in Chapter 4, Section 4.1. This study has not spoken to the third point, leverage points for sustainability. A greater focus was places on the process of typology building. The typologies resulting from this study form the basis for further investigation of a more statistically robust and informative typology which will be completed and validated as part of future work. With a robust typology, further study will identify current and future impact of each city type, as well as proffer specific initiatives which may reduce this impact, and address the resource needs of the people and economy of each city. Efforts to complete a typology show that there is still too limited data to form strong enough assertions about individual African cities based on secondary data. The typology's usefulness as a time- and fund-saving tool thus becomes limited and it is vital to validate the typology with locally sourced data. This is a necessary step before the typology could be utilised in decision-making.

A consistent observation in each resulting typology was that the groups demonstrated different levels of socio-metabolic transition. As GDP increased, the shape of resource profile shifted from biomass intensive to fossil fuel intensive. Biomass consumption remains high, as it is a primary human need, but fossil fuel consumption increases to a higher level. Construction material consumption also increases with GDP with influence from population growth. Water consumption varied by group, and it is still unclear as to its main driver. From the literature and clustering process, some attributes of each resource indicator are offered here:

- Biomass is an area-dependent resource (Krausmann et al., 2008), the majority of which is likely to be locally sourced. Thus ‘used extraction’ likely provides a decent proxy for consumption. Distinguishing between biomass that is used for food and household energy and biomass used for industry may give insights into the stage of development of a city.
- Fossil fuel consumption is tied to economic production and transport fuel (Creutzig et al., 2015). The predominance of public para-transit in low-income cities explains lower fossil fuel consumption. Increases in fossil fuel consumption are expected with increased private transportation and economic production.
- Electricity consumption is present to some degree in all African countries, but due to national grids, it is difficult to determine which cities use more or less. It may be presumed that more emphasis is given to larger cities as minimal infrastructure can reach more people. Increased density of cities has demonstrated greater electricity access, which in turn tends to show higher levels of consumption. The level of consumption overlooks consistency of electricity delivery, and many cities experience a form of load-shedding or electricity rationing.
- Construction material consumption may not follow the expected patterns of population growth, as use of construction materials are more strongly linked to wealth. This is

because they are defined using formal building materials, which overlook that the demographic shift will lead to larger slum development, which makes use of construction materials attained informally. This means that they are less well tracked, and this examination may have overlooked a large magnitude of construction materials used in informal building. Construction materials are most likely locally sourced, leading to different building forms in different cities. Thus examination of typical building types and quantity of materials required per site give insight into construction materials consumed.

- Industrial mineral consumption, unlike biomass consumption, may not be entirely locally sourced and not be fully represented by ‘used extraction,’ due to the nature of the global economy. From available data, only a few countries show relatively high use of industrial mineral, and it is typically low throughout African countries, concurring with the manifestation of primarily extractive industries throughout the continent. Industry is likely focused in key cities within each nation. Thus some qualitative information may go a long way to estimating industrial mineral consumption in cities.
- Observation suggests that water consumption tends to be higher in more water scarce areas, either because it is easier to track water, or because it is a more essential resource in hotter or dryer spaces. Density of the city is not a strong a determinant of water access, likely due to the existence informal or decentralised water delivery systems. Like electricity, increased consumption tends to concur with increased access.
- Carbon dioxide emissions have been stated to be a proxy for consumption (Satterthwaite, 2009), yet the origin of these emissions is not necessarily within the city. This relates to a larger question of responsibility, as many consumers of carbon-intense goods are in cities, and whether carbon emissions should be attributed to the city. A definition of a city, which includes external activities (such as air travel or industries in rural spaces) as part of city function and responsibility would allow city practitioners to take stronger steps towards carbon mitigation.

Through all the typologies, the primary outcome is that there are effectively four types of African city: resource poor, resource deficient but on the cusp of transition from biomass predominant to fossil fuel reliant economy, resource sufficient, and resource affluent. Each group shows different levels of resource intensity, though it should be noted that most of the cities showing resource affluence also have high inequality, so their membership in this group may be questionable. Inclusion of a socioeconomic indicator in the clustering process may allow better delineation of these categories.

5.2. Limitations

Operating in a data-scarce environment shapes one's attitude towards data. The data-collection process was marked with great enthusiasm when new data were found, but also presented difficulty in properly scrutinising the origin, consistency and accuracy of said data. This is because there were minimal other datasets available for validation. The quality of data therefore become of secondary concern in comparison to the actual presence of data. In presenting the results of work in data-scarce areas, a data rating system, such as the one adapted by Hoekman (2015), may prove of use. Such a rating system would allow the utilisation of data with a clear indication as to its limits and how that affects study results. Making use of scaling techniques which are reliant on population size and estimates of GDP based on population variables meant that differentiation between per capita resource indicators was limited. Therefore distinctions between cities of the same nation were not that profound, and they were typically grouped together. Alternative scaling techniques would remedy this.

In data analysis, the study faced a challenge in assessing aggregated data, and making assertions about large city systems by means of averaged observations. This is particularly unfortunate as inequality experienced in many African cities greatly affects understanding of where resource consumption takes place, and by whom resources are consumed. In defining a useful role for urban metabolism studies in informing city governors, measures of spatial and economic inequality are vital to include. Thus a clearer picture of resource flows and consumption can be made.

The typologies in this study remain a comparison of African cities only. This has allowed clearer scrutiny of the types of African cities at present. However, the resource profiles in this form are not comparable other cities globally. Thus clustering cities not by relative magnitude of the resources consumed (as in clustering pathway A and C – see Section 3.2), but by the resources' proportion of use within the city (as in pathway B) would lend itself to useful comparison with other cities.

Utilisation of limited data suggests that before a final typology is identified and used with confidence, validation of the produced typologies must be completed. Validation of the typologies requires more specific research, and so was not attempted in this study, but will form part of future work.

Producing a study of multiple different cities without firsthand experience of them, means that the researcher must be humble about the results. As one is not embedded in these places consultations with local actors would help to validate or question the typologies.

5.3. Future work

The next stages of this work will involve more concerted efforts on city data acquisition, both to validate the existing scaling method and the various resultant typologies of cities. The hope is that robust sources of city-level data will aid in more direct analysis of cities without relying on national data for proxy. Of course, this would require the time and resources to explore individual cities, something which the typology is meant to circumvent.

Purchasing more disaggregated national trade and material data will offer true readings of consumption, particularly for construction materials, ores and industrial minerals. Relying on the data that was freely available provided insights, but was limited in many respects.
The key focus of future work should revolve around scaling, as sound data is the basis of this research. Potential approaches are listed below:

- Scaling requires finding stronger urban and rural delineations, such as:
    - Finding the degree of rural electrification
    - Qualitatively distinguishing types of materials used in cities instead of rural spaces. For example tracking the locations of power plants would give robust indications for whether fossil fuels are part of cities’ consumption or not
    - Discerning biomass used for food and energy from other types of use will give a better indication of biomass as a food or household energy, instead of biomass which will scale as an industrial or construction material
    - Patterns of workers and industrial sectors will allow more focused delineation of resource consumption. However, this data may still be very scarce for individual cities, so even qualitative estimates or suggestions could show useful distinctions.

For example qualitative discussions on prime industrial centers of the country, will effectively focus total consumption of industrial minerals in these cities, and show marked differences between cities in countries

- Case studies in each city or country can enrich efforts to find more contextually appropriate scaling exponents. This would require full urban comparisons in single countries. To establish a cohesive range, studies for at least one country would be needed for each category of rich and poor, prime or distributed urban populations, and fast growing or stable urban populations.
- Deviations from Zipf's law observed in rank-size relationship can inform deviation from average power law and suggest more accurate differences between cities of the same nation.

The typologies in this study represent relative resource intensity of African nations only. Inclusion of some appropriate international comparison cities will allow a global comparison, while still retaining the specific focus on African cities.

Urban planning in African cities would be greatly informed by focused studies of the inter-reliance of service delivery systems in cities. As Bristow and Kennedy (2013) demonstrated with Toronto, it may be invaluable to understand the relative importance of each system, both in reaction to natural disasters, but also addressing the slower disaster of poor resource access. Such studies will help target key systems to focus on, without needing initial quantitative evidence.

The future of urban metabolism studies in African cities would benefit from focusing on the nexus between formal and informal resource flow systems. The magnitude of each system are comparable and worth tracking. Finding new conceptions to describe formal and informal systems is important for demonstrating their inter-reliance.

Finally, the growing field of African urbanism would benefit from studies which move away from generalisations of the continent's development and isolate more context specific behaviours. This should go hand in hand with encouraging an ethos of research-informed decision-making by city governments.

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Chapter 6: Appendices

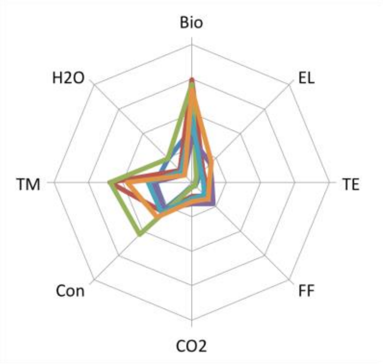
6.1. Ranking of city by aggregate resource impact

City Name	Total Energy Consumption (ktoe)	City Name	Per Capita Total Material Consumption (kt)
BU-Gitega	2.17	BU-Gitega	161.75
CH-Moundou	3.74	CO-Moroni	161.93
MALI-Gao	4.38	ST-Sao Tome	233.64
DRC-Bandundu	8.21	TO-Sokode	314.03
CO-Moroni	11.26	DRC-Bandundu	317.01
TO-Sokode	12.12	CV-Praia	531.01
RW-Gisenyi	12.55	RW-Gisenyi	535.61
NI-Maradi	15.14	SY-Victoria	612.22
MAD-Mahajanga	15.64	MAD-Mahajanga	732.80
ST-Sao Tome	23.44	ZI-Gweru	737.36
LI-Monrovia	26.72	MALI-Gao	816.07
MN-Nouadhibou	28.33	CH-Moundou	835.73
GB-Bissau	29.61	LE-Maseru	1,019.18
CH-N'Djamena	29.72	GAB-Port-Gentil	1,021.80
BU-Bujumbura	30.59	TZ-Dodoma	1,038.35
TZ-Dodoma	30.99	NG-Ogbomosho	1,224.94
CAR-Bangui	34.55	BE-Porto Novo	1,248.88
ETH-Mek'ele	35.17	GAM-Banjui	1,285.70
BF-Bobo Dioulasso	42.11	NI-Maradi	1,433.01
CV-Praia	42.40	SW-Manzini	1,438.37
SL-Freetown	47.02	MN-Nouadhibou	1,467.96
NG-Ogbomosho	49.95	NA-Walvis Bay	1,483.96
ZI-Gweru	55.32	DJ-Djibouti	1,485.11
SO-Hargeisa	59.23	ETH-Mek'ele	1,509.97
GAM-Banjui	59.27	GB-Bissau	1,593.83
GH-Sekondi-Takoradi	63.74	SE-Thies	1,610.66
NI-Niamey	63.90	BO-Francistown	1,669.68
GAB-Port-Gentil	66.65	KE-Kisumu	1,703.48
SE-Thies	78.84	BU-Bujumbura	1,770.14
BE-Porto Novo	79.38	MZ-Nampula	1,794.75
MALI-Bamako	81.96	SA-Stellenbosch	1,855.35
LE-Maseru	86.17	SW-Mbabane	1,868.06
KE-Kisumu	88.99	GH-Sekondi-Takoradi	1,926.38
BO-Francistown	89.99	TU-Sousse	1,947.45
NA-Walvis Bay	91.85	RC-Pointe-Noire	2,301.30
SW-Manzini	96.81	LI-Monrovia	2,372.77
TZ-Zanzibar	98.75	EQG-Malabo	2,423.15
ER-Asmara	99.91	CDI-Yamoussoukro	2,714.56
RW-Kigali	110.11	BF-Bobo Dioulasso	2,720.08
TZ-Mwanza	111.44	TO-Lome	2,859.24
TO-Lome	124.33	MAL-Blantyre	2,886.89
DRC-Lubumbashi	124.76	TU-Sfax	2,928.01
SW-Mbabane	128.29	TZ-Zanzibar	3,036.77
BF-Ouagadougou	136.96	SL-Freetown	3,036.89
NG-Ilorin	145.34	CAR-Bangui	3,118.30
GU-Conakry	152.99	ZI-Bulawayo	3,129.76
SO-Mogadishu	172.67	NG-Ilorin	3,220.87
NG-Zaria	173.39	MAL-Lilongwe	3,316.83
TU-Sousse	174.44	TZ-Mwanza	3,397.25
SU-Nyala	174.87	MS-Port Louis	3,406.98
SS-Juba	177.53	MZ-Maputo	3,595.88
MAL-Blantyre	183.55	BE-Cotonou	3,638.10
MAD-Antananarivo	187.31	ER-Asmara	3,693.12
CDI-Yamoussoukro	189.76	NG-Zaria	3,780.30
MAL-Lilongwe	213.54	BO-Gaborone	3,941.75
BO-Gaborone	216.51	DRC-Lubumbashi	3,949.48
SY-Victoria	235.70	RW-Kigali	3,957.81

ZA-Ndola	236.99	RC-Brazzaville	4,459.34
SA-Stellenbosch	243.83	SU-Nyala	4,657.16
NG-Benin City	251.51	SS-Juba	4,722.87
BE-Cotonou	254.90	EG-Fayyum	4,931.00
ZI-Bulawayo	258.20	NG-Benin City	5,299.21
ZA-Kitwe	265.25	NI-Niamey	5,557.58
MN-Nouakchott	265.99	CH-N'Djamena	5,567.74
MZ-Nampula	270.91	SO-Hargeisa	5,697.39
TU-Sfax	275.37	KE-Mombasa	5,773.60
DJ-Djibouti	277.94	NG-Kaduna	5,924.01
NG-Kaduna	284.31	EG-Asyut	5,993.08
KE-Mombasa	343.12	MC-Rabat	6,039.87
NG-Port Harcourt	358.76	LY-Benghazi	6,388.19
UG-Kampala	395.49	AL-Constantine	6,510.75
NG-Abuja	411.49	ZA-Ndola	6,725.42
MS-Port Louis	436.66	AL-Oran	6,899.33
MC-Rabat	447.69	ZI-Harare	7,162.92
ETH-Addis Ababa	450.01	NG-Port Harcourt	7,319.61
CA-Yaounde	522.22	MAD-Antananarivo	7,411.17
GAB-Libreville	524.40	ZA-Kitwe	7,509.34
CA-Douala	529.45	GAB-Libreville	7,637.54
EG-Fayyum	534.71	AN-Huambo	7,720.70
NA-Windhoek	541.29	NA-Windhoek	7,915.30
RC-Pointe-Noire	558.09	MC-Tangier	8,049.25
MZ-Maputo	575.94	NG-Abuja	8,292.80
NG-Ibadan	576.18	BF-Ouagadougou	8,301.33
EQG-Malabo	607.68	TU-Tunis	8,435.88
MC-Tangier	617.40	EG-Port Said	8,569.33
ZI-Harare	621.69	SA-Mangaung	9,036.73
LY-Benghazi	622.30	CA-Yaounde	9,374.75
AN-Huambo	624.55	CA-Douala	9,495.00
GH-Kumasi	662.04	MC-Fes	9,867.98
NG-Kano	665.67	UG-Kampala	9,940.32
EG-Asyut	668.57	MC-Marrakesh	10,944.57
GH-Accra	674.37	NG-Ibadan	11,269.00
MC-Fes	775.31	MC-Kenitra	11,560.69
TZ-Dar es Salaam	782.09	GU-Conakry	11,626.74
DRC-Kinshasa	795.36	LY-Tripoli	12,164.61
TU-Tunis	812.05	MN-Nouakchott	12,823.00
MC-Marrakesh	863.74	NG-Kano	12,854.53
MC-Kenitra	913.46	MALI-Bamako	12,935.28
SE-Dakar	979.15	SA-Nelson Mandela Bay	14,016.45
EG-Port Said	1,006.50	CDI-Abidjan	14,654.09
ZA-Lusaka	1,008.78	SO-Mogadishu	15,620.93
RC-Brazzaville	1,125.31	ETH-Addis Ababa	16,024.28
CDI-Abidjan	1,142.58	GH-Kumasi	16,666.85
AL-Constantine	1,181.28	GH-Accra	16,954.35
LY-Tripoli	1,201.91	SE-Dakar	18,947.00
AL-Oran	1,261.10	KE-Nairobi	19,118.01
KE-Nairobi	1,280.64	TZ-Dar es Salaam	20,856.45
SA-Mangaung	1,306.08	DRC-Kinshasa	23,653.99
SU-Khartoum	1,922.00	AL-Algiers	23,817.92
SA-Nelson Mandela Bay	2,075.14	ZA-Lusaka	27,802.50
MC-Casablanca	2,310.80	MC-Casablanca	28,666.87
NG-Lagos	2,407.80	SA-Tshwane	36,128.74
AN-Luanda	3,652.54	NG-Lagos	41,636.53
AL-Algiers	5,075.11	SA-eThekwini	42,710.61
SA-Tshwane	5,616.22	SU-Khartoum	43,252.64
SA-eThekwini	6,693.97	AN-Luanda	43,468.79
SA-Cape Town	7,315.15	SA-Cape Town	46,483.30
EG-Alexandria	8,845.47	EG-Alexandria	59,418.36
SA-Johannesburg	15,650.58	SA-Johannesburg	96,137.85
EG-Cairo	40,239.17	EG-Cairo	261,629.40

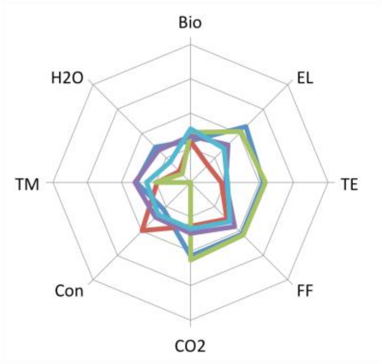
6.2. National Resource Profiles

Group 1 – 3.1 t/cap – 0.4 MWh/cap



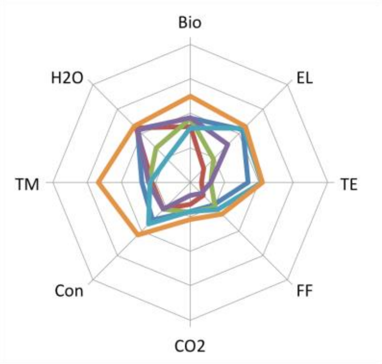
Burundi, Central African Republic, Chad, Democratic Republic of the Congo, Rwanda, Uganda

Group 2 – 4.4 t/cap – 0.5 MWh/cap



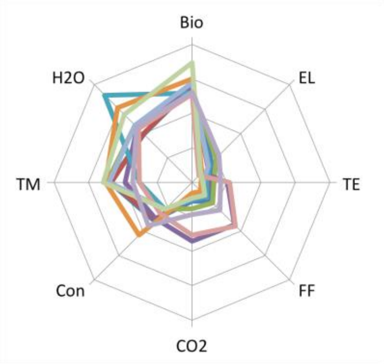
Cape Verde, Comoros, Republic of Congo, Gambia, Togo

Group 3 - 2.5 t/cap – 1.3 MWh/cap



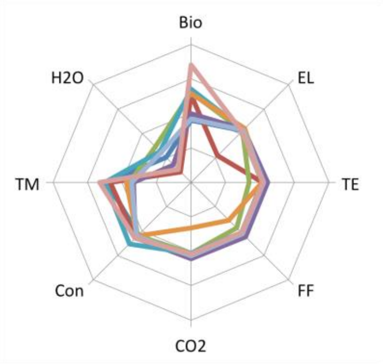
Cote D'Ivoire, Eritrea, Liberia, Malawi, Mozambique, Zambia

Group 4 – 2.4 t/cap – 1.3 MWh/cap



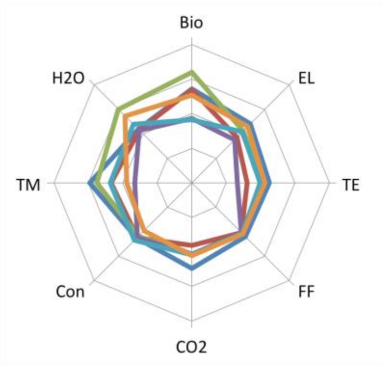
Burkina Faso, Ethiopia, Guinea, Guinea Bissau, Madagascar, Mali, Niger, Sierra Leone, Somalia, Tanzania

Group 5 – 4 t/cap – 2.4 MWh/cap



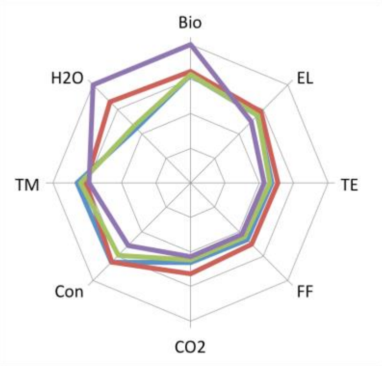
Angola, Benin, Cameroon, Djibouti, Ghana, Lesotho, Sao Tome & Principe, Sudan

Group 6 – 4.5 t/cap – 2.2 MWh/cap



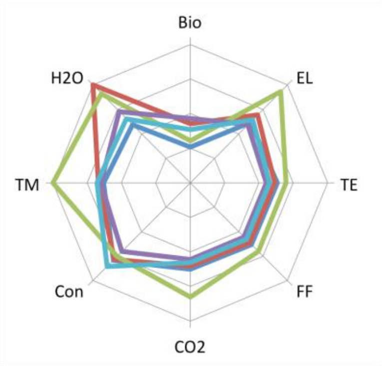
Gabon, Kenya, Mauritania, Nigeria, Senegal, Zimbabwe

Group 7 – 13.8 t/cap – 9.7 MWh/cap



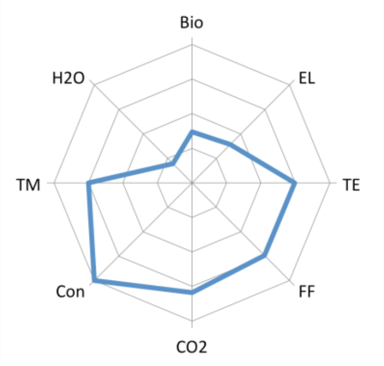
Botswana, Mauritius, Namibia, Swaziland

Group 8 – 8.3 t/cap – 12.6 MWh/cap



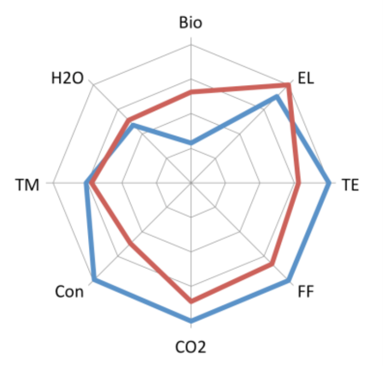
Algeria, Egypt, Libya, Morocco, Tunisia

Group 9 – 9.7 t/cap – 29.2 MWh/cap



Equatorial Guinea

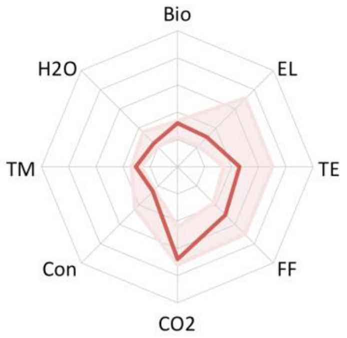
Group 10 – 11.8 t/cap – 42.6 MWh/cap



Seychelles, South Africa

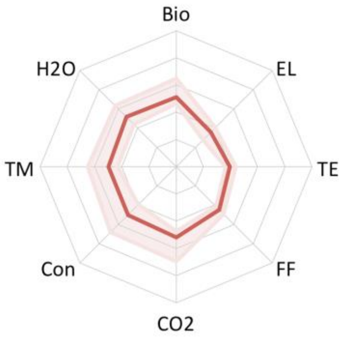
6.3. Typology of resource consumption by per-unit-GDP measure

Group 1 - 89 t/USD - 29 MWh/USD



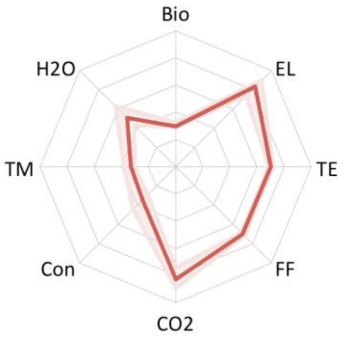
AN-Huambo, AN-Luanda, CV-Praia, EQG-Malabo, GAB-Libreville, GAB-Port-Gentil, RC-Brazzaville, RC-Pointe-Noire

Group 2 - 226 t/USD - 43 MWh/USD



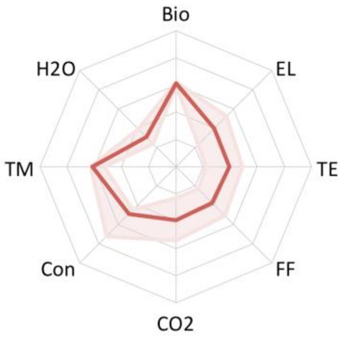
ER-Asmara, NG-Abuja, NG-Benin City, NG-Ibadan, NG-Ilorin, NG-Kaduna, NG-Kano, NG-Lagos, NG-Ogbomosho, NG-Port Harcourt, NG-Zaria, SL-Freetown

Group 3 - 166 t/USD - 27 MWh/USD



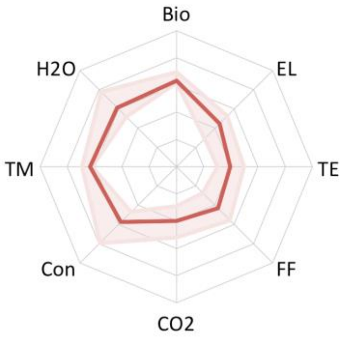
LY-Benghazi, LY-Tripoli, SA-Cape Town, SA-eThekwini, SA-Johannesburg, SA-Mangaung, SA-Nelson Mandela Bay, SA-Stellenbosch, SA-Tshwane

Group 4 - 134 t/USD - 37 MWh/USD



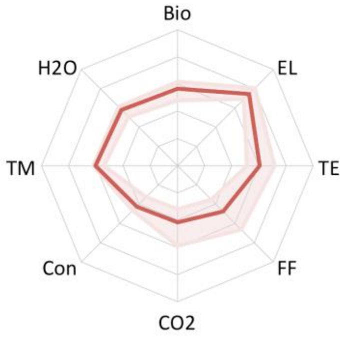
CH-Moundou, CH-N'Djamena, DRC-Bandundu, DRC-Kinshasa, DRC-Lubumbashi, RW-Gisenyi, RW-Kigali, SU-Khartoum, UG-Kampala

Group 5 - 239 t/USD - 27 MWh/USD



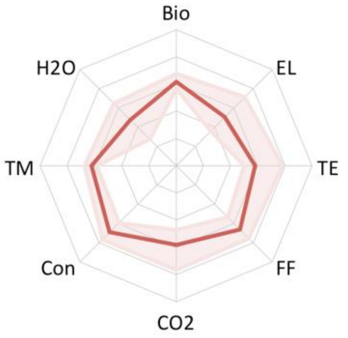
BF-Bobo Dioulasso, BF-Ouagadougou, BU-Bujumbura, BU-Gitega, CAR-Bangui, ETH-Addis Ababa, ETH-Mek'ele, GU-Conakry, MAD-Antananarivo, MAD-Mahajanga, MALI-Bamako, MALI-Gao, NI-Maradi, NI-Niamey, TZ-Dar es Salaam

Group 6 - 455 t/USD - 27 MWh/USD



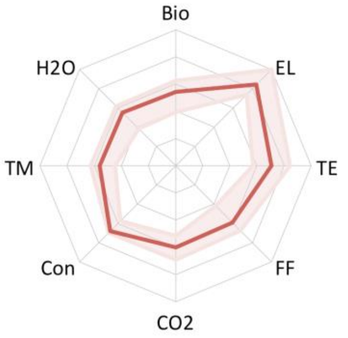
CA-Douala, CA-Yaounde, CDI-Abidjan, CDI-Yamoussoukro, ZA-Kitwe, ZA-Lusaka, ZA-Ndola

Group 7 - 340 t/USD - 34 MWh/USD



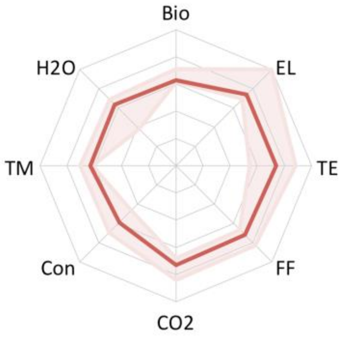
BE-Cotonou , BE-Porto Novo, CO-Moroni, GB-Bissau, GH-Accra, GH-Kumasi, GH-Sekondi-Takoradi, KE-Kisumu, KE-Mombasa, KE-Nairobi, SE-Dakar, SE-Thies, SS-Juba, SU-Nyala, TZ-Dodoma, TZ-Mwanza, TZ-Zanzibar

Group 8 - 349 t/USD - 35 MWh/USD



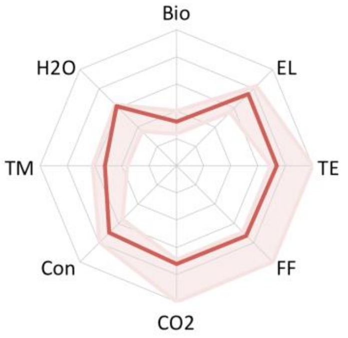
BO-Francistown, BO-Gaborone, LE-Maseru, MAL-Blantyre, MAL-Lilongwe, MZ-Maputo, MZ-Nampula, NA-Walvis Bay, NA-Windhoek, SW-Manzini, SW-Mbabane

Group 9 - 480 t/USD - 43 MWh/USD

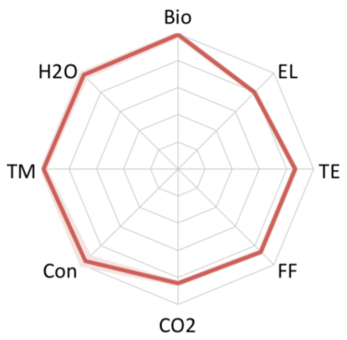


DJ-Djibouti, GAM-Banjui, LI-Monrovia, MN-Nouadhibou, MN-Nouakchott, ST-Sao Tome , TO-Lome, TO-Sokode, ZI-Bulawayo, ZI-Gweru, ZI-Harare

Group 10 - 266 t/USD - 38 MWh/USD



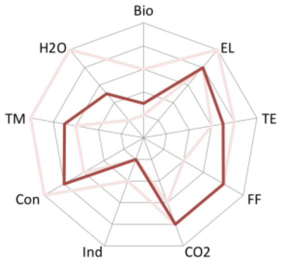
AL-Algiers, AL-Constantine, AL-Oran, EG-Alexandria, EG-Asyut, EG-Cairo, EG-Fayum, EG-Port Said, MC-Casablanca, MC-Fes, MC-Kenitra, MC-Marrakesh, MC-Rabat, MC-Tangier, MS-Port Louis, SY-Victoria, TU-Sfax, TU-Sousse, TU-Tunis



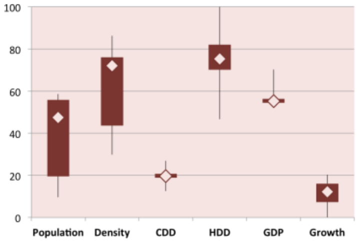
SO-Hargeisa, SO-Mogadishu, Group 11 - 4081 t/USD – 64 MWh

6.4. Clustering with classification trees – including industrial materials

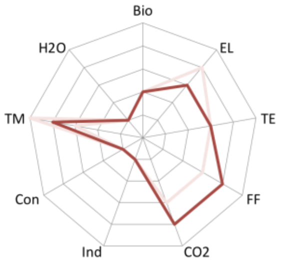
Group 1



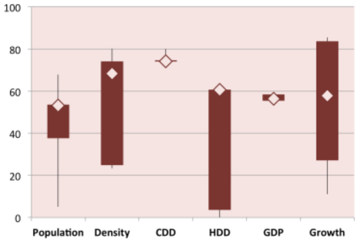
AL-Algiers' AL-Constantine' AL-Oran' MC-Casablanca' MS-Port Louis' TU-Sousse



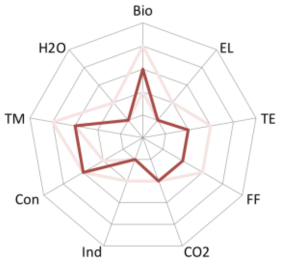
Group 2



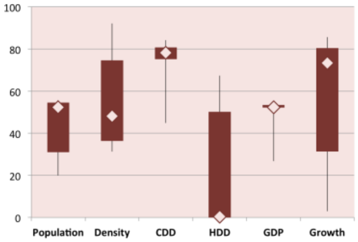
AN-Huambo' AN-Luanda' GAB-Port-Gentil' LY-Benghazi' LY-Tripoli



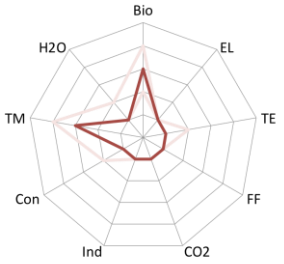
Group 3



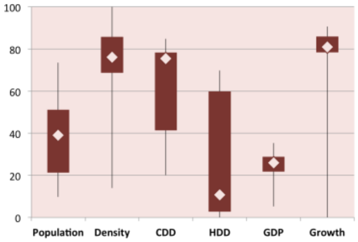
BE-Cotonou ' EG-Asyut' EG-Fayum' GH-Accra' GH-Kumasi' KE-Mombasa' RC-Pointe-Noire' SS-Juba' SU-Nyala' UG-Kampala



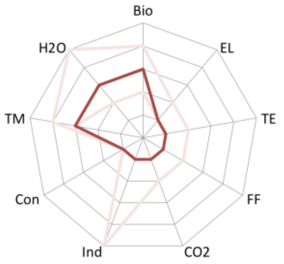
Group 4



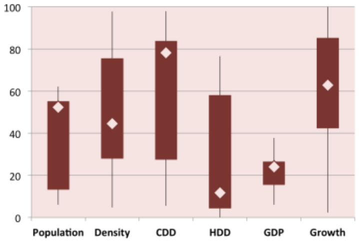
BE-Porto Novo' BF-Bobo Dioulasso' BU-Bujumbura' CDI-Yamoussoukro' DRC-Kinshasa' ETH-Mek'ele' LI-Monrovia' MZ-Nampula' NI-Maradi' SL-Freetown' SO-Hargeisa' TZ-Mwanza' TZ-Zanzibar' ZI-Gweru



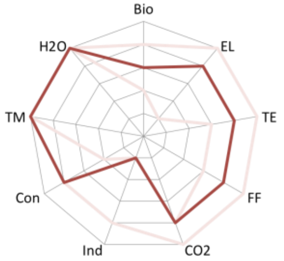
Group 5



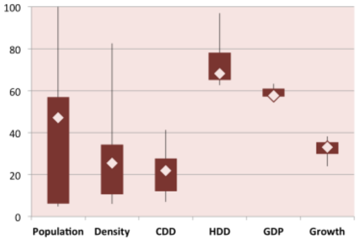
BF-Ouagadougou' CAR-Bangui' DRC-Bandundu' DRC-Lubumbashi' ETH-Addis Ababa' GB-Bissau' GU-Conakry' MAD-Antananarivo' MAD-Mahajanga' MAL-Blantyre' MALI-Bamako' MALI-Gao' MN-Nouadhibou' NI-Niamey' SE-Thies' SO-Mogadishu' TO-Sokode' TZ-Dar es Salaam' TZ-Dodoma



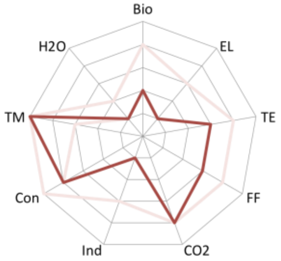
Group 6



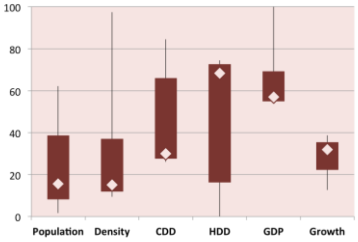
BO-Francistown' EG-Cairo' SA-Cape Town' SA-Mangaung' SA-Nelson Mandela Bay' SW-Manzini' SW-Mbabane



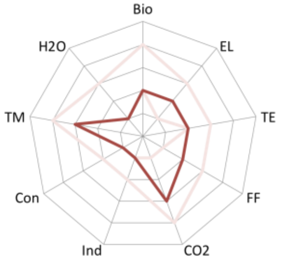
Group 7



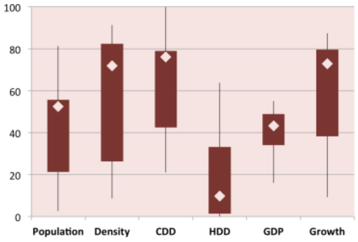
BO-Gaborone' EG-Alexandria' EQG-Malabo' SY-Victoria' TU-Sfax' TU-Tunis



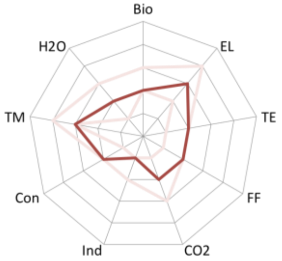
Group 8



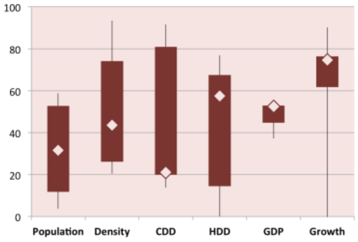
BU-Gitega' CA-Douala' CA-Yaounde' CDI-Abidjan' CV-Praia' DJ-Djibouti' ER-Asmara' GAM-Banjui' KE-Kisumu' MAL-Lilongwe' MZ-Maputo' NG-Ilorin' NG-Lagos' NG-Ogbomosho' NG-Port Harcourt' NG-Zaria' RC-Brazzaville' ST-Sao Tome ' SU-Khartoum' TO-Lome



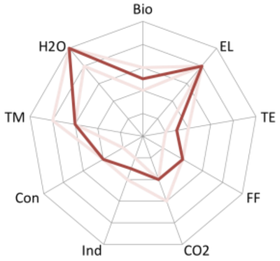
Group 9



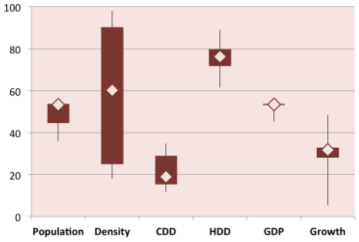
CH-Moundou' CH-N'Djamena' CO-Moroni' GH-Sekondi-Takoradi' KE-Nairobi' MC-Tangier' RW-Gisenyi' RW-Kigali' ZA-Kitwe' ZA-Ndola' ZI-Bulawayo



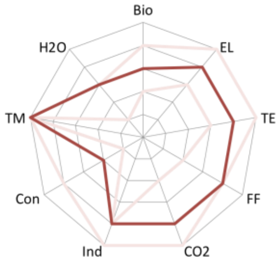
Group 10



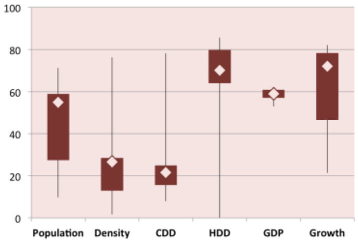
EG-Port Said' MC-Fes' MC-Kenitra' MC-Marrakesh' MC-Rabat' ZI-Harare



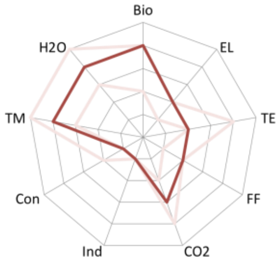
Group 11



GAB-Libreville' NA-Windhoek' SA-eThekwini' SA-Johannesburg' SA-Stellenbosch' SA-Tshwane' ZA-Lusaka



Group 12



LE-Maseru' MN-Nouakchott' NA-Walvis Bay' NG-Abuja' NG-Benin City' NG-Ibadan' NG-Kaduna' NG-Kano' SE-Dakar