Understanding household energy metabolism in the city of Cape Town

by

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Declaration

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Abstract

Urban metabolism assessments enable the quantification of resource flows, which is useful for finding intervention points for sustainability. Globally, household energy consumption accounts for 72% of greenhouse gas emissions; therefore, a household energy metabolism assessment would reveal intervention points to reshape household energy consumption to inform decision-makers about a more sustainable urban energy system. In the Global South, this means providing sufficient access to energy to those still lacking, while reshaping energy consumption in households that are accessing energy in abundance. Current household energy consumption studies tend to limit the focus of study to outflows in the form of greenhouse gas emissions and are mostly undertaken at city or national level.

Consequently, this study assessed the energy metabolism of different households in Cape Town, thereby assisting in improving urban metabolism assessment methods. A method was developed to assess household energy metabolism focusing on energy inflows in the form of carriers, and through-flows in the form of services, to identify intervention points for sustainability. This method was subsequently applied to the city of Cape Town. Surveys were used to collect data, and a final sample size was 360 households representing 56 suburbs. Households were categorised into four groups based on their average income: low-income, low-middle-income, high-middle-income and high income. According to the services accessed, each income group was placed on an energy ladder, which indicates the drivers for energy access to be either satisfying subsistence needs or to effect comfort, convenience and cleanliness.

Results show that many low-income households in Cape Town fully access the service of entertainment, which falls under comfort, convenience and cleanliness, but severely lack access to water heating, which is in the subsistence category. To make the energy system more sustainable, decision-makers' focus regarding low-income households could be shifting to a more efficient energy carrier, as the paraffin mainly used in these households is inefficient, unsafe and expensive. Regarding middle and high-income households, the focus could be toward changing energy behaviour and reshaping consumption patterns.

Opsomming

Assesserings van stedelike metabolisme maak die kwantifisering van hulpbronstroming moontlik, wat nuttig is wanneer na ingrypingspunte vir volhoubaarheid gesoek word. Huishoudelike energieverbruik is verantwoordelik vir 72% van kweekhuisgasvrystellings; dus sou ʼn assessering van huishoudelike energiemetabolisme ingrypingspunte kon identifiseer vir die hervorming van huishoudelike energieverbruik, ten einde besluitnemers oor ʼn meer volhoubare stedelike energiestelsel in te lig. In die globale Suide beteken dit die voorsiening van voldoende toegang tot energie vir diegene wat dit steeds ontbreek, terwyl energieverbruik hervorm moet word in huishoudings met oorvloedige toegang daartoe. Hedendaagse studies van huishoudelike energieverbruik is geneig om die fokus van die studie tot uitstroming in die vorm van kweekhuisgasvrystellings te beperk, en die meeste word op stedelike of nasionale vlak onderneem.

Gevolglik het hierdie studie die energiemetabolisme van verskillende huishoudings in Kaapstad geassesseer en sodoende bygedra tot die verbetering van metodes om stedelike metabolisme te assesseer. ʼn Metode is ontwikkel om huishoudelike energiemetabolisme te assesseer deur te fokus op energie-instroming in die vorm van draers, en deurstroming in die vorm van dienste, ten einde ingrypingspunte vir volhoubaarheid te identifiseer. Hierdie metode is voorts in Kaapstad toegepas. Opnames is gedoen om data vir ʼn finale steekproef van 360 huishoudings oor 56 woonbuurte in te samel. Huishoudings is op grond van hulle gemiddelde inkomste in vier groepe gekategoriseer: lae-inkomste, lae-middel-inkomste, hoë-middel-inkomste en hoë-inkomste. Elke inkomstegroep is op ʼn energieleer geplaas op grond van die dienste waarvan hulle gebruik maak. Die energieleer dui die beweegredes vir die energiegebruik aan as óf om aan bestaansbehoeftes te voldoen, óf vir gerief, gemak en sindelikheid.

Die resultate toon dat baie lae-inkomstehuishoudings in Kaapstad ten volle van vermaakdienste gebruik maak (wat onder gerief, gemak en sindelikheid sou val), maar ernstige gebrek aan toegang tot waterverwarming beleef (wat as bestaansbehoefte gekategoriseer sou word). Om die energiestelsel meer volhoubaar te maak, kan besluitnemers se fokus ten opsigte van lae-inkomstehuishoudings na ʼn meer doeltreffende energiedraer verskuif, aangesien paraffien, wat hoofsaaklik in

hierdie huishoudings gebruik word, ondoeltreffend, onveilig en duur is. Ten opsigte van middel- en hoë-inkomstehuishoudings kan die fokus op energiegedrag en die hervorming van verbruikspatrone wees.

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Table of contents

List of figures

List of tables

List of acronyms and abbreviations

CT	Cape Town
EC	European Commission
EU	European Union
HH	Household
kWh	Kilowatt hour
MFA	Material Flow Analysis
LPG	Liquefied petroleum gas
SFA	Substance Flow Analysis
UK	United Kingdom
USA	United States of America
WWF	World Wide Fund for Nature

List of nomenclatures

kg	kilograms
kWh	kilowatt-hour
lt	litres
MJ	megajoules

List of appendices

Chapter 1 – Introduction

1.1 Background

Energy is an integral part of human wellbeing and one of the basic services required to thrive. It provides the means to cook, to heat, to cool and light up homes, and to charge mobile phones. Three of the Sustainable Development Goals (SDGs) directly refer to energy: Goal 7, Affordable and Clean Energy, advocates for improved energy access; Goal 11, Sustainable Cities and Communities, refers to resource efficiency and efficient transport, with clear implications for energy; and Goal 12, Responsible Consumption and Production, addresses consumption and production patterns, which includes energy consumption (UN 2015). The prevalence of energy in the SDGs indicates that the link between energy and wellbeing is taken note of globally, but it also highlights the need to achieve a sustainable global energy system.

The modern energy system causes significant environmental impacts. In cities, energy consumption is responsible for up to 86% of greenhouse gas emissions (Barragán-Escandón *et al.*, 2017), making it a large contributor to climate change. According to Weisz & Steinberger (2010), material and energy consumption patterns are putting severe pressure on biodiversity, with detrimental consequences to the planet. Energy systems are also the cause of the current air pollution crisis (Carreón & Worrell, 2017), and it is thus essential to manage energy flows with interventions like energy efficiency (Weisz & Steinberger, 2010), reduced energy consumption (De Almeida *et al.*, 2011), and substituting fossil fuel energy carriers with renewable sources (Barragán-Escandón *et al.*, 2017) or more efficient options (Camara *et al.*, 2018).

Approximately 800 million people living in cities in low and middle income countries do not have adequate access to basic energy (Weisz & Steinberger, 2010). It is estimated that more than a third of the population lacks sufficient access to modern energy (Kowsari & Zerriffi, 2011). In Africa, countries may appear to be energy efficient, but this is due to the lack of energy access (Musango *et al.*, 2017). A study on the resource profiles of 120 African cities showed that countries with high resource consumption do not necessarily have high per capita resource consumption (Currie & Musango, 2016).

A sustainable city is one that is not only compatible with the amount of available resources and with nature, but also with human aspirations (Giampietro & Mayumi, 2000a).

1.2 Urban metabolism for a sustainable energy system

Cities account for up to 80% of global greenhouse gas emissions, therefore energy research should be undertaken more frequently in urban contexts (Currie *et al.* 2017; Musango *et al.* 2017). The concept of urban metabolism proves useful in understanding resource flows in cities and consequently provides insight into transitioning to more sustainable resource systems. The same is true of energy flows, and a number of studies (e.g. Barragán-Escandón et al., 2017; Carreón & Worrell, 2017; Weisz & Steinberger, 2010) have undertaken assessments of urban energy systems in order to identify intervention points towards improved urban energy sustainability.

The study of urban metabolism makes use of an ever-evolving metaphor for the city. Initially, cities were likened to organisms, in which a city takes resources from its surrounding environment, trade, and economic regions, processes it to provide goods and services, and produces waste, often in the form of emissions to the atmosphere and as solid waste that goes to landfills (Kennedy *et al.* 2011; Zhang *et al.* 2015; Li & Kwan 2017; Musango *et al.* 2017). The city's metabolism therefore consists of resource inputs and outputs, processed like an organism's digestive system (Carreón & Worrell, 2017; Thomson & Newman, 2017; Zhang *et al.*, 2015). This linear approach simply extracts raw materials from the environment and disposes of waste; a truly unsustainable approach (Musango *et al.*, 2017). While the organism metaphor is still used in some disciplines, in order to account for the interactions within the city, a number of scholars (Barrera *et al.*, 2017; Zhang *et al.*, 2010) instead liken a city to an ecosystem; this view accounts for internal interactions that convey resource flows in a networked metabolic structure (Kennedy *et al.* 2011; Zhang *et al.* 2015; Barrera *et al.* 2017; Musango *et al.* 2017). It is key that, just like an ecosystem, the city's energy patterns be studied as a system (Carreón & Worrell, 2017). This network perspective attempts to explore the many complexities and interactions found within a city and provides ideas for how a city can mimic an efficient ecosystem, for example, by recycling and harvesting resources within the system for future use (Musango *et al.*, 2017).

The connection between urban metabolism studies and sustainable development was first made in 1992 (Kennedy *et al.*, 2011). While this is a fairly recent association, consensus exists in the literature that it is an insightful linkage (Currie & Musango 2016; Musango *et al.* 2017; Thomson & Newman 2017). To achieve a sustainable energy system, it is vital to understand how energy is consumed in the city, as a clearer understanding will reveal more tangible intervention points. Urban metabolism provides a unique framework to understand the energy flows and identify intervention points for reshaping these flows in more sustainable manners (Barrera *et al.*, 2017; Carreón & Worrell, 2017).

1.3 The need to focus on household level energy

Cities can be examined at different levels, of which the household is the smallest structural level (Barrera *et al.*, 2017). As a sector, household energy usage accounts for up to 72% of greenhouse gas emissions (Abrahamse *et al.*, 2005, 2007; Banfi *et al.*, 2008; Benders *et al.*, 2006). Despite technical innovation in the form of energy efficiency and renewable energy technologies, household energy consumption continues to rise (Kennedy *et al.*, 2007; McCalley & Midden, 2002). Households are therefore a critical point of intervention.

Many households in the Global South do not have access to high quality energy services (Howells *et al.*, 2005). The lack of access to electricity in particular requires these households to consume alternative, often inefficient or physically harmful energy carriers. Approximately 2.5 billion people use only traditional biofuels as their cooking fuel, which also has adverse health impacts, resulting in more than 1.6 million deaths annually (Kowsari & Zerriffi, 2011). These households are expected to experience an increase in energy consumption, which means increased greenhouse gas emissions (Musango *et al.* 2017). Hence, the focus in the Global South should be on improving access in the most efficient way while addressing high levels of consumption in other parts of the city (Currie *et al.* 2017), ultimately reducing greenhouse gas emissions while increasing access.

The majority of urban metabolism studies look at ‘whole cities’ and make overarching recommendations for the world’s cities (Kennedy *et al.* 2007; Musango *et al.* 2017; Thomson & Newman 2017). While this is useful for benchmarking against other cities, it does not provide intervention points to create change within individual cities. Some studies do, for instance, consider various consumption groups within cities (Li & Kwan, 2017), while others make mention of per capita consumption (Currie & Musango, 2016); however, on the whole, these arguments remain focused on cities as whole entities.

Carreón and Worrell (2017) suggest that a key gap in energy metabolism studies is that most were undertaken at city-level, using a top-down approach that used national data, thereby disregarding the dynamics of space and time within the city. The literature calls for higher resolution metabolism studies in cities compared to the current, coarse resolution approach (Gouveia & Seixas, 2016; Voskamp *et al.*, 2018; Zhang *et al.*, 2015). Thomson and Newman (2017) highlight that a city’s metabolism consists of many metabolisms. It is therefore vital to conduct more in-depth studies of cities to explore metabolisms of different resource types or metabolisms at different levels.

Studying energy at household level proves useful, as it provides the closest look at how human activity contributes to energy consumption. It follows that researchers persistently recommend a household focus for metabolism studies (Currie & Musango, 2016; Gouveia & Seixas, 2016; Zhang *et al.*, 2015). Some household metabolism assessments (e.g. Biesiot & Noorman, 1999; Moll et al., 2005; Yang et al., 2012) have been undertaken, however, there has been mention of the concept of household energy metabolism in the literature since 1999. A household energy metabolism assessment provides the means to understand varied household energy flows, thereby drawing a more detailed picture of energy consumption (Zhang *et al.* 2015).

A differential understanding of household energy consumption needs bottom-up, household-specific data. In order to take such an approach, detailed datasets are needed (Biesiot & Noorman, 1999). However, quantitative data needed for a differential understanding of household energy consumption is often lacking (Carreón & Worrell, 2017; Donato *et al.*, 2015; Li & Kwan, 2017; Zhang *et al.*, 2015). Data are mostly available at national level in an aggregated format, which makes it challenging to look at specific resources in cities (Weisz & Steinberger, 2010) and at household level. It is possible that the smart meter and smart home revolution can be instrumental to fill these data gaps (Gouveia & Seixas, 2016), but for the moment, and especially in the Global South, the lack of data persists.

In summary, a number of key gaps in household energy studies need to be filled:

a. Household energy metabolism assessments that have been conducted focus predominantly on greenhouse gas emissions, therefore these only consider energy outflows and disregard the inflows and the processes that influence both inflows and outflows.
b. Household energy metabolism studies fail to address the various forms of possible energy inflows (in the form of carriers) possible for different household types.
c. Household energy metabolism assessments neglect to address the throughflows of energy inside the household in the form of different energy activities or services.
d. Household energy metabolism assessments fail to account for energy access, which is relevant in the Global South.

1.4 Problem statement

Despite the proliferation of energy efficient technologies, energy consumption continues to rise around the world. This has widespread social and environmental consequences, requiring that energy systems be made more sustainable. Given the central role that cities play as energy consumers, it is crucial to understand the different energy consumption patterns therein, so as to identify intervention points for reshaping energy flows towards a more sustainable energy system. This includes addressing not only electricity, but also alternative energy carriers servicing many households in the Global South. This requires understanding how household characteristics and activities shape energy flows. While some households may consume large amounts of energy and have the potential for reducing this consumption, others still require sufficient access to energy carriers that do not threaten their health. Existing household energy metabolism assessments tend to use disaggregated city-level data, resulting in coarse estimates. In light of this, bottom-up assessments may offer robust insights on how household types use energy. In the city of Cape Town, South Africa, this bottom-up data are severely lacking, and since the city is home to a broad range of income groups and dwelling types, it is a useful location for undertaking a differential household energy metabolism assessment.

1.5 Research objectives

The overall research objective of this study was to assess the energy metabolism of different households in Cape Town. This was achieved through two specific sub-objectives:

1. To quantify household energy consumption and associated household activities.
2. To examine drivers of household energy consumption.

1.6 Rationale for the study

There is a data gap in Cape Town regarding household energy data, particularly of a wider array of energy carriers. This study addresses this gap by providing relevant data to support practical policy recommendations for decision-makers, based on specific household composition and income groups. This study aids in improving infrastructure planning, as it provides a high-resolution image of household energy consumption in Cape Town. Many households in Cape Town are yet to receive sufficient access to energy, therefore understanding the needs and consumption of these households aids in servicing them in the most efficient manner. There is also a lack of appropriate methods in the literature to measure household energy consumption, specifically focusing on energy services and energy carriers; thus this study contributes to developing robust methods.

1.7 Significance for the study

This research is beneficial to sustainable energy research as it provides practical and specific interventions points at household level that the city of Cape Town can consider for future energy efficiency projects and campaigns. Researchers interested in methods for understanding household energy consumption patterns may find this research useful, as it creates a unique framework for understanding household energy flows for countries in which unequal energy access persists.

The study also benefits scholars undertaking urban metabolism assessments in data scarce environments. It provides insights into the methods used to collect energy consumption data for energy inflows and energy throughflows in different households. International organisations interested in sustainable urban planning and transitions, such as UNHabitat, the World Bank and the Africa Development Bank, can make use of the findings to support their knowledge dissemination and advocacy efforts.

1.8 Scope of the study

a. The study was limited to Cape Town's residential sector.
b. The assessment was limited to direct energy consumption in households.
c. The assessment analysed energy carriers flowing into the household, energy services accessed within the household, and the drivers behind these services.
d. The study focused on two drivers of household energy consumption: satisfying subsistence needs; and convenience, comfort, and cleanliness.
e. This study assessed the energy consumed in the household as a behavioural entity, not the house as a structural entity.

1.9 Assumptions of the study

The assumptions stated for this study were that:

1. Improved access to energy as well as more efficient use of energy leads to a more sustainable energy system.

2. Different dwelling types, household size, location, and income groups portray different household energy flows.

1.10 Research strategy

The research strategy undertaken by this study is briefly outlined in Figure 1.1. It commenced with a review of literature in the fields of urban metabolism and household energy consumption. It then identified a case study to focus on, which was the city of Cape Town. Following this, a methodology that included data collection and consequent data analysis was designed. Finally, the findings of the analysis were related back to the literature to identify similarities and discrepancies.

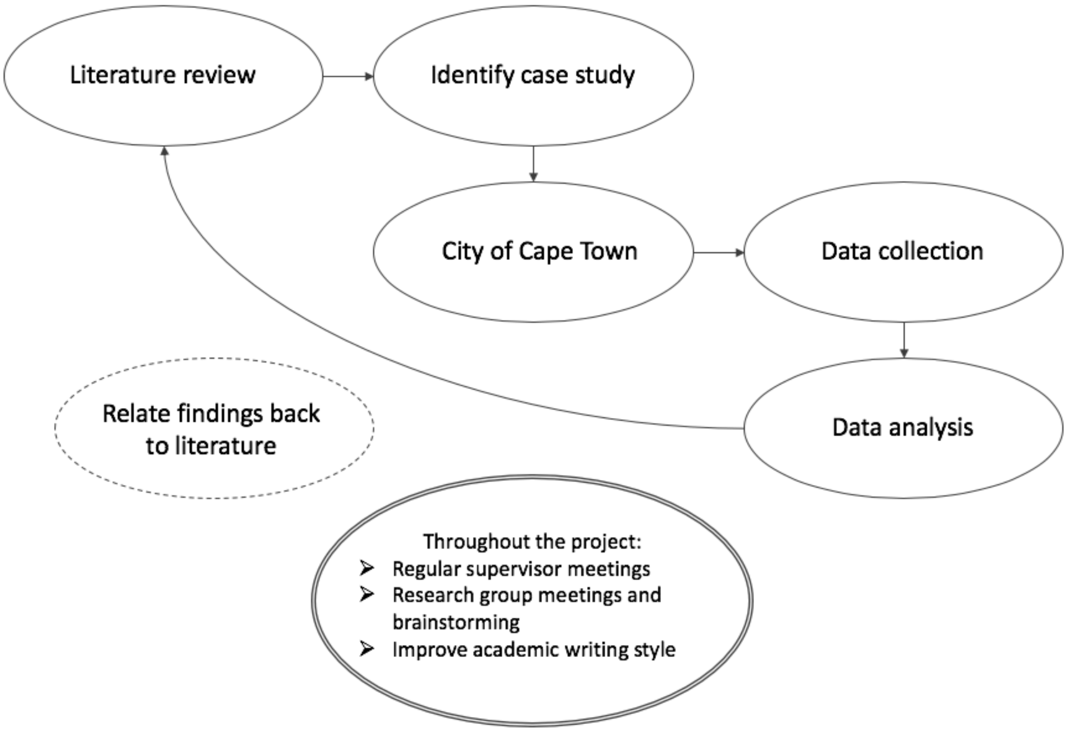

Figure 1.1: Research strategy

Throughout the project, regular supervisor meetings, and research group meetings were conducted in order to review sections of the thesis and brainstorm ideas for data collection and analysis. It was also important to participate in online courses and read books about academic writing in order to convey the ideas in a manner that is clear and concise.

1.11 Thesis outline

Chapter 1 provides background for the study and presents its rationale and significance, as well as the problem statement and research objectives.

Chapter 2 reviews the literature on urban metabolism and household energy consumption in order to create a framework that can be applied to various households from various income groups, in order to understand their current energy situation.

Chapter 3 outlines the methodology employed for the research as well as its limitations.

Chapter 4 presents and discusses the research findings.

Chapter 5 concludes with recommendations for the City of Cape Town Municipality and future household energy metabolism assessments.

Chapter 2 – Literature Review

2.1 Introduction

The concept of urban metabolism provides a useful approach for finding interventions for urban sustainability. It can be scaled according to the structural, societal, and resource levels of a city (Zhang *et al.*, 2015). This is useful because this study's focus is on household energy consumption, and urban metabolism assessments can be scaled to address specific resources (e.g., energy) at specific levels (e.g., household). Urban metabolism uses the concept of flows to understand how resources move through a city (Currie *et al.*, 2017), making it possible to understand flows that shape or have the potential to reshape urban areas to become sustainable. However, only limited studies have assessed the energy metabolism at a household level. Understanding the urban energy system aids in understanding a household's energy metabolism, a crucial study for understanding how different areas of a city consume energy differently. This further provides insights about practical intervention points of the urban energy system.

This chapter reviews literature on urban metabolism, household metabolism, energy metabolism, and household energy consumption in order to fully understand how energy flows into, through, and out of the household. The chapter explores the issue of energy access and proposes an approach for analysing both the households with, and those still lacking, sufficient energy access.

Further, this chapter highlights the research gaps that can be addressed in energy urban metabolism assessment and how it relates to sustainable development, and how household energy metabolism can be useful to address these gaps. This chapter also provides key aspects of household energy metabolism assessments, relevant parameters, assessment methods, and units of study utilised in conducting a household energy metabolism. In doing so, the existing research gaps in household energy metabolism assessments are identified, helping to shape how this study may contribute to addressing these gaps.

2.2 The concept of urban metabolism

The origin of the term ‘urban metabolism’ is highly contested. In 1883, Marx first imagined the notion that a society as a whole has a resource metabolism, in which nature is transformed as needed to provide society with the necessary commodities (Carreón & Worrell, 2017; Musango *et al.*, 2017; Voskamp *et al.*, 2018). Some argue that the first explicit mention of the term ‘urban metabolism’ was made in 1965 by Wolman, who presented the metabolism of a hypothetical American city to demonstrate the metabolic needs of a city as the materials that the city’s inhabitants need to sustain their home, work, and leisure lives (Carreón & Worrell, 2017; Kennedy *et al.*, 2007; Li & Kwan, 2017; Zhang *et al.*, 2015). Others believe, however, that Heodor Weyl pioneered the term in 1894, in his discussion of food consumption, comparing the nutrient discharge with the food intake in the city of Berlin (Lederer & Kral, 2015).

Odum, another pioneer, formulated a unique unit of study for urban metabolism (Zhang *et al.*, 2015). He calculated the ‘emergy’ of a system using solar equivalents of various energy sources (Li & Kwan, 2017). Critique for this unit includes a lack of universal understanding of emergy, and therefore it has mostly fallen into disuse (Zhang *et al.*, 2015). The current unit of study is predominantly ‘Joules’ (Biesiot & Noorman, 1999; Moll *et al.*, 2005).

The most frequently cited definition of urban metabolism is that of Kennedy *et al.* (2007: 44), which defines it as “the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste”. The authors originate from the Industrial Ecology discipline and, as the definition suggests, are particularly focused on the quantification of resource flows.

The above definition is criticised for being too restrictive in its implied methods and practical application of an urban metabolism assessment. Musango *et al.* (2017) specifically highlight the authors’ bias towards quantification, and their consequent disregard for emergent properties possible through resource exchange. Similarly, Barrera *et al.* (2017) argue that the definition should also include the social and political aspects of a city, such as how resources are distributed. Currie and

Musango (2016) and Musango *et al.* (2017) call for the inclusion of people and information flows.

Currie and Musango (2016: 4) define urban metabolism as the "collection of complex sociotechnical and socioecological processes by which flows of material, energy, people, and information shape the city, service the needs of its populace, and impact the surrounding hinterland". This definition includes a significantly broader scope, namely a shift from a purely accounting view to one that accounts for complexity and an explicit consideration for the needs of the residents in a city, thereby addressing not only efficiency, but also equity. This study, however, aims to understand a very specific aspect of resource flows in the city; that of energy consumption within households. For this specific application, the broad definition provides a foundation of accounting various technical flows in to and out of the city. This foundation aids in contextualising flows of specific resources on a specific scale of the city, which is energy in this case.

Urban metabolism studies examine a city in terms of flows. Manuel Castells popularised the idea of societal flows in his book, *The Rise of the Network Society* (Castells, 1996). In the urban metabolism field, addressing resource movement in terms of flows suits the organism metaphor (Zhang *et al.*, 2015). In the most linear depiction of a city, resources enter and wastes leave (Musango *et al.*, 2017). This linearity is exemplified in Figure 2.1. The city's infrastructure supports this linear movement of resources from point A to point B as they are required within the city. These flows can therefore be further disaggregated into inflows, throughflows, and outflows (Zhang *et al.*, 2015). The majority of urban metabolism studies are grounded in this linear structure (Barragán-Escandón *et al.*, 2017). This approach is criticised, however, for being inefficient and unsustainable (Musango *et al.*, 2017).

a) Linear metabolism / unsustainable/ inefficient / organism perspective

Figure 2.1: Linear urban metabolism

Source: Musango (2018) as an adaptation from Musango et al. (2017)

Kennedy *et al.* (2007: 44) define a sustainable city as a place where "inflows of material and energy and outflows of waste [do not] exceed the capacity of the city and its hinterland". This definition, which corresponds with the linear metabolism perspective, is problematic because it grants the city permission to continue harvesting from an unidentified hinterland. Musango *et al.* (2017) posit that linear metabolisms continue to pressurise the hinterland and that this is unsustainable, as these resources are rapidly depleting (Musango *et al.*, 2017). It is therefore unlikely that a linear metabolism perspective on urban resource flows can support a transition to sustainability.

Circular metabolism opposes the linear metabolism perspective. This is where a city addresses socio-political and socio-ecological dynamics, and essentially harvests the resources (e.g., energy, water, materials, people, and information) that would have been discarded from the city to once again meet some of the city's needs (Musango *et al.*, 2017). This circular metabolism is depicted in Figure 2.2. This makes for a more sustainable city, as less raw resources are needed and the city produces less waste.

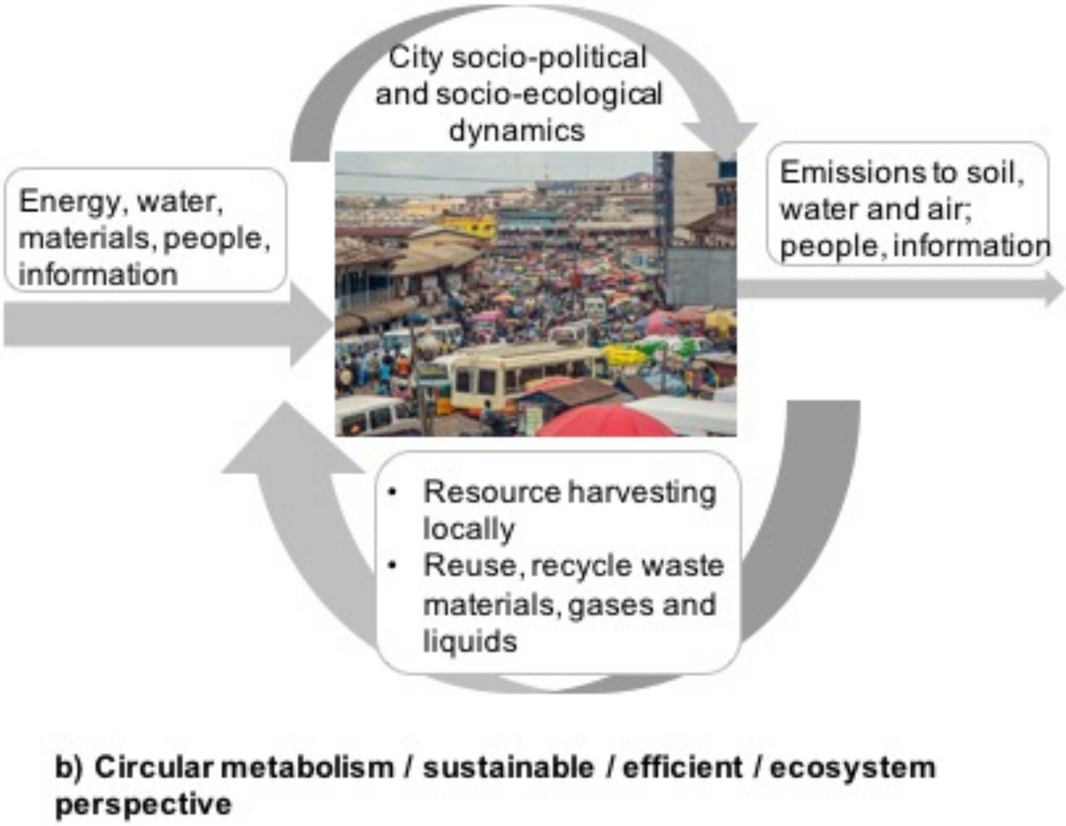

Figure 2.2: Circular urban metabolism

Source: Musango (2018) as an adaptation from Musango et al. (2017)

Illustrating with energy, Barrera *et al.* (2017) state that the energy systems of cities should aim to keep the rate of energy consumed as close as possible to the rate at which the city can supply its own energy (Barrera *et al.*, 2017). This means that sources are local and the inputs and outputs are connected, referred to as cradle-to-cradle (Barragán-Escandón *et al.*, 2017). This opposes the current reality in which cities have the capacity to import energy when its own sources are depleted (Barrera *et al.*, 2017; Zhang *et al.*, 2010).

A literature review on cyclical energy systems revealed that although cities can potentially harvest and re-purpose 'lost' energy to supplement the city's energy inflows through exergy analysis and energy harvesting, like capturing heat from the city and converting it into useful energy (Barragán-Escandón *et al.*, 2017; Leduc & Van Kann, 2013), this harvested energy remains a supplement. Barragán-Escandón *et al.* (2017) specifically indicate that mega cities in particular are unable to supply the entire city with renewable energy produced at the city's borders. This is due to the reliance on technology, which is not fully developed, and that a drastic change is not only dependent on technology, but also on a change in consumption behaviour.

According to Fernandez (2014), growing cities require more raw inputs, while cities with stable populations may be able to recycle and harvest more resources locally. On the contrary, Brunner (2007) argues that apart from the former Soviet bloc, modern cities continually grow. The mega cities referred to by Barragán-Escandón *et al.* (2017) are likely growing cities, which provides a further reason for why a circular metabolism cannot be achieved currently. However, if cities harvest only a portion of their resources from within the cities limits – and the city's resource demand increases with less than what is harvested locally – it enables the city's resource consumption to be efficient and sustainable.

The circular metabolism is embedded in an ecosystem perspective, which views resource flows as influenced and conducted by multiple actors, and encourages cyclical movement of flows (Musango *et al.*, 2017). Many believe this approach to be the best way to make resource flows in cities more efficient, and therefore to create more sustainable cities (Barrera *et al.*, 2017; Carreón & Worrell, 2017; Leduc & Van Kann, 2013; Voskamp *et al.*, 2018; Zhang *et al.*, 2015). This approach can be seen as a lens through which to view the city's resource flows, which requires consideration for the city's complexities, using system thinking rather than a linear perspective. A circular metabolism is one intervention found within the ecosystems approach. Just like ecosystems are efficient on their own, cities should become more efficient and cyclical (Barrera *et al.*, 2017). To these authors, a sustainable city can ultimately survive on its own without any 'help' from outside, both in the form of resource extraction and waste emissions.

2.2.1 Defining the hinterland

While many of the authors interested in urban metabolism mention that cities depend on their hinterlands for resources like energy, water, materials, and people (Currie *et al.*, 2017; Currie & Musango, 2016; Kennedy *et al.*, 2007; Krausmann *et al.*, 2008; Musango *et al.*, 2017; Thomson & Newman, 2017), it is challenging to draw a border around these hinterlands in the same way as one draws a border around the urban area and the municipal regions within. There seems to be consensus in the literature that the hinterland begins on the city's official administrative boundaries to include the area beyond these boundaries, over which city-level decision-makers do not have control (Bristow & Kennedy, 2013; Chen & Chen, 2016; Krausmann, 2013; Yang *et al.*, 2013). In contrast, the outer boundaries of hinterlands are fluid and changing, with a tendency to expand as cities continue to grow and develop (Lee *et al.*, 2016; Weisz & Steinberger, 2010). Predominantly in the Global North, countries can, for example, import products when they run out of the raw materials to produce them (Giampietro & Mayumi, 2000b), illustrating that a city's location and wealth may also impact the size of its hinterland.

Lee *et al.* (2016) categorise the hinterland in levels: regional hinterland, national hinterland, and international hinterland. This helps to account for the effects of globalisation. These boundaries do not necessarily correlate to the administrative boundaries, for example the regional government zone. The regional hinterland is described here as the area beyond the core urban area that depends on it for its economic wellbeing, both in terms of natural resource flows, employment, and markets. At the same time, it is defined as the area from which 75% of its population travels to the core urban area for work (Lee & Ahn, 2016). The regional hinterland therefore depends on the study approach. Delineating between a city's regional, national, and international hinterland allows the opportunity to better track the origin of resources.

Hinterlands can be further delineated according to the specific resources. Drawing from Currie and Musango's (2016) definition of urban metabolism, these hinterlands are for material, energy, people, and information. For example, the energy hinterland stretches to all the places from which the city imports energy sources like coal, oil, or the resources with which to construct solar panels or wind turbines. It includes the processing areas where electricity is generated or fuel for transport is produced and ultimately brings the energy into the city in various forms. The city's regional energy hinterland may therefore only include the processing of energy, while its national energy hinterland could include the area where extraction takes place. This allows one to attribute, for example, the greenhouse gas emissions of electricity production to either the area where the electricity is produced, or the area where it is consumed.

2.2.2 How to undertake an urban metabolism assessment

Since the late 1990s an ever-increasing number of urban metabolism studies have been carried out (Musango *et al.*, 2017). The way in which urban metabolism explorations proceed to demystify resource flows in cities is three-phased. First, different materials or types of resources are identified and their flows made explicit (Currie & Musango, 2016). Second, the flows are quantified in order to identify intervention points (Voskamp *et al.*, 2018). Third, the flows are shaped in order to achieve more sustainable resource consumption (Zhang *et al.*, 2015).

The identification and quantification of the various resources and their flows can be done according to the scale and level of the study. From an urban metabolism perspective, the first such distinction is typically made between the energy and material flows of a city (Zhang *et al.*, 2015), as energy is typically measured in Joules, while material is measured in mass or volume. Depending on the research objectives, studies may disaggregate resources in different ways during the identification process and perhaps adjust the energy units to be more accessible to policy-makers who will relate better with units like kWh for electricity, litres for liquid fuel, and kilograms for biomass. Donato *et al.* (2015) examined house construction, and therefore distinguished between materials, energy, and water needed. Giampietro and Mayumi (2000) studied the flows of commodities across borders and therefore distinguished between the flows of various products. The varied approaches of these studies indicate that identification takes place at the scale or level set in the research objectives of each study.

The research method often dictates the way in which flows are disaggregated. Material flow analysis (MFA) identifies the stocks and flows of resources in cities based on their mass and using the same unit throughout (Kennedy *et al.*, 2011). It remains one of the most commonly applied methods, likely because it is the Statistical Office of the European Communities' standardised methodology for national-level analysis (Musango *et al.*, 2017). Barles (2009) was one of the first researchers to address scale when she applied the Eurostat method to convert a national MFA of France to a city-level MFA of Paris. Figure 2.3 represents the standard Eurostat method for MFA and also illustrates the typical urban metabolism approach to view a city in terms of inflows, throughflows, and outflows. The researcher can also choose to focus on only one element of a single resource, where the appropriate method would be substance flow analysis (SFA) (Musango *et al.*, 2017).

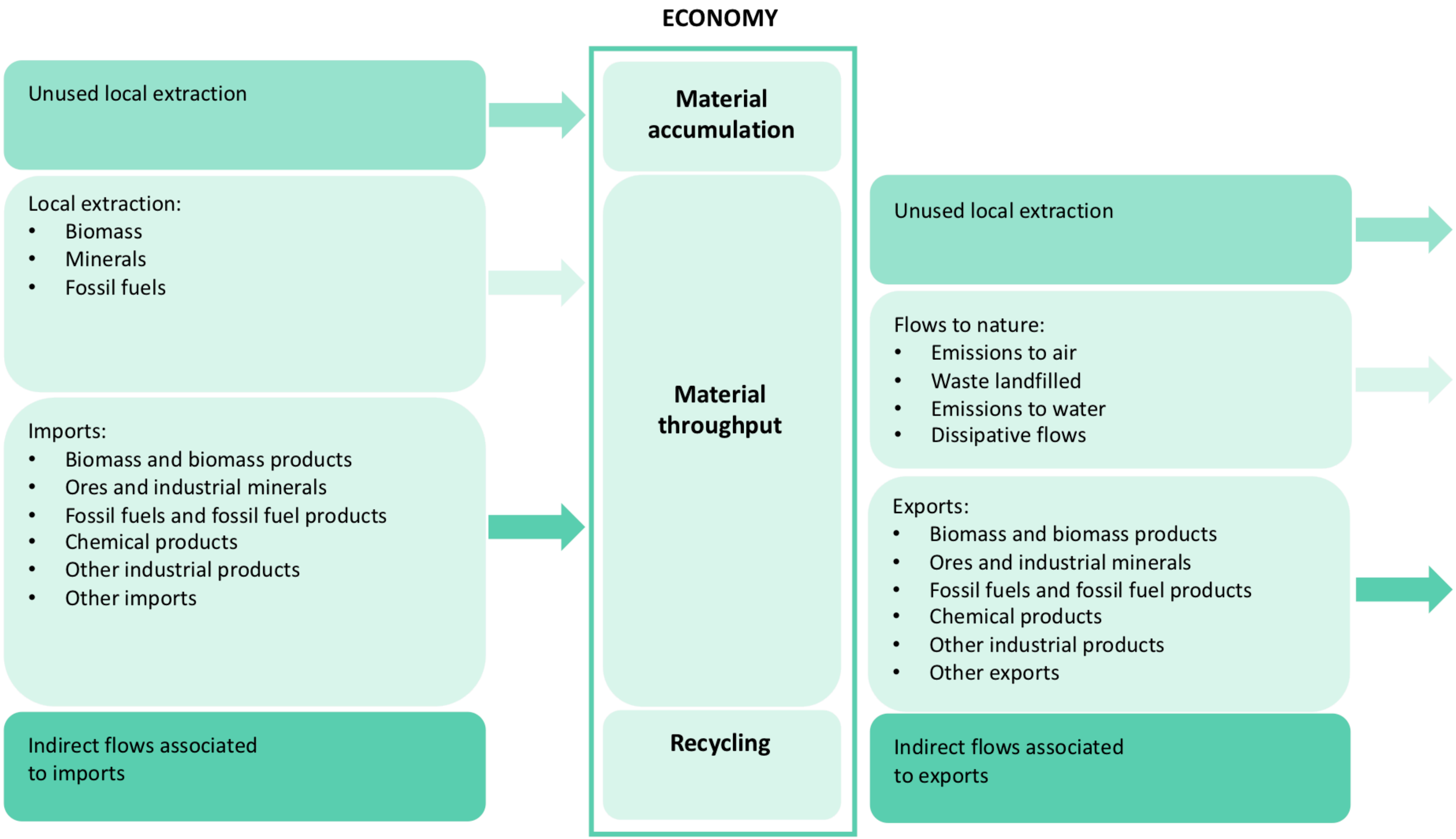

Figure 2.3: Eurostat 2001 Material Flow Analysis method, adapted

Source: Adapted from Voskamp et al. (2017)

MFA provides a good foundation within which to discuss the aggregation of resources into different flows. The basic disaggregation in Figure 2.3 shows that local extraction is aggregated into biomass, minerals, and fossil fuels. However, Voskamp *et al.* (2017) criticises the method for its lack of standardised resource categories. Regardless of the categories presented in Eurostat (2001), researchers continue to disaggregate flows according to their research needs. Barles (2009), for example, disaggregates material into agriculture and food products, minerals and mineral products, construction materials, fertiliser and chemical products, manufactured products, and fossil fuels; all of which will represent a resource flow of the city. Each of these flows can be disaggregated further. For example, in their study of urban food consumption in Manila, Chakraborty *et al.* (2016) disaggregate food into the following: cereals and pulses; vegetables, fruits, and nuts; meat, fish and eggs; dairy products; basic ingredients (disaggregated into oil, sugar, and so forth); and other processed products. Already it is clear that within these food flows, there exist further disaggregated food flows, such as to specific crops. In the same study, meat is disaggregated into further categories. Figure 2.4 displays the combined material flows of the two studies.

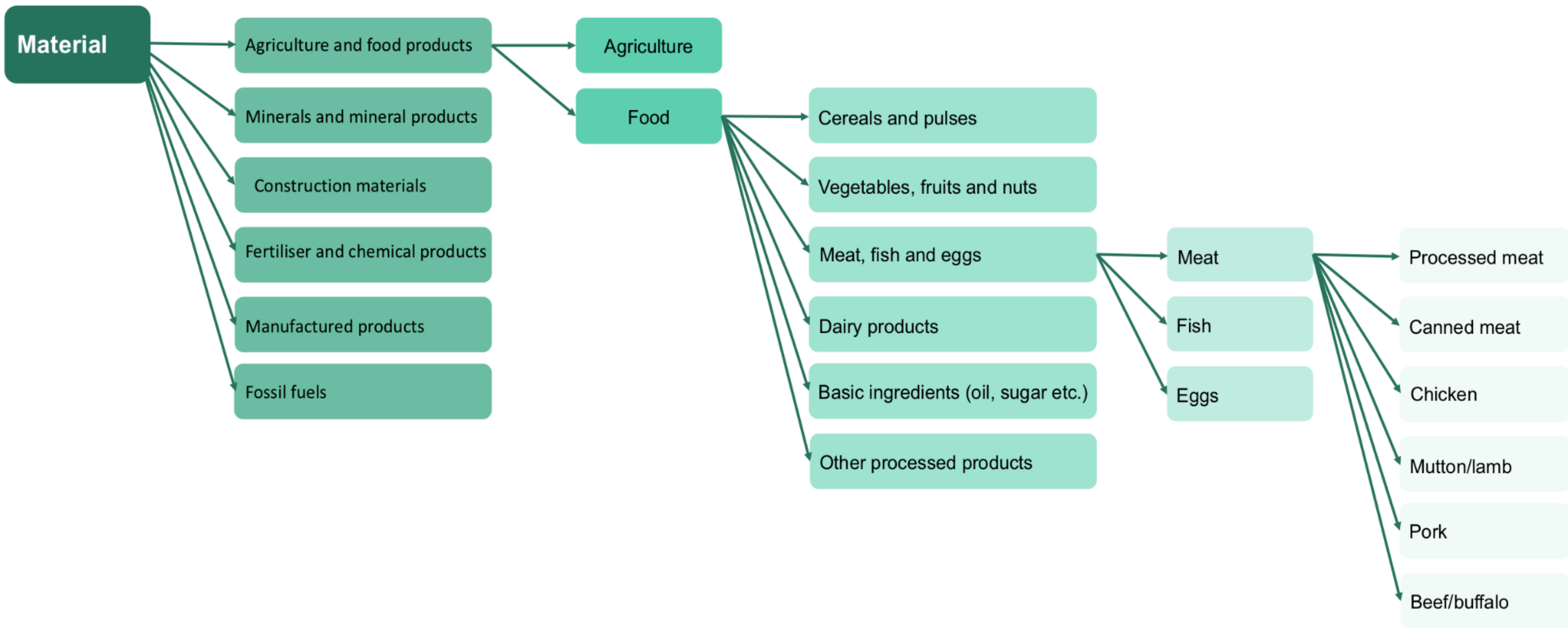

Figure 2.4: Material categories, adapted

Sources: Adapted from Barles (2009) and Chakraborty et al. (2016)

Although Figure 2.4 only collates two studies' material categories, it presents the gaps for further disaggregation. For example, the three flows, namely minerals, construction materials, and fossil fuels, could include various materials. The category of vegetables, fruits, and nuts could also be disaggregated into at least three separate flows. While Chakraborty *et al.*'s (2016) study grouped mutton and lamb together as a single category or flow, a study in a different context might consider these to be two separate categories. Thus, Figure 2.4 illustrates ample possibilities to disaggregate flows in the identification phase. This depends entirely on the research objectives and context and, when using a standardised method like material flow analysis, it also depends on the method.

Once the flows and quantities are explicit, it is possible to set targets for making certain flows more efficient (Currie & Musango, 2016). This is a responsibility that Zhang *et al.* (2015) strongly argue, where a city's resource flows should be 'controlled' in order to make cities more sustainable. Another view is to 'decrease' the city's metabolism, as this curbs the encroachment of farmland, forests, and biodiversity (Kennedy *et al.*, 2007). Decreasing a city's metabolism is understood as reducing the quantity of resources flowing from the hinterland in to and out of the city by making the resource consumption more efficient or recycling and harvesting resources in the city to reduce raw resource input. To control or decrease a single flow could result in unexpected consequences that are unforeseen by those exercising the control over certain flows. Brunner (2007) suggests rather using the term 'reshaping' resource flows in cities, depending on a city's context and priorities. This is because a scarce resource in one city may not be scarce in another. This allows a context-specific systems perspective and the possibility that flows may be shaped in various ways depending on the consequences that arise due to interventions.

The European Commission (EC) published a staff working document in which they present a diagram depicting the European Union's (EU) material flows for 2014 (EC, 2018). This diagram (Figure 2.5) illustrates how a city's flows can be identified and quantified, and how following this, it would be possible to find intervention points to reshape these flows; for example, creating a circular flow by harvesting building stock from the demolition site and discarded products, and recycling it to once again provide material to the city. Brunner (2007) argues that flows can also be reshaped when the stocks enter the urban system; if these stocks are utilised correctly, the wastes they produce will be more appropriate for recycling, and this would once again lessen the need for raw inputs. Further disaggregation of some of the flows in Figure 2.5 may also reveal more opportunity for local resource harvesting. For example, disaggregating domestic extraction into the specific materials may allow for the opportunity to utilise these stocks in the most effective manner.

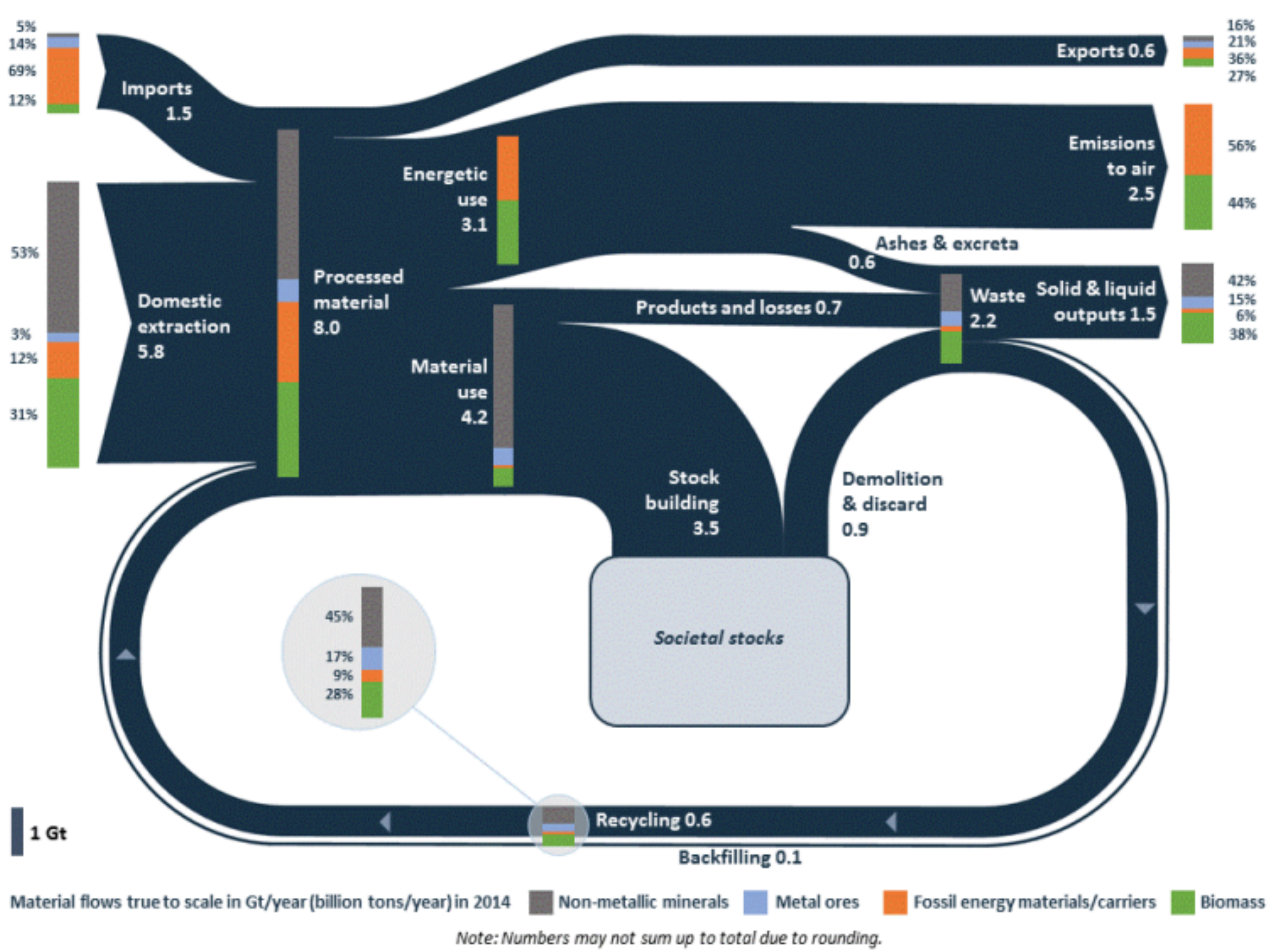

Figure 2.5: European Union material flows for 2014

Source: European Commision (2018)

2.2.3 Urban metabolism research gaps

While the theoretical approach is developed enough for practical applications, urban metabolism assessments of cities are still limited, particularly in the Global South (Kennedy *et al.*, 2007; Musango *et al.*, 2017; Voskamp *et al.*, 2018). Possible reasons are i) urban metabolism lacks standardised methods (Kennedy et al., 2011; Musango et al., 2017; Zhang et al., 2015), and ii) is simpler to conduct where rich data for resource flows already exists (Currie *et al.*, 2015). Another argument is that cities have different contexts and should be approached individually, which implies that a standard method might not be as viable to large-scale practical applications of urban metabolism as the literature suggests.

2.3 Urban energy metabolism and achieving sustainability

While urban metabolism can highlight intervention points for lightening resource dependence in cities, its inclusion of all types of resources may hinder its ability to make practical and spatially explicit recommendations for cities. Thomson and Newman (2017) believe energy, water, and waste should be viewed together as a nexus. This urban nexus is defined by Chen and Chen (2015: 1) as follows:

> *"Different from conventional urban studies stressing single element (e.g., energy, water, land, carbon, etc.) for efficient resource use and management, the urban nexus highlights the interlinkages among various elements and their twisted conversion pathways (e.g., extraction, supply, distribution, end use, disposal, etc.) via the parallel production and consumption chains in terms of socio-economic sectors."*

The authors emphasise studying the nexus, as the flows of resources influence one another, and isolating a single resources once again attempts to reduce a complex system to single, controllable elements (Chen & Chen, 2015). The first step to understanding nexus is to get detailed and accurate data about each resource flow. As part of a larger project to examine the urban nexus at household level, this study aims to collect and analyse detailed energy flows, which will contribute to further nexus study. This study focuses on energy, while two separate studies focus on household water[1] and food waste[2] respectively.

Energy consumption in cities is continuously increasing (Kennedy *et al.*, 2007). In agrarian societies, only a small population could be supported by the available resources, as they relied only on the energy from the sun to produce biomass, which met societal needs such as cooking (Krausmann *et al.*, 2008). The shift away from solar energy as the main energy carrier (the sun allows the production of biomass) to fossil fuels is a crucial socio-metabolic transition in the modern society, particularly in how it has shaped transportation capabilities, and forms the basis for understanding energy consumption (Krausmann *et al.*, 2008). Krausmann *et al.* (2008) emphasise that this is an ongoing transition, which explains why biomass remains a key energy carrier in many cities. A key difference between these regimes is that the amount of biomass was abundant for small agrarian societies and was able to replenish itself faster than human demand (a sustainable energy system). In a fossil fuel society, these resources are rapidly depleting, as the demand is much higher than the supply of fossil fuels, resulting in an unsustainable energy system.

The aim for urban energy metabolism assessments is to facilitate in identifying opportunities to make the city's energy system more sustainable. It is therefore necessary to understand what is meant by a sustainable energy system. There are two strong arguments in the urban energy metabolism literature to guide the conceptualisation. Firstly, a city that can decrease its greenhouse gas emissions and combat climate change is often regarded to be transitioning towards achieving sustainability (Carreón & Worrell, 2017; Donato *et al.*, 2015). Secondly, and more practically, a circular metabolism perspective of the city's energy system can enable the city to achieve sustainability (Giampietro & Mayumi, 2000a). Figure 2.6 is a depiction of an imagined circular energy metabolism of a city (Barragán-Escandón *et al.*, 2017). This system would use decentralised renewable energy technologies and harvest energy within the urban boundaries. This would not only include capturing heat, but also using biomass waste from the city to produce energy, which again

[1] This is the PhD study for Paul Currie

[2] This is master's study for Ann Gacheri Kaimenyi

emphasises the importance of the urban nexus, as material resources can become useful to the energy resource.

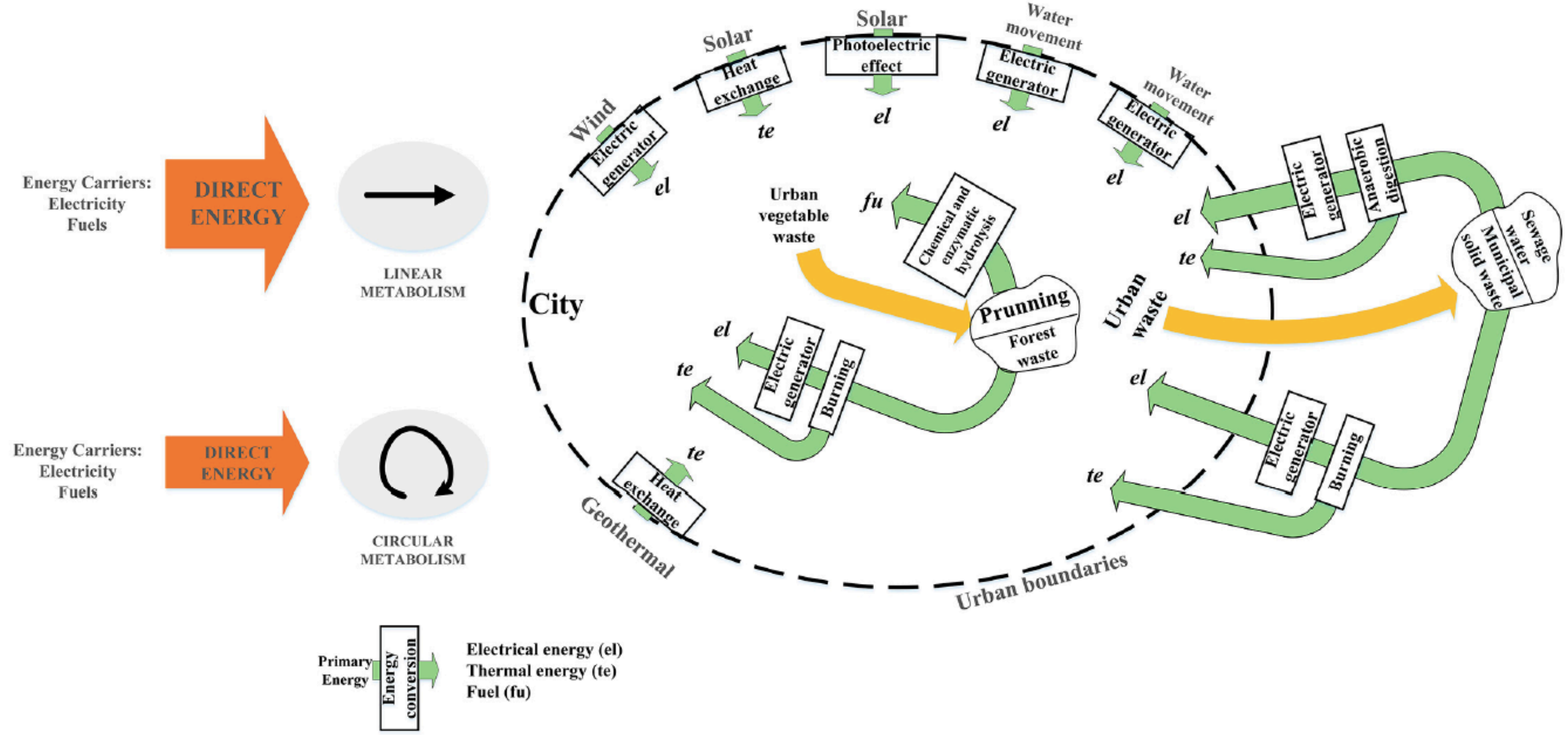

Figure 2.6: Circular urban energy metabolism using renewable energy

Source: Barragán-Escandón et al. (2017)

The key focus outlined in Figure 2.6 is on limiting resource consumption. The agrarian society was considered sustainable because the region's energy resources depletion was limited, while the fossil fuel society is not (Barragán-Escandón *et al.*, 2017). The end goal is a completely circular energy metabolism, the hinterland of which would not exceed the city's limits. However, Section 2.2 argued that it is unlikely to achieve a completely circular metabolism for all resources in the continually expanding cities. Although this is true for energy, we do not need an entirely circular energy system if we can limit our energy extraction; for instance, producing renewable energy through extracted limited raw materials for the production of solar panels or wind turbines.

Achieving a sustainable energy system in expanding mega cities is perhaps an unachievable ideal. This study is of the same view with Carreéon and Worrell (2017) that in order to progress toward a sustainable energy system, an important starting point is to understand the flows of energy through the city. This would then enable reshaping the city's energy flows, ideally reducing energy requirements from the hinterlands, in a manner appropriate for the specific city. In addition, sustainability stretches beyond resource consumption to address issues of inequality. Therefore, approaching a sustainable energy system also means understanding how people access and use energy differently in the city, to ensure access to safe, reliable, and modern energy sources for all citizens.

2.3.1 Understanding the urban energy system

Energy is a unique resource to examine as it does not flow in the same manner as most resources. Instead, it flows through the different phases of the urban energy system. Zhang *et al.* (2011) disaggregate the system into five phases: energy exploitation, energy transformation, industry, living, and recovery. Carreón and Worrell (2017) indicate three phases of energy system: (i) energy sources, which are connected by (ii) energy carriers, to meet (iii) the city's energy demand. Both studies emphasise that energy flows from one phase to the next. Understanding the energy system therefore requires understanding urban energy flows. Neither study, however, addresses the energy flows found at household level, disaggregated by type of carrier or activity, or services the energy is used for.

Based on Zhang *et al.* (2011), Carreón and Worrell (2017), and Chen and Chen (2016), who provide more detail into the city's energy sectors, it is possible to create a conceptualisation of the city's energy system. The energy system is depicted in Figure 2.7. Energy exploitation is the first phase of the system. This allows identification of the source of the various energy flows. This phase includes all mining activities for raw materials. In the second phase, energy is transformed into carriers. The physical infrastructure of grids, refineries, and power plants transform energy into the carriers of fuel, electricity, gas, etc., which hold the energy. Figure 2.7 includes the disaggregation of Carreón and Worrell (2017) for this phase. Both sections of the phase indicate separate energy flows.

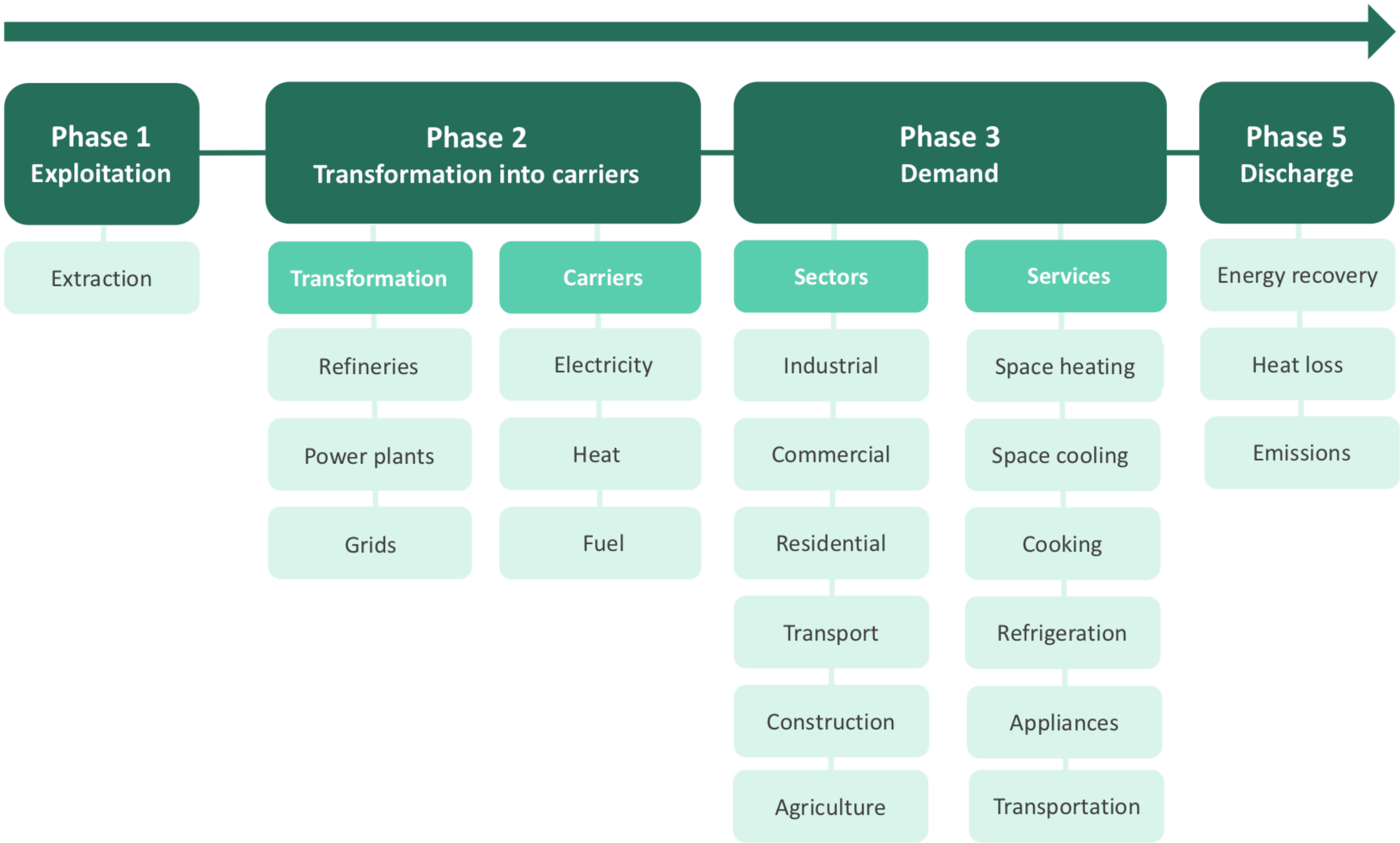

Figure 2.7: The urban energy system, adapted

Sources: Adapted from Carreón & Worrell (2017), Chen & Chean (2016), and Zhang et al. (2010)

The third phase is energy demand. According to Carreón and Worrell (2017), this phase can be divided into energy sectors and end use, which represent two flows within the same phase. Figure 2.7 shows a further disaggregation possible in sectors based on Chen and Chen (2016), who provide detail on the various energy sectors found in a city. Some disagreement exists around the difference between energy end use and energy services. What Carreón and Worrell (2017) regard as end use, Bristow and Kennedy (2013) and Barrera *et al.* (2017) regard as services. Carreón and Worrell (2017) regard energy services as a further phase after energy end use. This study makes use of the views of Bristow and Kennedy (2013) and Barrera *et al.* (2017), based on Fell (2017), who regard energy services as the function performed using energy. A fourth phase needs to be added in order to account for Zhang *et al.*'s (2010) energy recovery. The top arrow in Figure 2.7 indicates that the entire system represents the flow of energy through the city. Not all energy may flow through all the phases, but it always flows from left to right, from exploitation to discharge.

It should be noted that this is not an exhaustive list of the various sub-flows in each of the phases of the urban energy system. These are examples in order to establish the various phases and the notion that energy flows through certain city systems from one phase to the next. As argued in Section 2.2.2, disaggregation is done based on the needs and context of the study.

2.3.2 Urban energy metabolism studies and assessments

Urban energy metabolism studies use energy metabolism to account for greenhouse gas emissions (Chen & Chen, 2016; Zhang *et al.*, 2014), to find intervention points to reduce the city's energy flows (Weisz & Steinberger, 2010), to improve resilience, and to make a city's metabolism more circular (Bristow & Kennedy, 2013; Kuznecova *et al.*, 2014). The majority of urban energy metabolism assessments are positioned in the perspective that quantification leads to the emergence of intervention points for sustainability and are specifically focused on measuring greenhouse gas emissions (Donato *et al.*, 2015; Shahrokni *et al.*, 2015).

Chen and Chen (2016) translate the city's energy activities into carbon flows in order to model the carbon metabolism and associated energy use activities. Zhang *et al.* (2014) study the energy metabolism of various sectors in a city as well as their associated carbon footprints. Both studies believe carbon flows should be central to urban energy metabolism assessments, as this helps to understand the carbon profile of cities and consequently the amount of pressure a city's energy system places on the environment and thus the city's contribution to climate change risk (Chen & Chen, 2016; Zhang *et al.*, 2014). The focus is therefore mainly on the energy outflows. Weisz and Steinberger (2010) similarly focus on the energy outflows in their review of the various ways in which a city can reduce both its energy and material flows. Seeing as sustainability is not only about reducing greenhouse emissions and combating climate change, but also about addressing societal inequalities, the notion of focusing strongly on greenhouse gas emissions is limited. Energy assessments must also expand beyond carbon to include the local dynamics of energy provision and use, so as to understand future energy demand, infrastructure pressures, and how to effectively plan fast-growing cities.

There is another prevailing gap in addressing the throughflows of energy within the urban system. While Chen and Chen (2016) deem the flows between sectors important, they mainly address the inflows in the form of extraction and the eventual outflows to the carbon sink. This correlates with the first and last phase of the energy system and leaves a gap for addressing the flows within namely carriers, sectors, and services. This gap is addressed by Zhang *et al.* (2010) who argue that urban metabolism struggles to address ecological trophic levels within the energy system. They shifted the focus to analyse the relationships within this system using throughflow analysis and ecological network utility analysis, and found a total of 73 different metabolic pathways between 17 energy sectors (Zhang *et al.*, 2010). They therefore concluded that it is possible to make the city's energy flows more efficient by adjusting these relationships (Zhang *et al.*, 2010). For example, to balance out a system where demand is higher than supply, energy consumption must either be lowered, or energy production must be increased. Consequently, it is possible to grasp the adequacy of supply of primary energy sources to meet the needs of the energy service phase.

Taking a slightly different approach, the urban energy metabolism studies of Bristow and Kennedy (2013) and Kuznecova *et al.* (2014) are interested in resilience. Bristow and Kennedy (2013) regard the energy stocks available in Toronto as well as the time these stocks last to assess the city's energy resilience, while Kuznecova *et al.'s* (2014) focus was to establish a method to quantify urban resilience for Latvia, Lithuania, and Estonia. While the former displays a practical application for urban energy metabolism in assessing the time and intensity at which a city can continue its energy production in the event of a shock, the latter concludes that sustainability and resilience go far beyond controlling the energy system and includes socio-economic, environmental, and governance indicators. For example, a resilient city should also address diversity, efficiency, robustness, adaptability, and resourcefulness (Kuznecova *et al.*, 2014). These studies' contrasting approaches highlight the ability of urban energy metabolism to be adjusted according to the research needs.

In reviewing the literature on urban energy metabolism, the goal of identifying intervention points for energy usage reduction is apparent. An overwhelming intervention point, present beyond the boundaries of urban energy metabolism literature, is the correlation between the transport sector and a city's density. The core argument is that sprawling cities require more energy for transportation, as the distances are greater. More dense cities allow for mass transit systems, which are too expensive to build in large, sprawling cities. This reduces the energy consumed by private cars in the low density suburban sprawl, thereby lowering the city's overall energy flows (Barrera *et al.*, 2017; Currie *et al.*, 2017; Kennedy *et al.*, 2007; Thomson & Newman, 2017; Weisz & Steinberger, 2010). Kennedy *et al.* (2007) add that a closer proximity to work further increases efficiency, while Currie *et al.* (2017) suggest that in cities with large urban sprawls, measures to increase the occupancy in private cars reduces the total number of private car trips from the transportation system. Other interventions identified for the energy system are reducing electricity transmission losses, which could be as high as 10%, and improving the quality of lighting to reduce the need for more individual lights (Carreón & Worrell, 2017). Weisz and Steinberger (2010) mention policy as a way to change certain economic production activities or to change high-income lifestyles, both of which lower the city's overall energy flows.

2.3.3 Gaps in urban energy metabolism studies

While it is encouraging to see an increasing number of energy metabolism studies done for cities, Carreón and Worrell (2017) identify a clear gap: most energy metabolism studies are overwhelmingly linear, using only accounting approaches and input-output analysis, disregarding causal relationships between elements like climate, demographics, and infrastructure. This relates with the above discussion that studies address mostly the first and last phase of the system and not the phases in between. Figure 2.7 exemplifies many other phases and flows within the energy system, providing opportunities for quantification beyond carbon emissions. Beyond quantification are possibilities to address the other mentioned aspects of sustainability, such as equality.

When considering the intervention points identified, the energy literature is firmly embedded in a perspective of reducing and controlling. Weisz and Steinberger (2010) argue that energy access is widely overlooked in energy metabolism studies. Interventions in areas that still lack access to energy might therefore involve increasing inflows or perhaps shifting the energy carrier within a certain flow in order to provide more reliable, affordable, or efficient energy services. The concept of a sustainable energy system should go beyond quantifying carbon emissions and reducing energy flows (Leduc & Van Kann, 2013). Brunner's (2007) call to reshape flows rather than to reduce or control, once again arises, and the energy metabolism literature can benefit from this perspective, as reshaping will allow for increased flows or a change in energy carriers where necessary.

Another gap in the literature on urban energy metabolism is that most of these studies were done at city level, taking a top-down approach using national data, thereby disregarding the dynamics of space and time within a city (Carreón & Worrell, 2017). Musango *et al.* (2017) specifically mention the need for conducting bottom-up research in cities in order to account for these dynamics. This study therefore focuses on the smallest structural entity of the city, the household.

2.4 Defining the household as a unit of study

Cities exist in various structural and societal scales and levels (Giampietro & Mayumi 2000; Barrera *et al.* 2017; Musango *et al.* 2017). Similar to hinterlands, the scales and levels within a city can be delineated according to resources. Barrera *et al.* (2017) provide a useful representation of the levels within the energy system, distinguishing between macro-, meso-, aggregated-, and micro-level. Each of these levels can then be divided into behavioural and structural categories. Table 2.1 provides more detail.

Table 2.1: Levels of organisation of energy systems

Levels of organisation	Behavioural	Structural
Micro	Households, firms	Buildings (houses)
Aggregated	Urban land uses	Squares or neighbourhoods Groups of buildings
Meso	Economic sectors	Urban districts
Macro	Economic sectors Cities	Cities

Source: Barrera et al. (2017)

As Table 2.1 shows, the smallest scale of the energy system can be understood as buildings or houses. On a behavioural level, it specifies the smallest scale as the household, which indicates a difference between a house and a household. The smallest scale of a city is, however, the individual. Moll *et al.* (2005) and Biesiot and Noorman (1999) argue that while individuals perform different consumer activities, these are mostly focused within the household and therefore the household, not the individual, is the smallest unit. In terms of energy consumption, this study views the household as the smallest unit, as energy consumption within the household contributes to services that are shared between the individuals within. Furthermore, the household is a standardised unit in metabolic studies, and the majority of energy consumption studies present their data for the household as a whole.

Donato *et al.*(2015: 905) define a household as “a group of persons who share the same living accommodations, who pool some, or all, of their income and wealth and who consume certain types of goods and services collectively”. While a house is the physical structure or dwelling in which people habituate, the household is the group of people living inside the house. The current study is interested in household energy consumption because it is the group of people within the house performing activities that consume energy, not the house itself consuming the energy.

There is some disagreement on whether it is wise to take such a micro look. Giampietro and Mayumi (2000) believe that studying the parts of a complex system instead of the system as a whole hinders one from finding sustainable solutions. Zhang *et al.* (2015) advise that making the focus too narrow may exclude some important aspects found only at city level. A possible reason why these authors caution against a narrow view is that often, the national systems, for example the energy supply or the city infrastructure, impact household energy consumption (Moll *et al.*, 2005). This describes the household as nested within a complex system; however, given that complex systems can contain nested systems or networks (Sales-Pardo *et al.*, 2007), a household can be understood to also be a complex system. Within the household, it is possible to find interventions for more sustainable energy consumption. This can demonstrate resonance with the city-level system, as understanding household energy consumption patterns is valuable for shaping not only the household, but also the city as a whole. The study therefore does not, as Zhang *et al.* (2015) warns, reduce the system's complexity to study the household. Rather, the details emerging from this study can be situated in larger system processes of the city.

2.4.1 Defining household energy metabolism

There exists no clear definition of a household energy metabolism. However, the literature provides definitions of household metabolism, from which a definition for energy in particular can be inferred. The most basic definition of household metabolism is "the integral patterns of natural resources flowing into and out of households" (Biesiot & Noorman, 1999: 369). Donato *et al.* (2015) provide further detail by defining household metabolism as the biophysical assessment of households from the point of view of raw materials, energy carriers, and water required, and emissions and wastes resulting from household consumption patterns. The inputs are further categorised into direct inputs of energy (electricity, heat, and vehicle fluids) and material, and indirect inputs of economic goods and services.

Based on the above, a household energy metabolism can be understood as the process by which energy flows, which are sourced and delivered through various carriers, are conveyed through the house to service a household's direct and indirect energy requirements, and result in waste or emissions. Section 2.3.2 on urban metabolism highlighted that throughflows are equally important to inflows and outflows, therefore the reference to throughflows in the current definition.

A brief distinction between direct and indirect energy consumption in the household is needed, as total household energy requirements include both. Direct energy is energy consumed within the household and includes energy for space heating, water heating, cooking, lighting, and electronics, while indirect energy is used for the production, transportation, and disposal of goods and services consumed by the inhabitants of the house (Abrahamse *et al.*, 2007; Benders *et al.*, 2006; Moll *et al.*, 2005). While Benders *et al.* (2006) indicate that the majority of household energy consumption research includes only direct energy, the case for including indirect energy has strengthened significantly, and other scholars have considered the total household energy to include indirect consumption (Barrera *et al.*, 2017; Donato *et al.*, 2015; Moll *et al.*, 2005). The current household energy metabolism literature overwhelmingly studies both direct and indirect household energy consumption. In the case of this study, only the direct energy consumption is presented because (i) it is specifically focussed on energy access, a concept which refers only to direct energy, and (ii) indirect energy is the subject of further research, particularly around implications of transportation as well as water and food consumption.

2.4.2 Household energy metabolism assessments

While the first approach to model the household's total energy requirements was developed in the 1970s (Moll *et al.*, 2005), there persists a lack of household energy metabolism assessments. This section discusses both the energy metabolism as well as the broader household metabolism assessments that have been done, as energy is a core resource in the household. Research about household energy consumption was drawn from beyond the urban metabolism field.

Existing household metabolism assessments are mostly embedded in a sustainable development approach. However, they vary considerably with regard to the resources studied. Both Moll *et al.* (2005) and Donato *et al.* (2015) identified intervention points for making the household more sustainable, but the former addresses total household energy requirements while the latter reviewed a body of household metabolism research papers, therefore including both energy and material resources. Yang *et al.* (2012) and Biesiot and Noorman (1999) focused on the environmental effects of household resource consumption, with a strong focus on greenhouse gas emissions. The former analyses emissions from energy, material, food, and waste, while the latter is interested only in total energy consumption. Frostell *et al.* (2015) also studied total household energy requirements, but went beyond accounting to find ways of changing the energy consumption behaviour.

Within this variance exists a strong focus to measure the emissions impact of households, whether this pertains to the energy consumption alone or a more broad study of household resource requirements (Donato *et al.*, 2015).

When conducting a household metabolism assessment, there are various parameters to consider. According to Donato *et al.* (2015) , there is consensus on the importance of considering a household's income or expenditure. This is because monthly expenditure is positively correlated to energy consumption (Biesiot & Noorman, 1999; Jones *et al.*, 2015; Moll *et al.*, 2005; Poortinga *et al.*, 2004; Sovacool, 2011). Both Moll *et al.* (2005) and Biesiot and Noorman (1999) include this parameter; however, Yang *et al.* (2012) does not. This could be because their study focus was on how the larger city is impacted by household energy consumption and conceptualisation of the hinterland beyond the city boundaries. However, Donato *et al.* (2015) state that while indirect energy is directly correlated to income, direct energy consumption seems to stabilise as income levels rise, because higher income often means residents can afford more energy-efficient equipment. Benders (2006) also finds that higher income could lead to lower direct energy expenditure. However, this is challenged by the rebound effect, in which people purchase energy-efficient appliances or cars and then proceed to use these appliances, or other appliances in their house, more often, thereby increasing overall consumption (Abrahamse *et al.*, 2005; Greening *et al.*, 2000; Maréchal, 2009; Owens & Driffill, 2008; Sahakian, 2011; Salo *et al.*, 2016).

Household size and composition are key parameters for understanding household energy flows, and the authors who make mention of house and family size are numerous (Biesiot & Noorman, 1999; Donato *et al.*, 2015; Gouveia & Seixas, 2016; Jones *et al.*, 2015; Poortinga *et al.*, 2004; Weisz & Steinberger, 2010). A positive correlation is demonstrated between household size and absolute emissions (Donato *et al.*, 2015). While Biesiot and Noorman (1999) also consider the family size, Moll *et al.* (2005) specifically distinguish between the number of people in the household and the household composition, which considers the number of pensioners, children, and adults in the household, as pensioners and children typically do not consume as much total energy as adults. Household size and composition is also key to highlight the tipping point to shift from one energy fuel type to another.

The building type also influences household energy metabolism (Carreón & Worrell, 2017; Donato *et al.*, 2015). Some of the variables studied by authors are the dwelling type, age, size, type of glazing and windows framing, bearing structure, type of external walls, and location (Carreón & Worrell, 2017; Gouveia & Seixas, 2016). In this regard, Yang *et al.* (2012) specifically studied the age of the house as well as the dwelling type, and found a positive correlation between age and energy consumption, as the construction of older houses did not have the same energy-efficient building techniques available today. There is also a direct correlation between the size of the house and energy consumption, as larger houses have more space heating and cooling appliances (Gouveia & Seixas, 2016).

In their literature review, Donato *et al.* (2015) argue that the methods for conducting household metabolism assessments have not yet reached maturity. When considering the diversity in approaches to the household's resources, it is understandable that most of the studies reviewed use hybrid methods. Moll *et al.* (2005) and Biesiot and Noorman (1999) use a combination of input-output analysis and process analysis to account for the complex nature of quantifying indirect energy consumption. Biesiot and Noorman (1999) outline that the direct energy requirements can be determined by i) considering the money spent on energy, ii) dividing this into energy activities, iii) accounting for the energy requirements of these activities, and iv) converting this energy into CO_2 emissions. The framework is useful, as it provides a method to quantify various household activities in energy terms. The framework can be applied to different scenarios, thereby facilitating the projecting of future energy consumption. Moll *et al.* (2005) point out that increasing consumption activities have resulted in an indisputably unsustainable path.

2.4.3 The need for a differential household energy metabolism

Top-down approaches dominate in household metabolism assessments. Noorman (1999) and Yang *et al.* (2012) acquired their datasets from national data and disaggregated it to the household level. Yang *et al.* (2012) acquired supplementary data from household surveys.

Both Moll *et al.* (2005) and Donato *et al.* (2015) argue for the need to undertake a bottom-up approach to assessing household metabolism. Moll *et al.* (2005) found significant variances in consumption patterns between the countries they studied, and concluded that it is crucial to study different types of households before identifying intervention points. Biesiot and Noorman (1999) share a similar view that different households display different lifestyles and therefore different consumption patterns. Therefore, a differential household energy metabolism approach is crucial in order to account for variances in consumption patterns, lifestyles, countries, or areas within specific cities.

In order to conduct a differential household energy metabolism assessment, reliable and accurate data is crucial (Moll *et al.*, 2005). Biesiot and Noorman (1999) recommend collecting the following datasets before attempting a household energy metabolism assessment: 1) energy production and consumption data; 2) economic input-output matrices; 3) household budget surveys; and 4) goods and services price information.

The studies focusing specifically on direct household energy consumption fall mostly outside of the urban metabolism field, but prove useful in identifying methods for collecting bottom-up data. Smart meters in households are proving a very effective and reliable way of collecting quantitative energy consumption data, as it accounts for exact consumption (Elkhorchani & Grayaa, 2016; Shakeri *et al.*, 2017; Zhou *et al.*, 2016). Studies that do not utilise smart meters often measure electricity consumption using utility bills (De Almeida *et al.*, 2011; Gouveia & Seixas, 2016). Neither one of these approaches are appropriate for a study on direct energy consumption across a range of income groups and energy carriers, as an approach is needed that accounts for the different energy sources a household may access, which is not depicted in smart meter data. While smart meters are excellent for tracking direct electricity consumption, it does not indicate exactly how this electricity is used in the house, for example, which appliances it services. A holistic understanding of household energy consumption means examining how multiple carriers feed into a variety of services accessed.

2.5 Conceptualising energy flows in the household

Existing household energy metabolism assessments account for the total energy requirements and total emissions. However, there are more phases to a household's energy consumption than merely the total requirements and outputs. Limited studies have explored how energy flows into and through the household (Biesiot & Noorman, 1999; Sovacool, 2011). They measure the total amount of energy flowing in and through, but this number can be further disaggregated into different flows, based on energy carriers and energy services.

Both Sovacool (2011) and Barrera *et al.* (2017) advocate that household energy consumption studies should address services. Barrera *et al.* (2017) indicate that the usefulness of viewing energy flows as services is due to the simplicity in translating the energy activities performed in a household, thereby making explicit what the individuals in a household choose to consume. It relates energy consumption to activities, which is easier for consumers to comprehend than referring to the amounts of Joules, kWh, or litres of carriers consumed. In this way, intervention points become more tangible or accessible to the individual.

The main energy services within the household across different regions are similar. Based on work in the United States of America (USA) and Western Europe, Abrahamse *et al.* (2005) developed an energy service hierarchy and suggest that space heating is the highest energy consuming service, followed by water heating, refrigeration, lighting, cooking, and finally space cooling. Sovacool (2013) examined middle-income households from a broad range of countries and suggests that the primary energy services (in order) are space heating, water heating, cooking, appliances, and lighting. Kwak *et al.* (2010) who studied North Korean households, finds space heating and space cooling to be major contributors to energy consumption due to the country’s four distinct seasons. In Finland, which experiences colder weather than most countries, space heating is the primary energy service (Salo *et al.*, 2016).

In contrast to hierarchies developed by country, studies that compare energy services between low- and high-income households have observed differing energy hierarchies. Sovacool (2011) finds that the energy services in low-income households are predominantly lighting and cooking, while other surveys also include hot water, television, and radios. A study on energy services in rural African regions listed cooking, lighting, and water heating as primary energy services (Howells *et al.*, 2005). Offering an interesting contrast is the types of additional energy services found in high-income households: swimming in heated swimming pools or cooking with the television on are some mentioned services (Sovacool, 2011). This once again stresses the need for a differential household energy metabolism assessment in order to understand whether households in the same city may appear strikingly different when their energy inflows and throughflows are analysed.

Sovacool (2011) stresses that services also make it possible to identify the level of access of the household, by a proposing an energy ladder. This energy ladder differs from the traditional energy ladder, which focuses only on carriers and suggests that households transition to more efficient fuel types as their economic situation improves (Kowsari & Zerriffi, 2011). Sovacool's (2011) energy ladder includes three drivers to be applied to the various steps of the ladder: satisfying subsistence needs; convenience, comfort, and cleanliness; and conspicuous consumption.

The basic energy carriers for a large number of households around the world is fairly consistent. Sovacool (2011) identifies electricity, natural gas, coal, liquefied petroleum gas, kerosene, fuel oil; with electricity being the most dominant energy carriers. However, as with differences in service between low- and high-income households, subsistence households may demonstrate the widest range of possible energy carriers.

Figure 2.8 conceptualises the energy ladder and household energy services of various income groups according to Sovacool (2011). Households driven by subsistence only can be regarded as not having sufficient access to energy.

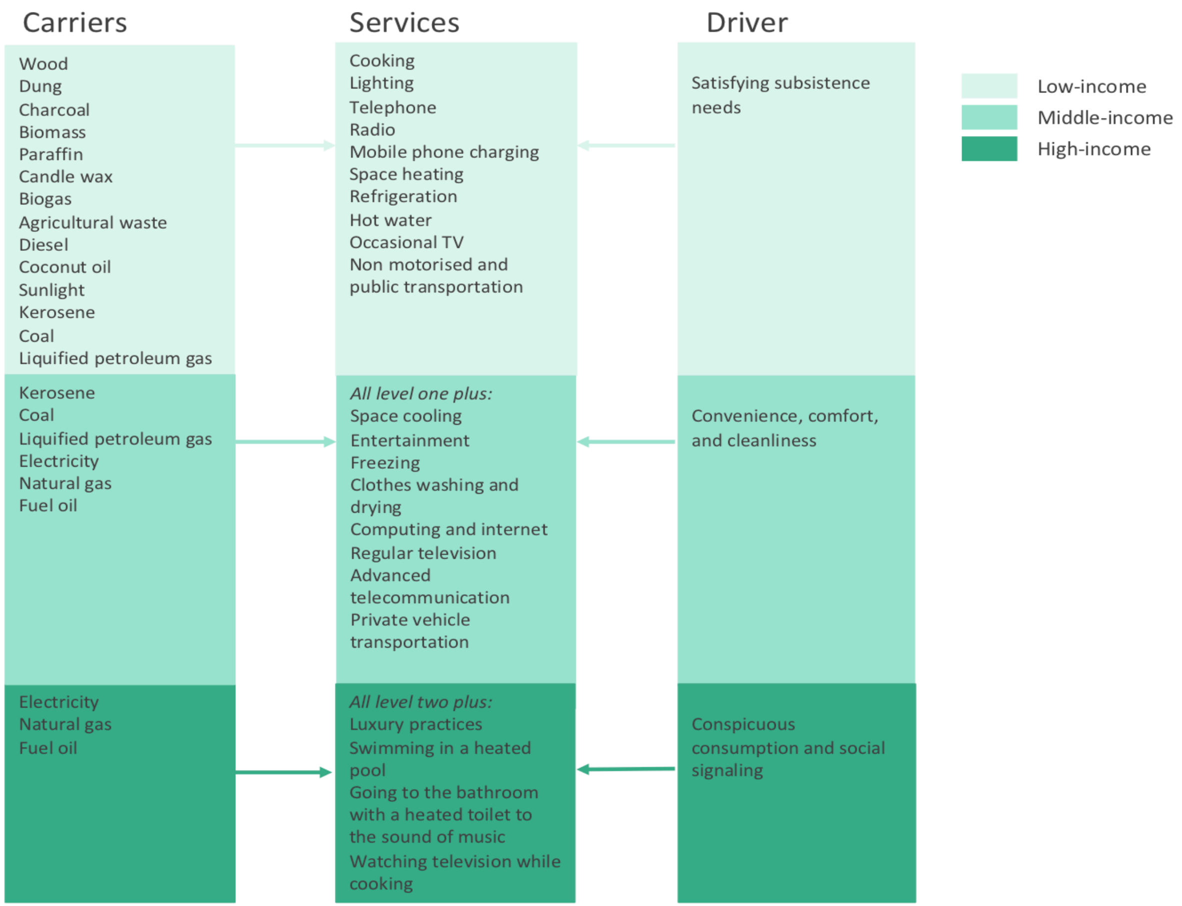

Figure 2.8: Household energy ladder, adapted

Source: Adapted from Sovacool (2011)

A useful way to look at energy access is to consider the concepts of 'energy poverty', 'fuel poverty', and 'energy vulnerability'. Although all are conceptualisations aimed at identifying the lowest group on the energy ladder, they differ quite significantly. Energy poverty is a term typically used to refer to inadequate energy access in the Global South, and links to the wider relationship between energy and development (Bouzarovski & Petrova, 2015). Fuel poverty and energy vulnerability refer to people typically in the Global North who have access to energy, but cannot afford to purchase sufficient amounts (Bouzarovski & Petrova, 2015; Gillard *et al.*, 2017; Middlemiss & Gillard, 2015). The difference between the two is that energy poverty is a state of being, while energy vulnerability can change according to external factors such as the dwelling quality, energy costs, stability of household income, and so forth (Middlemiss & Gillard, 2015). Bouzarovski and Petrova (2015) categorise all three terms under the umbrella term of 'domestic energy deprivation'.

It is essential to consider energy in terms of drivers rather than a state of being, as it provides a clear pathway for improving energy security, which is important especially in the Global South where energy access is a concern. Rather than containing the household in a negative state of being, the energy ladder creates a conceptualisation of being able to climb up to a position in which energy consumption ceases being driven by subsistence and starts being driven by comfort, cleanliness, and convenience.

To achieve a more sustainable energy system may in some cases mean changing the energy carrier. Camara *et al.* (2017) explicitly state the importance of addressing the forms in which low-income households access energy, as a change in energy carrier could result in higher energy efficiency. These households could therefore climb to the second level of the energy ladder without experiencing an increase in energy spending. Examples of key intervention points in the Global South are improved cook stoves and cleaner fuel, such as a transition away from solid fuels and paraffin toward gas or electricity and improved wood burning stoves with, for example, chimneys (Budya & Yasir Arofat, 2011; Foell *et al.*, 2011; Howells *et al.*, 2005; Maes & Verbist, 2012; Parikh, 2011; Williams *et al.*, 2015). This shows that improved access to modern energy carriers (like electricity) is not the only possible intervention, but that in some cases, changing the fuel type from solid fuel to liquid petroleum gas or kerosene (widely considered to be modern fuel types) can also be beneficial (Foell *et al.*, 2011). Improved cook stoves and cleaner fuel is mostly discussed within the context of improving health, however Williams *et al.* (2015) and Maes and Verbist (2012) discuss it in conjunction with air pollution, and Williams *et al.* (2015) include hardships experienced by the women collecting solid fuels on foot. Given that a sustainable energy system must consider both social and environmental factors, the quality of cooking fuel or technology must necessarily reduce pollutants as well as negative health impacts.

2.6 Summary

This literature review introduced the concept of urban metabolism and applied it to behavioural energy in the household, the smallest unit of the energy system. It highlighted the usefulness of studying different households within the same city, for example. Gaps in household metabolism assessment specifically in the data-scarce Global South were discussed, with most studies overlooking details of which carriers constitute the energy inflows into households and which energy services are implicated in the use of these energy flows. Approaching energy consumption in terms of services also allows a more analytic approach to understanding and addressing energy access.

By collecting household level energy data on carriers and services accessed in the household, a better understanding of a city's household energy consumption across income groups is possible. This can reveal clear intervention points to reshape certain energy flows, change carriers, improve the efficiency of energy services, and approach universal access to safe energy.

Chapter 3 – Research Design and Methodology

3.1 Introduction

The overall research objective of this study was to assess the energy metabolism of different households in Cape Town. This was achieved through the two following sub-objectives:

1. To quantify direct household energy consumption and associated household activities.
2. To examine drivers of household energy consumption.

I used a mixed methods approach to understand different households' energy flows in terms of energy carriers and services, while also examining the drivers behind energy consumption to understand energy access. I followed a positivist approach in my collection of quantitative data to assess, quantify, and understand household energy consumption. This is because I induced findings about household energy consumption by gathering facts about energy activities. In contrast, I followed a social constructivist approach in my collection of qualitative data to understand energy drivers. This is because the study assumes that meaning is constantly being produced through social interactions of people. The drivers behind energy consumption therefore brings an element of meaning to the conversation about household energy consumption, and this meaning is produced by the people that use the energy.

This study forms part of a larger research project that includes household consumption of food and water, and production of wastes, and a number of methods were performed collaboratively with other co-researchers. However, this chapter retains focus on the methods that relate only to this study on household energy metabolism.

3.2 Research design and process

My research design and approach are depicted in Figure 3.1. It shows how I organised the process according to the two objectives, selecting data collection and data analysis methods for each and detailing what each method was to achieve. It also shows how I collected and processed the data. There were two key milestones in the research process. The first was creating a conceptualisation of Cape Town's household energy flows in terms of carriers, services, and drivers, and the second was creating a diagram connecting the drivers, carriers, and services of high-, middle-, and low-income households in Cape Town.

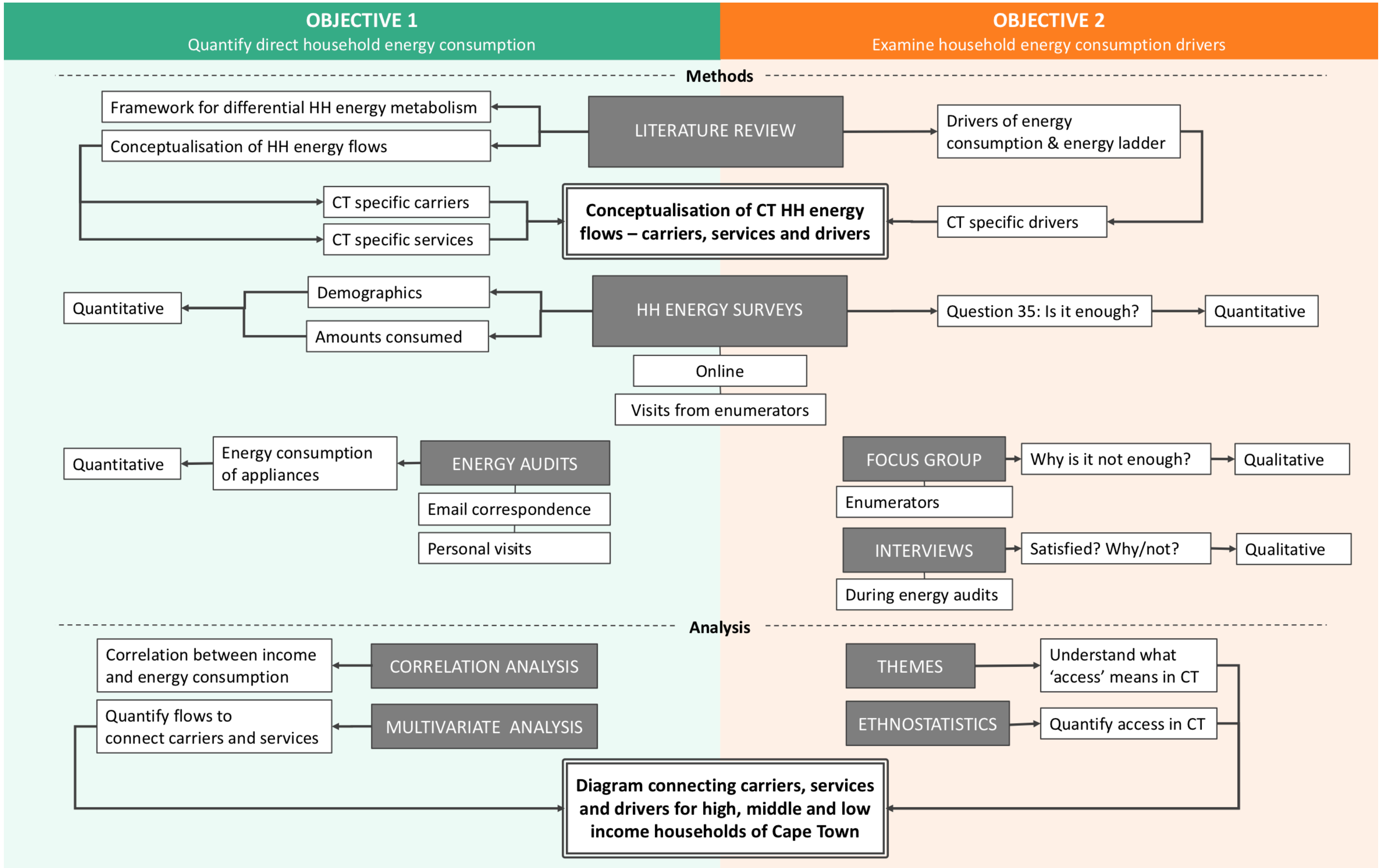

*Figure 3.1: Research design and approach. *HH = household ; CT = Cape Town*

Source: Author

3.3 Objective 1: To quantify direct household energy consumption

To reach this objective, I used three methods to collect data: literature review, household energy consumption surveys, and household energy audits. I analysed the data using statistical modelling and multivariate analysis. Each of these are discussed in the sub-sections that follow.

3.3.1 Literature review

The literature review had two aims within this objective. The first was to create a framework for differential household energy metabolism by reviewing the literature on urban metabolism, energy metabolism, and household energy consumption. The second was to conceptualise the flows of energy through the household, specifically the flows of energy carriers and energy services. The energy system that emerged from the literature review was an essential aspect in creating a depiction of household energy flows. However, this energy system was created based on studies from the Global North. Therefore, it was essential to adapt the carriers and services to correspond to the carriers and services accessed by the residents of Cape Town as a city in the Global South.

This conceptualisation is depicted in Figure 3.2. The relationship between carriers and services was quantified based on the data received, and is discussed in detail in Chapter 4. Based on the iterative process between the reviewing literature and collecting data, I made several adaptations to the services found in the literature:

- The literature distinguishes between refrigeration and freezing, but I categorised the two together as Refrigeration, as the majority of respondents own combination fridge/freezers, therefore requiring a single classification.
- I added the service of Personal grooming, as appliances such as hair dryers and electric shavers are a regular addition to households in Cape Town.
- The literature refers to 'mobile phone charging', however, as residents of Cape Town often use tablets for communication, I grouped mobile phones and tablets together as Communications.
- I added the service of House cleaning to account for the presence of dishwashers.

- I grouped the services of computing and entertainment together as Entertainment, since many residents watch television or on-demand streaming services on their computers.

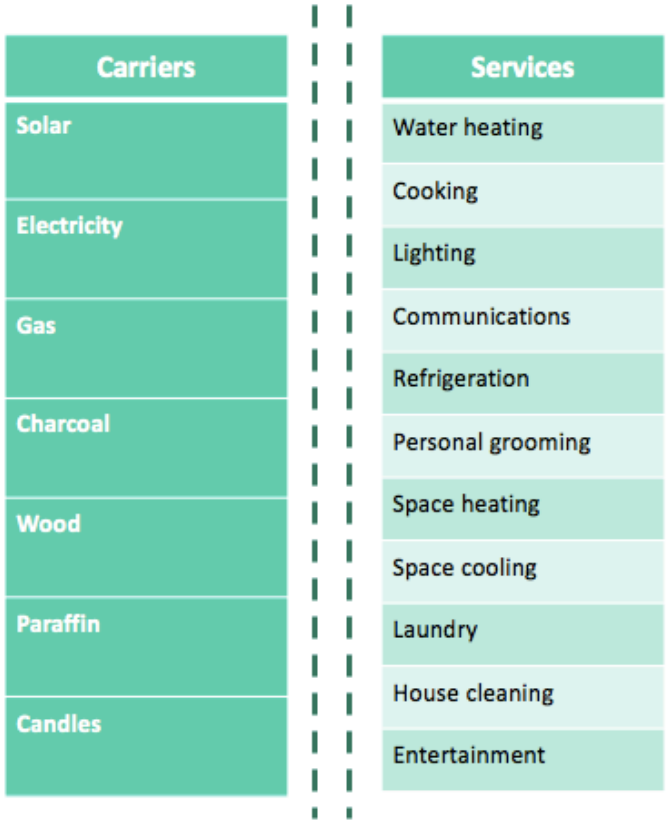

Figure 3.2: Cape Town's household energy carriers and services
Source: Author

3.3.2 Household energy consumption surveys

Survey design

I designed surveys based on the household energy consumption studies reviewed in Chapter 2. The following socio-economic and demographic parameters were of importance:

- Household composition
- Highest education level in the household
- Dwelling type
- Suburb
- Total monthly household income

In order to understand energy activity, I designed questions around the use of 44 key household appliances. I categorised the appliances twice: first by energy carrier and second by the energy services detailed in Figure 3.2. Table 3.1 details the two categorisations. The survey questions and answer choices for energy are provided in Appendix A.

Table 3.1: Categorisation of appliances into energy carriers and services

Carriers	Appliances	Services	Appliances
Solar	Solar water heater	**Water heating**	Electric geyser
Electricity	Electric geyser		Solar water heater
	Fridge		Gas geyser
	Fridge/freezer	**Cooking**	Electric hob
	Deep freezer		Gas hob
	Bar fridge		Electric oven
	Electric hob		Gas oven
	Electric oven		Cooking with wood
	Light bulbs		Cooking with charcoal
	Electric heater		Cooking with paraffin
	AC heating		Gas braai
	Fan		Kettle
	AC cooling		Coffee machine
	Dishwasher		Toaster
	Top load washing machine		Blender/food processor
	Front load washing machine		Microwave
	Tumble dryer	**Lighting**	Light bulbs
	Television		Paraffin lamps
	Laptop		Candles
	Mobile phone	**Communications**	Mobile phone
	Desktop computer		Tablet
	Tablet	**Refrigeration**	Fridge
	Music equipment		Fridge/freezer
	Gaming console		Deep freezer
	Kettle		Bar fridge
	Coffee machine	**Personal grooming**	Electric shaver
	Toaster		Hairdryer
	Microwave		Hair iron/curler
	Blender/food processor	**Space heating**	Fireplace
	Electric shaver		Electric heater
	Hairdryer		Gas heater
	Hair iron/curler		Paraffin heater
Gas	Gas geyser		AC heating
	Gas hob	**Space cooling**	Fan
	Gas oven		AC cooling
	Gas braai	**Laundry**	Top load washing machine

	Gas heater		Front load washing machine
Charcoal	Cooking with charcoal		Tumble dryer
Wood	Cooking with wood	**House cleaning**	Dishwasher
	Fireplace	**Entertainment**	Television
Paraffin	Cooking with paraffin		Laptop
	Paraffin lamp		Desktop computer
	Paraffin heater		Music equipment
Candles	Candles for lighting		Gaming console

Source: Author

The appliances in Table 3.1 clearly differentiate between energy carriers, for example ‘cooking with paraffin’ and ‘candles for lighting’. The appliances that are electric only did not require this classification. On the survey, appliances were mostly grouped together according to service; for instance, all oven types were listed under the question of cooking and respondents were able to select more than one appliance, accounting for households that may have a gas hob and electric oven, or those that sometimes cook with the oven and sometimes cook on the fire. Categorising kettles proved a challenge, as they are used to heat water, but the water heated is then used for cooking. In households without geysers, water is often heated in the kettle for bathing. However, since the majority of households use the kettle predominantly to heat water for cooking, I decided to categorise the kettle under cooking. Water heating is limited here to the water heated for bathing.

In order to make the survey accessible, I asked about the number of hours and frequency with which respondents use appliances. The phrasing depended on the nature of the appliance and I always chose the option that would resonate most with respondents. For example, I enquired about the number of loads (times) respondents did washing instead of the number of hours. I asked how frequently they used small kitchen appliances like a kettle, coffee machine, or toaster, instead of enquiring about the number of hours or minutes. For appliances like ovens or heaters, it was possible to enquire about the number of hours respondents used the appliance for. The survey provided bracketed answers, for example “3-5 hours per day” or “2-4 loads per week” to account for estimations. The accessible nature of the survey allowed residents to complete it online, without the help of an energy expert and without access to the wattage or size of their appliances.

Survey dissemination and data collection

The survey was hosted using SurveyMonkey, was available in Afrikaans, English and Xhosa, and could be completed on mobile, desktop, or tablet. The survey period was from 1 August 2018 to 30 September 2018. Surveys were distributed to respondents in two ways: using an online link and through door-to-door visits from enumerators. The expectation was that online surveys would mostly reach middle-and high-income households, with enumerators filling the gaps, as the surveys began populating the SurveyMonkey system. Participants were incentivised to take the survey by offering each completed survey the chance to win one of four R1000 shopping vouchers to the shopping mall of their choice.

As a research group, we distributed the survey online to our personal and professional networks and encouraged participants to forward it to their networks. I approached various neighbourhood organisations' Facebook groups and posted the survey on these groups in order to reach participants beyond our personal networks. As the survey covered four resource types, the average completion time was 30-40 minutes, which posed a risk for online respondents to stop filling the survey due to fatigue with questions.

A group of enumerators emerged in snowball fashion through a contact that a member of our research team made at the University of Cape Town. The contact has done similar research in the past and identified people in her network that were able to visit low-income households in various areas of Cape Town, and fill in hard copies of the surveys. The enumerators were assigned suburbs that they were familiar with, and asked to survey, in equal proportions, informal dwellings, apartments, and freestanding houses. Between August and October, the research team had three meetings with the enumerators, which are detailed in Appendix B. During these meetings, we explained the research, went through the surveys to ensure that everyone interpreted the questions the same way, and signed confidentiality agreements with the enumerators. These meetings proved useful in highlighting limitations to the survey and drawing out recommendations for its iterative improvement, as well as for future research.

The following challenges were faced specifically when surveying low-income households:

- Some enumerators found that respondents were concerned about the image they portrayed toward the stranger at their door, which led to some respondents presenting themselves as better-off, while others presented themselves as more impoverished. This challenge was overcome partly by enumerators, who were able to observe the home and offer adaptive engagement with respondents, as well as by excluding the inconsistent or outlier responses as part of the data cleaning process.

- The mobile version of the survey was difficult to navigate, thereby reducing the number of responses from those using only mobile internet; these were perceived by the research team to be lower-income households not visited by enumerators.

Final survey sample size and survey reach

Table 3.2 summarises the total reach of the survey, income groups, and household composition. This allows an understanding of whether the survey reached the intended audience of predominantly low- and middle-income households across Cape Town.

Table 3.2: Summary of survey sample, income, and household composition

Total number of households surveyed	**676**		
Total number of completed surveys	**391**		
Total number of completed surveys for Cape Town	**366**		
Total number of useful surveys for Cape Town	**360**		
Analysed surveys as per income bracket	**Input online**	**Enumerator**	**Total surveys analysed**
R1 – R1600	1	23	24
R1601 – R3200	4	32	36
R3201 – R6400	6	51	57
R6401 – R12800	11	38	49
R12801 – R25600	23	47	70
R25601 – R51200	54	21	75
R51201 – R102400	35	0	35
R102401 – R204800	7	2	9
More than R204800	3	2	5
Final sample size	**144**	**216**	**360**
Number of suburbs present	56 of 190 Cape Town suburbs		
	Average	**Median**	
Household income	R27 757.33	R19 200.50	
Household size	3.3	3	
Adults per household	2.4	2	

Source: Author

It is clear that a significantly larger number of surveys were received than analysed. I applied a series of filters to the received surveys in order to reach the final sample size of 360. This sample excludes incomplete surveys as well as surveys done in other cities beyond Cape Town. It also excludes responses that showed inconsistencies, oddities, or that presented outlier responses. While only 265 of these surveys presented useful household sizes (some respondents skipped this question), I decided to apply the average household size for each bracket to the responses that did not indicate a household size, thereby providing the means to include these surveys into the final sample size.

Responses came in from 56 of Cape Town’s 190 suburbs, with the most responses (66) received from the suburb of Khayelitsha. The enumerators, tasked with reaching lower-income households, surveyed a larger group of respondents than the online survey. However, some of their respondents earn a middle to high income. This indicates that within suburbs like Khayelitsha, Mfuleni, and Mitchell’s Plain, there reside many middle- and high-income residents, and that enumerators visited these households too. However, the spread of households across income groups and various suburbs is sufficient for studying the energy flows of low- and middle-income households and including a glimpse into the energy consumption in high-income households.

3.3.3 Household energy audits

The surveys provided me with data on the number of appliances present in the household, and the number of hours these appliances are used. For simplicity, the survey did not include any questions on the size or wattage of various appliances or the intensity at which people use them. In order to collect feedback on these aspects, I conducted energy audits at various houses. The document used to collect the data, which is found Appendix B, detailed the make, model, energy efficiency class (if applicable), wattage (located beneath or behind appliances), and intensity at which participants use these appliances. The intensity was particularly important, as no appliance runs on its maximum wattage. For instance, we tend to switch a fan on at a specific setting and we heat the oven only to a certain temperature.

At the end of the resource survey, participants could indicate whether they were interested in further research, and I selected participants from this list. I completed detailed audits for seven houses. The data analysis section will detail how I used this data, as well as in-depth desktop research, visits to appliance stores, and comparison to findings in online catalogues to quantify the responses into the final energy values.

3.3.4 Data collected for Objective 1

The data collected for the first objective, both from household energy surveys and household energy audits, was predominantly quantitative. The survey data was in the form of answered surveys, which were exported and organised digitally in Microsoft Excel. The data from follow-up energy audits were collected straight into Excel in order to make transferring the data easy. The data points came in the form of South African Rands (monthly energy expenditure), units applicable to each energy source (kg, litres, etc.), bracketed hours of use (e.g., “1-2 hours per day” or “3-4 times per week”), bracketed percentages (e.g., “10%-20%”), types of appliance, percentage intensity of typical use, and number of appliances.

3.3.5 Objective 1 data analysis: Statistical modelling and multivariate analysis

Initially, I planned to categorise household energy consumption according to low-, middle-, and high-income groups in Cape Town. However, the middle-income group proved too large. To minimise the potential for outliers, I therefore categorised the middle-income group into two groups: lower-middle-income and upper-middle-income groups. This is based on the StatsSA categorisation. The four groups are presented in Table 3.3.

Table 3.3: Classification of household groups

Income group	Monthly household income
Low-income	R0 – R6 400
Lower-middle-income	R 6 401 – R 12 800
Upper-middle-income	R12 800 – R51 200
High-income	R51 201+

Source: Author

I interpreted these data using statistical modelling. A statistical model identifies the key variables of a process and proceeds to create a representation of it, thereby capturing and describing the process (Hofstee, 2006). The type of statistical model I created was a correlation map to understand the correlation between income and energy consumption. I used the Pearson’s correlation coefficient in order to understand the strength of the relationship between income and energy consumption. As suggested by Bryman *et al.* (2011), I first created a scatter diagram to determine whether the relationship was indeed linear, and continued to determine the strength and direction of the correlation.

In order to understand services and carriers and how they relate to income, I used multivariate analysis. This type of analysis uses statistics to explore the relationship between three or more variables (Bryman *et al.*, 2011). Together, this created a differential picture of household energy consumption behaviour in Cape Town. This is appropriate for a household energy metabolism assessment, as it can represent the energy services and carriers of different households (key variables) in the form of flows (processes). I used pivot charts in Excel to summarise the data and made a visual representation of these data with pie charts and bar charts in Excel, and with Sankey diagrams using SankeyMatic.net. Sankey diagrams visually display flows of any kind, with the width of the flows depicted through their varying breadths (SankeyMatic, n.d.). I used this method of analysis to first quantify the energy services and then to connect the energy carriers and energy services in the various households using a Sankey diagram.

Since the data were collected using questions that were easy for respondents to answer, they came in a variety of units and formats. Thus the data were standardised to present total units in Joules/year. I followed the following steps to achieve a clean, numeral-only dataset:

1. Reduced all bracketed answers to a single averaged number using lookup tables. For example, “1-2 hours” became “1.5” and “3-5 times” became “4”.
2. Calculated an average timespan in hours for each appliance measured in times per day or per week.
3. Calculated an energy average with which to multiply the hours of usage, based on the findings of the energy audits and desktop research.
4. Created an Excel spreadsheet with the raw survey data and included necessary equations to reach an annual consumption value in Joules/year for each appliance.
5. Summed the annual consumption values for each appliance into totals for each carrier and each service according to the categorisation in Table 3.1.
6. Organised data using tables and applying various filters to make extracting data for individual income groups easy.

To elaborate on points 2, 3, and 5, I used various methods for calculating the energy averages and average length of time for which one uses certain appliances. These included home experiments, visits to appliance stores to gather information on the kilo-wattage of a range of appliances, online searches for appliance booklets that list the energy consumption or wattage, and the home energy audits. The data gathered and consequent energy averages reached for electric appliances is detailed in Appendix D. Some appliances required more modelling than simply multiplying the energy value with the amount of hours and intensity. The mental models for these appliances are listed in Table 3.4.

Table 3.4: Mental model for selected appliances

Appliance & question asked	Mental model
Light bulbs Percentage of light bulbs switched on for 5 or more hours per day	Nightfall to midnight = 6 hours. All those light bulbs were assumed to be on for 6 hours. The remaining light bulbs were stated to be on for 1 hour each to account for some being on for more and some for less.
Candles Amount of hours candles used for lighting	1kg of candle wax = 11,67kWh equivalent Packet of 450g candles holds 7 candles 1 candle = 75g 1kg candles = 13.3 candles 1 candle = 0.075kWh equivalent At home experiment: 7.5cm of a 24cm candle burns in 3 hours. 1 hour = 0.1 candles 1 candle hour = 0.088kWh equivalent
Coffee filter machine Amount of times used	At home experiment: 1 cup of coffee takes 4 minutes to brew Stated assumption: 2 cups for the average coffee-making session. 8 minutes per time
Blender Amount of times used	At home experiment: Blender takes 45 seconds to make a small smoothie Blender takes 2 minutes to make a large smoothie containing frozen fruit. Average of 1.4 minutes per time
Toaster Amount of times used	At home experiment: Time the length of a toasting session using the 4 out of 6 setting. 2.6 minutes per time
Electric shaver	Asked four different men about the length of time and frequency for which they charge their shavers. Conclusion: 8 hours charging per week
Hairdryer	Stated assumptions: The shortest hair-drying session is 30 seconds and the longest is up to 5 minutes. Stated length of time per hair-drying session: 2 minutes
Hair iron/hair curler	Stated assumption: 15 minutes average per session to account for longer sessions and shorter sessions

Source: Author

The processes in Table 3.4 assisted in assigning a length of time per single use of the appliance. This could then be multiplied by the number of times the appliance is used, and the energy intensity of that use. For laundry machines, translating from times used to energy consumption was a simpler process, as the energy consumption for washing machines and tumble dryers are listed in their booklets according to load. The average energy values for those are found in Appendix D. The final energy averages include not only the average wattage of each appliance, but also the efficiency and intensity where applicable. The intensity used was based on the intensities noted by participants during the energy audits.

Once the energy and hourly averages were confirmed, it was possible to create the equations in Excel (Step 5). Tables 3.5 and 3.6 summarise the equations for calculating the energy consumption based on reported activity, and energy consumption based on appliance usage, respectively. These equations were applied across each of the 360 surveys in the cleaned sample. Following this, it was possible to categorise the appliance usage into carriers and services as per Table 3.1.

Table 3.5: Calculations based on self-reported purchases of energy carriers

	Raw data	Multiply by	Equals	Multiply by	Equals	Multiply by	Equals	Multiply by	Equals
Solar PV	PV wattage	hours exposure per week averaged over summer/winter (6)	kWh/week	*52 weeks/year	kWh/year			*3.6 MJ/kwh	MJ/year
Electricity	Daily consumption or monthly spend	Interpreted using Eskom's step tariff system	kWh/year					*3.6 MJ/kwh	MJ/year
Gas	Bottles of gas per month	kg per bottle (9)	kg/month	kWh/kg (13.61)	kWh/month	Month/year (12)	kWh/year	*3.6 MJ/kwh	MJ/year
Charcoal	Bags of charcoal per month	kg/bag (5)	kg/month	kWh/kg (8.33)	kWh/month	month/year (12)	kWh/year	*3.6 MJ/kwh	MJ/year
Wood	Bags of wood per month	kg/bag (12)	kg/month	kWh/kg (5.1389)	kWh/month	month/year	kWh/year	*3.6 MJ/kwh	MJ/year
Paraffin	Litres of paraffin per month	kWh/litre (10.5)	kWh/month	*12 months/year	kWh/year			*3.6 MJ/kwh	MJ/year
Candles	Candles per month	kWh/candle (0.89)	kWh/month	*12 months/year	kWh/year			*3.6 MJ/kwh	MJ/year

Source: Author

Table 3.6: Calculations based on appliance usage

Service	Appliances	Raw data	Multiply by	Equals	Multiply by	Equals	Multiply by	Equals
Water heating	**Electric geyser, gas geyser, solar water heater**	Volume bathing/ showering	*4*dT/3412 dT = 23	kWh/day	*7 days/week *52 weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
Cooking	**Electric/gas hob, electric/gas oven, wood, charcoal, paraffin, gas braai, kettle, coffee machine, toaster, blender, microwave**	Hours used/ frequency per week	kWh/h or kWh/time	kWh/day	*7 days/week *52 weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
Lighting	**Electric light bulbs**	- Number of light bulbs - Percentage energy efficient - Percentage on for 5 or more hours a day	(five-hour-bulbs* 6hr/day) + (total bulbs – five-hour-bulbs*1hr/day)	Total light bulb hours per day	- Total bulb hours*decimal energy efficient - Total bulb hours*(1-decimal energy efficient)	- Energy efficient hours - Incandescent hours	- Energy efficient hours*kW of energy efficient bulb (0.05kW) - Incandescent hours*kW of incandescent bulb (0.01kW)	- Energy efficient kWh per day - Incandescent kWh per day
			(light bulbs cont.) Energy efficient kWh + Incandescent kWh	kWh/day	*7 days/week *52 weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
	Paraffin lamp, candles	Hours/day	*kWh/h	kWh/day	*7 days/week *52 weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year

Communications	**Mobile phone, tablet**	Hours charging/ day	*kWh/h	kWh/day	*7 days/week *52 weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
Refrigeration	**Fridge, freezer, fridge/ freezer, bar fridge**	Number of fridges	*kWh/fridge/ week	kWh/week	*52 weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
Personal grooming	**Electric shaver, hairdryer, hair curler**	Frequency per week	*kWh/time	kWh/week	*52 weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
Space heating	**Fireplace, electric heater, gas heater, paraffin heater, AC heating**	Hours used per day	*kWh/h	kWh/day	*7 days/winter week *18 winter weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
Space cooling	**Fan, AC cooling**	Hours used per day	*kWh/h	kWh/day	*7 days/ summer week *18 summer weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
Laundry	**Top load, front load, tumble dryer**	Frequency per week	*kWh/time	kWh/week	*7 weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
House cleaning	**Dishwasher**	Frequency per week	*kWh/time	kWh/week	*52 weeks/year	kWh/year	*3.6 MJ/kwh	MJ/year
Entertainment	**Television, laptop, desktop, music equipment, gaming consoles**	Hours per day	*kWh/h	kWh/day	* 7 days/week *52 week/year	kWh/year	*3.6 MJ/kwh	MJ/year

*Source: Author; *where no numerical value is indicated, this is the appliance-specific value, which is detailed in Appendix D.*

The appliances in Table 3.6 were organised according to energy services, but the same totals were used to aggregate appliances by carrier in order to study the relationship between the two. Where the calculations state a multiplication with kWh/h, the average energy value calculated for that appliance was inserted. Each of the appliances listed on the left therefore had its own set of equations to eventually reach the annual consumption or Megajoules/year column. For water heating, experts were consulted for the correct equation with which to measure energy consumption of a geyser based on the volume of water heated. For this equation, I used data from the water section of the household resource survey, which indicated the frequency of baths and showers as well as the length of time of showers and the fullness of baths. For space heating and space cooling, Table 3.6 details the stated amount of winter weeks as 18 and the stated amount of summer weeks as 18. This accounts for the three 'official' months for each season, with an added month to account for some usage in the shoulder seasons of autumn and spring.

Since the surveys collected self-reported data around both the purchase of energy carriers and appliance usage, it is useful to reflect on the effectiveness of the surveying method to collect metabolic data. The survey asked participants to i) provide the amount of each of the seven energy carriers they purchase per month, and ii) detail the number of hours or times they use the 44 appliances per day or week. Table 3.7 compares the average annual purchases per carrier with the average annual carrier consumption based on energy activity for the entire sample.

Table 3.7: Summary of household energy consumption based on purchases and activity

	Average annual household energy consumption based on reported purchases		**Average annual household energy consumption based on reported activity**	
Solar	7 MJ	7 MJ	638 MJ	683 MJ
Electricity	13 904 MJ	3 862 kWh	11 996 MJ	3 332 kWh
Gas	3 400 MJ	69 kg	1293 MJ	26 kg
Charcoal	734MJ	24 kg	812 MJ	27 kg
Wood	2 000 MJ	109 kg	1324 MJ	76 kg
Paraffin	1 344 MJ	36 litres	1504 MJ	40 litres
Candles	32 MJ	10 candles	32 MJ	10 candles
Total	21 421 MJ		17 599 MJ	

Source: Author

The megajoule (MJ) totals in Table 3.8 are also presented in the carriers' respective units in order to make the data more accessible. With the exception of paraffin, charcoal, and candles, all energy purchases exceed the energy consumed based on activity. Both charcoal and paraffin consumption are somewhat more than charcoal and paraffin purchases, while candles is the same. It is important to note that both columns are based on self-reporting, which inherently holds room for inaccuracies. There are three possible reasons for this discrepancy:

1. Respondents over-reported their monthly spending or under-reported the time spent using the various appliances.
2. The survey excluded certain crucial appliances contributing to energy consumption.
3. The energy values used to convert hourly usage to annual energy totals are inaccurate.

Figure 3.3 provides more detail by categorising the energy carriers purchased and energy carriers used based on activity, according to the nine income brackets, as they visually demonstrate the balance between values estimated from purchases and activity.

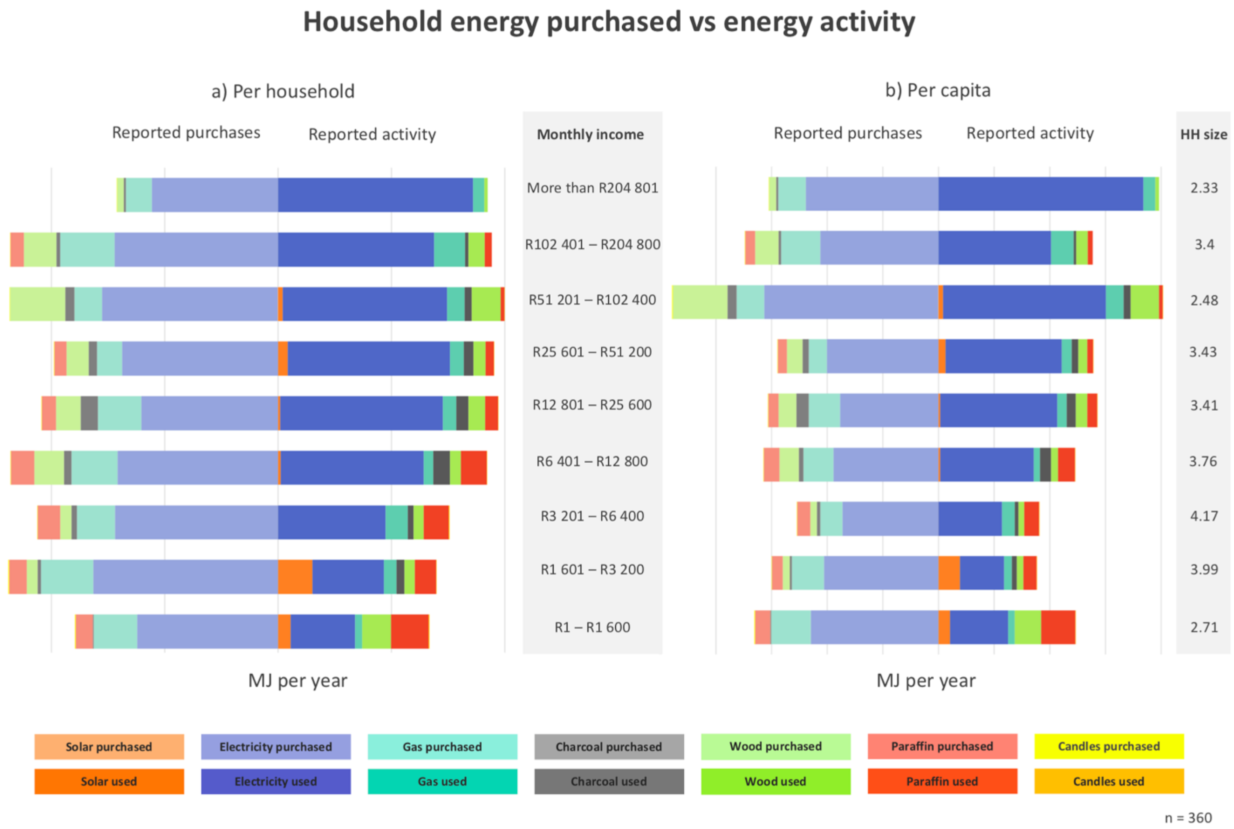

Figure 3.3: Purchased annual energy vs annual energy consumption based on activity
Source: Author

Figure 3.3(a) provides the average household consumption, while Figure 3.3(b) looks at per capita consumption, using the average household size for each income group. The average household size for each bracket is indicated on the right. For both figures, energy purchased is on the left of the axis and energy activity is on the right.

The discrepancies between energy carriers and energy purchases are fairly consistent between household level and per capita level, therefore the two figures can be discussed together for the reflection on methods. Looking at energy purchases, every income bracket, except the highest (More than R204 800), reported purchasing more energy than what they consume based on their activities. This discrepancy is, however, more pronounced in the lowest four income brackets (from R1 – R12 800). The three preceding brackets (R12 801 – R102 400) show a much smaller discrepancy between energy purchased and energy used. The pattern stops there, as the two highest income groups show significant discrepancies, first augmenting energy purchases and finally augmenting energy used.

For the four lower-income brackets, spend on both electricity and gas is generally higher than gas- and electricity-related activities. For the three preceding income brackets, electricity purchased is less than electricity used, which means that purchases for the alternative energy carriers are larger than their associated activities. Yet the overall weight remains on purchased energy. An interesting observation from the enumerators in informal settlements is that water charges are often included in the prepaid electricity price, therefore residents do not receive the amount of electricity units they pay for, because a set amount is deducted for water. This could explain the differences in electricity consumption for the lower-income brackets, but not the discrepancies for the other energy carriers. It may therefore be one or more of the three abovementioned reasons. The survey's reliance on self-reporting inherently lends itself to inaccuracies. Adding the two remaining factors to this - that the survey may have omitted certain crucial appliances and that the average energy value used to quantify energy activities may be inaccurate - one could understand the misbalance in results. For the energy values in particular, using a single average energy value may be problematic, as various sizes and wattages exist for most appliances. This is also true for non-electric appliances like paraffin lamps (that have different-sized wicks) or gas cookers (that have different-sized burner valves). The alternative energy carriers in particular require much more complex calculations to quantify, which would explain the variances in purchases versus usage for these carriers.

Overall, the method proved useful in quantifying a range of energy carriers and services. While metered data would have been more accurate, it is limited to electricity consumption, and does not convey how the electricity is used by the household. Especially in a city like Cape Town, where alternative energy sources are important to lower-income households, the survey achieved its objective of including these alternative energy sources in a household energy metabolism assessment. The method's biggest challenge was having to quantify hourly usage or frequency using average wattages and stated assumptions for the typical running time of certain appliances. The survey was, however, very accessible, and using the language in which respondents understand energy consumption rather than technical questions made it possible to distribute the survey more widely to get online and enumerator responses. While the specific energy values may be slightly inaccurate, the method still provided rich data with which to examine the relationship between carriers and services, and the methodological outcomes will allow improvements for further surveys. Including the appliances in data analysis is particularly useful, as it provides additional insight around energy activity and the opportunity to categorise this activity into energy services. This allows a discussion on energy access and energy consumption drivers, something that is impossible to do with accurate, yet generalised, household energy consumption totals.

3.4 Objective 2: To examine drivers of household energy consumption

To reach this objective, I used three methods: a literature review, household energy surveys, and a focus group with the enumerators. I analysed the data using themes and ethnostatistics.

3.4.1 Literature review

I reviewed the literature on energy drivers in order to gain an understanding of household energy access, especially in the Global South. The energy ladder was particularly useful in connecting energy drivers with energy carriers and services in the household. Following Savacool (2011), it was important to identify the drivers specific to the study. Since this study focus was in households in Cape Town that still require sufficient access to energy, I was interested in the two drivers lowest on the energy ladder: how a household could move from ‘satisfying subsistence needs’ (not having sufficient energy access) to ‘convenience, comfort, and cleanliness’ (having sufficient access). For this reason, I omitted the top driver, ‘conspicuous consumption’, as this focuses on the next level of the energy ladder (mostly associated with high-income households) and requires an in-depth study of its own. Merely considering the potential size of the high-income group in Table 3.1 attests to this.

Once I had selected the two energy drivers, it was possible to add this information to the conceptualisation of Cape Town’s household energy flows in order to create a conceptualisation of Cape Town’s household energy flows – carriers, services, and drivers. This conceptualisation is depicted in Figure 3.4. The services are re-organised according to the energy ladder in the literature as well as the energy services and carriers applicable to Cape Town. The energy ladder specifies that low-income households are driven by satisfying subsistence needs, while middle-income households are driven by convenience, comfort, and cleanliness.

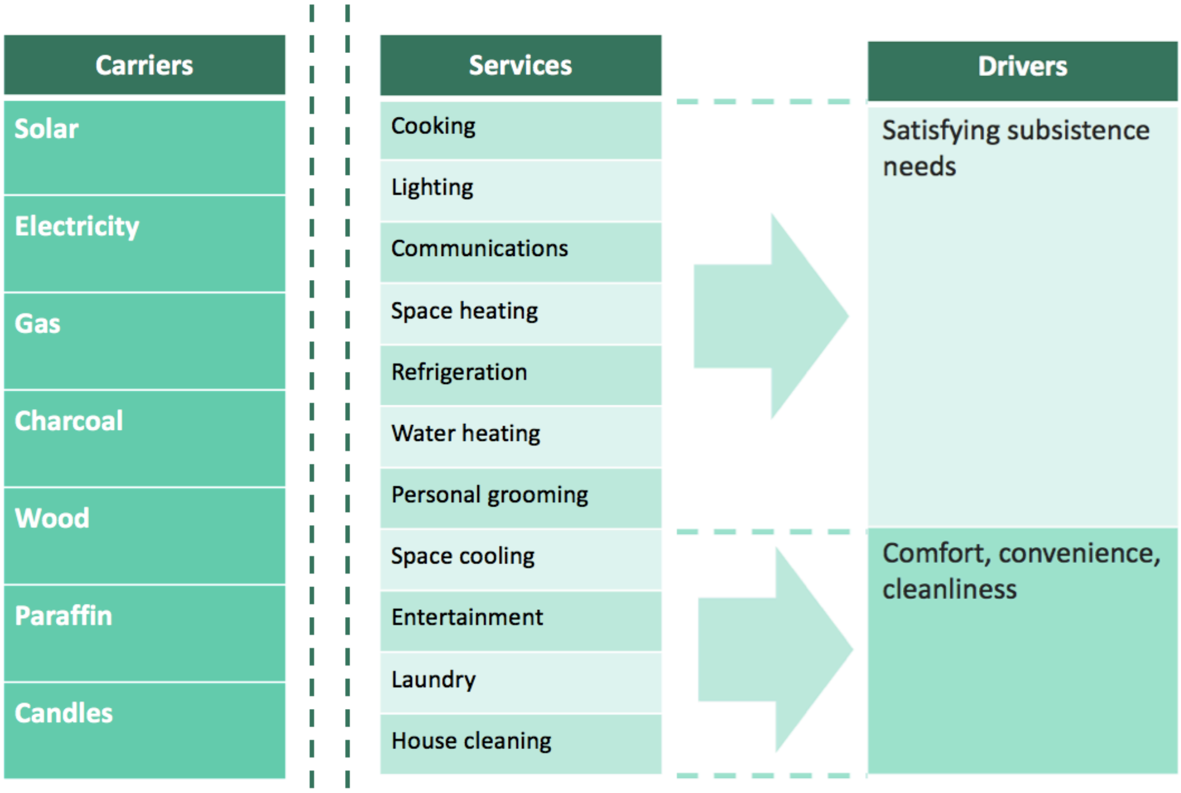

Figure 3.4: Conceptualisation of Cape Town's household energy flows
Source: Author

3.4.2 Household energy surveys

Question 35 on the household energy consumption surveys asked participants about their satisfaction with their energy. The question was: "Do the energy sources you currently have access to fulfil your energy requirements?" The answer provided a scale on which residents could select "yes", "somewhat", or "no", or anywhere in between. The question aimed to gain a basic understanding of whether residents felt they have enough energy per month. The responses contributed to the understanding of energy accessed and utilised from the perspective of local residents.

3.4.3 Focus group and energy audit interviews

Since the question on energy access remained a quantitative question, I had to gain a better understanding of what energy access and satisfaction meant to respondents. In order to do this, I conducted both a focus group session and a number of brief interviews. The focus group was held with enumerators after they completed their data collection. This session took place on 29 September 2018. The enumerators provided insight into how participants chose to interpret the question on access.

I conducted short interviews as part of the energy audits, making use of the additional time spent with respondents to gain a better understanding of their satisfaction and feelings around energy access. These questions read as follows:

1. Are you satisfied with the energy you're able to access? Why?
2. Are you satisfied with the quality of energy you use? Why?
3. Is there anything that bothers you about your energy supply?

In this way, it was possible to gain quality feedback from a small group of people that stretched across all the studied income groups.

3.4.4 Objective 2: Data analysis

Themes

I analysed the data from the focus group and energy audit interviews according to themes. Since the group of respondents was small, and since enumerators responded based on the themes they picked up, I gathered a small, albeit useful set of four to five themes and perspectives that could supplement the data around energy access and satisfaction in Cape Town.

Ethnostatistics

Ethnostatistics provides an analysis method for understanding statistics in a qualitative manner (Bryman *et al.*, 2011). Question 35 in the energy survey provided a quantitative answer (in the form of a percentage point), however, I interpreted this answer in order to speak in more detail about what access means to respondents. Table 3.7 represents my interpretation of the answer.

Table 3.8: Analysing energy drivers

Answer to Q35	Level of satisfaction
0% - 10% satisfaction	Dissatisfied
11% - 90% satisfaction	Somewhat satisfied
90% - 100%	Satisfied

Source: Author

3.5 Summary

I applied a mixed methods approach to gather energy consumption data in Cape Town to ultimately create a diagram connecting drivers, carriers, and services of low-, low-middle-, high-middle-, and high-income households. I visualised the quantitative data using Sankey diagrams to reveal how various household groups source and consume different energy services differently. The qualitative data contributed to my understanding of energy access and its various meanings.

Chapter 4 – Results and Discussion

The results presented in this chapter are based on energy activities in the household. A summarising figure allows comparison between carriers and services that households access based on income, and the distinction between aggregated household consumption and per capita consumption for each income bracket provides insight into the relationship between energy consumption and household size. Correlation maps between income and energy consumption provide further opportunity to analyse these relationships.

This chapter then delves into detail of the average household consumption for each of the four identified income groups, namely low-income, low-middle-income, high-middle-income, and high-income, presenting a full energy profile for each. This profile includes the breakdown of energy services, the breakdown of energy carriers, and a Sankey diagram, which combines the two to represent the detailed energy flows for each group. In this way, it is possible to quantify household energy flows into the household in the form of carriers, and through the household in the form of services.

The chapter closes with a discussion on energy drivers and energy satisfaction in order to add a qualitative dimension to the income groups studied.

4.2 Quantifying direct household energy consumption and associated household activities

Quantifying household energy consumption and its associated activities necessitated the understanding of the relationship between energy carriers and energy services. The first part of this section discusses energy carriers and services as they relate to the smallest income brackets studied, while the second part examines in detail the average household in each of the four larger income groups.

4.2.1 Correlation between income and energy consumption

Understanding the correlation between income and energy consumption is considered on a per capita level, as the household size decreases with an increase in income. The correlation between income and energy consumption is therefore studied at a per capita level. The correlation between income and per capita energy consumption is found in Figure 4.1. It should be noted that the correlation map includes the range found within each of the income brackets, therefore the staggered look of the map.

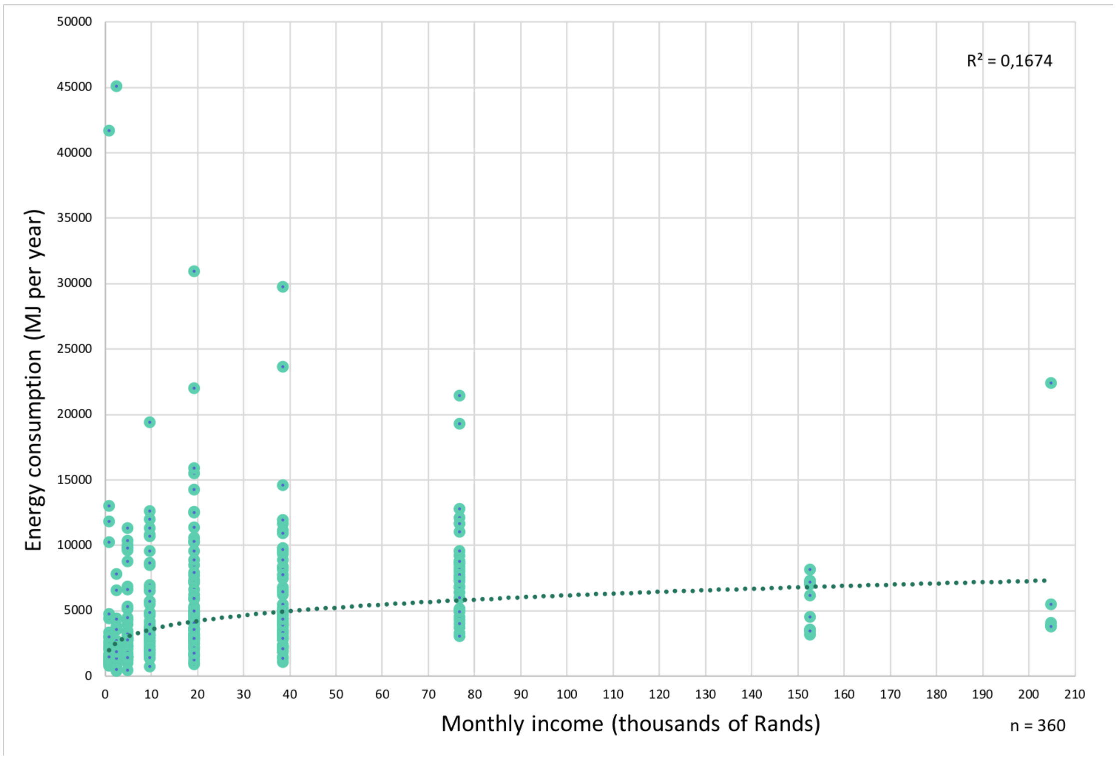

Figure 4.1: Correlation between income and energy consumption

Source: Author

It is clear when considering individual responses that there is almost no correlation between income and energy consumption. For total annual energy consumption, the correlation coefficient (R^2) is a mere 0.1674. This differs from the literature, which states a positive correlation between income and energy consumption. The very lowest consumer in each income bracket seems to increase somewhat with income, but this still does not provide the necessary support for a stronger correlation between income and energy consumption. The very highest consumer for each bracket does not show the same trend. It is now also clear to see that the sample size in the two highest income brackets were very small, and therefore skewed the chart in Figure 4.1. Four other correlation maps were created in order to chart the possible correlation between energy consumption and income for each of the four income groups. However, no strong correlation was found. These maps are found in Appendix E.

The main influencer for the lack of correlation may be the range found within each income bracket. The size of these brackets also increased with income. Had respondents been asked to indicate their exact income, a different picture may have presented itself. The nature of this study's approach to collecting data in a way that is comfortable for respondents means there is too large a range of energy consumption within each income bracket, and the findings cannot confirm the literature that states a positive correlation between energy consumption and income.

4.2.2 Understanding the relationship between carriers and services

Figure 4.2 represents energy consumption based on activity for the household brackets using the average consumption per bracket. This consumption is divided into energy carriers (the left-hand side of each diagram) and energy services (the right-hand side of each diagram). Energy carriers indicate the total amount of activity for each carrier for each income bracket, while energy services indicate the end-use of energy for each bracket. This diagram provides an initial look at how the balance between carriers and services changes with income.

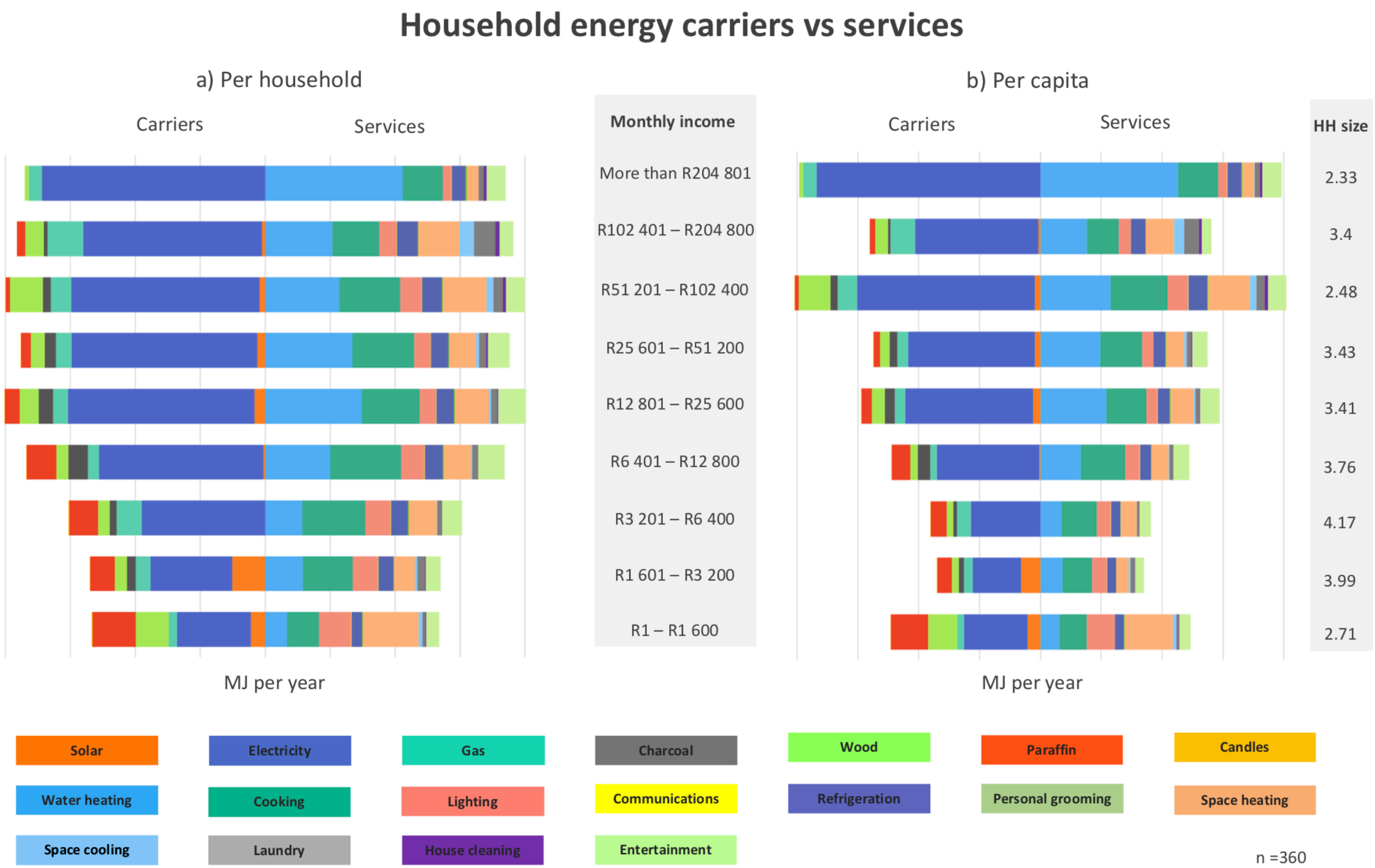

Figure 4.2: Household energy consumption divided into carriers and services

Source: Author

Figure 4.2(a) provides insight on household level and Figure 4.2(b) shows energy consumption per capita, which highlights the effect on average consumption as household size decreases and income increases.

Consumption of solar thermal energy in the form of solar water heaters is much more prevalent in the lower income groups as opposed to the higher income groups. This could be an indication that the government housing often includes low-pressure solar water heaters. It seems that there remains a lack of incentives for middle- and high-income households to invest in solar water heaters for water heating.

One of the most prominent energy services, water heating, increases with an increase in income from R1 per household per month up to R51 200 (the lower six brackets). Water heating here refers only to showering and bathing. Therefore, the higher the household's income, the higher the frequency or length of time residents spend taking baths and showers. Interestingly, this finding is consistent for both household and per capita level energy consumption, which means that even though household sizes decrease as income increases, the household's overall water heating activities continue to increase along the income increments. Beyond an income of R51 200 per household per month, water heating reduces at household level and remains consistent at per capita level, which indicates that the per capita water heating activities may stay consistent in households with an average of two or three residents; however, those per capita water heating activities are less in houses with more residents when they earn less. It could also indicate that lower income households still lack access to geysers for water heating.

The service of cooking seems to increase with income at both per capita and household level up to R12 800 monthly earning, after which it decreases consistently into the high-income brackets. This could be a reflection of the carriers used for cooking, as the lower-income groups clearly consume more alternative energy sources like paraffin and wood. Space heating is the third most prominent energy service, but it contributes a significantly smaller amount of the overall energy as opposed to water heating and cooking. This could be because Cape Town enjoys a temperate climate and not the sub-zero temperatures often experienced in the northern hemisphere where many of the studies referred to in Chapter 3 were conducted. Space heating is a fairly important service regardless of household income. Similar to cooking, space heating can be fulfilled with different energy carriers. Especially in the lowest income bracket, where space heating is significantly higher than the preceding brackets, the households also consume higher amounts of paraffin and gas, meaning that while the total amount of hours used heating the house may be far less than in a higher income house, the energy carriers are less efficient, thereby increasing the energy needed to allow the indicated amount of space heating time. The same is true for the income bracket of R51 201 – R102 400. In this bracket, wood is a significant energy carrier and space heating is much higher than the preceding brackets, therefore it could be concluded that in this bracket, fireplaces are often used for space heating, which carries a lower energy efficiency that electric heaters.

The service of lighting decreases as income increases, which is a very interesting finding, since the size of the house and therefore the amount of lights needed to provide lighting is usually positively correlated with income. There are various reasons for this, and they stem from the fact that lighting is provided by electricity, paraffin, and candles, although the presence of candles for this argument is considered insignificant. Seven of the nine income brackets use paraffin in the household, and since paraffin lamps are much less efficient than electric light bulbs, it is understandable that as paraffin consumption decreases with an increase in income, the energy needed to provide lighting also decreases. This could also be why lighting seems a fairly important energy service even though the literature would not allocate such a large portion of total household energy consumption to lighting. Further, higher income households may also be in the position to purchase more energy-efficient light bulbs, thereby reducing the total energy needed for lighting.

4.2.3 Quantifying energy flows for low-income households

This section explores the relationship between carriers and services in more detail by looking at four income groups: low-income, low-middle-income, high-middle-income, and high-income. The multivariate analysis made it possible to relate carriers and services to each of the four income groups using pie charts and Sankey diagrams.

Figure 4.3 visualises the average annual energy consumption for low-income households. Figure 4.3(a) indicates the categorisation into carriers and Figure 4.3(b) categorises energy consumption into services.

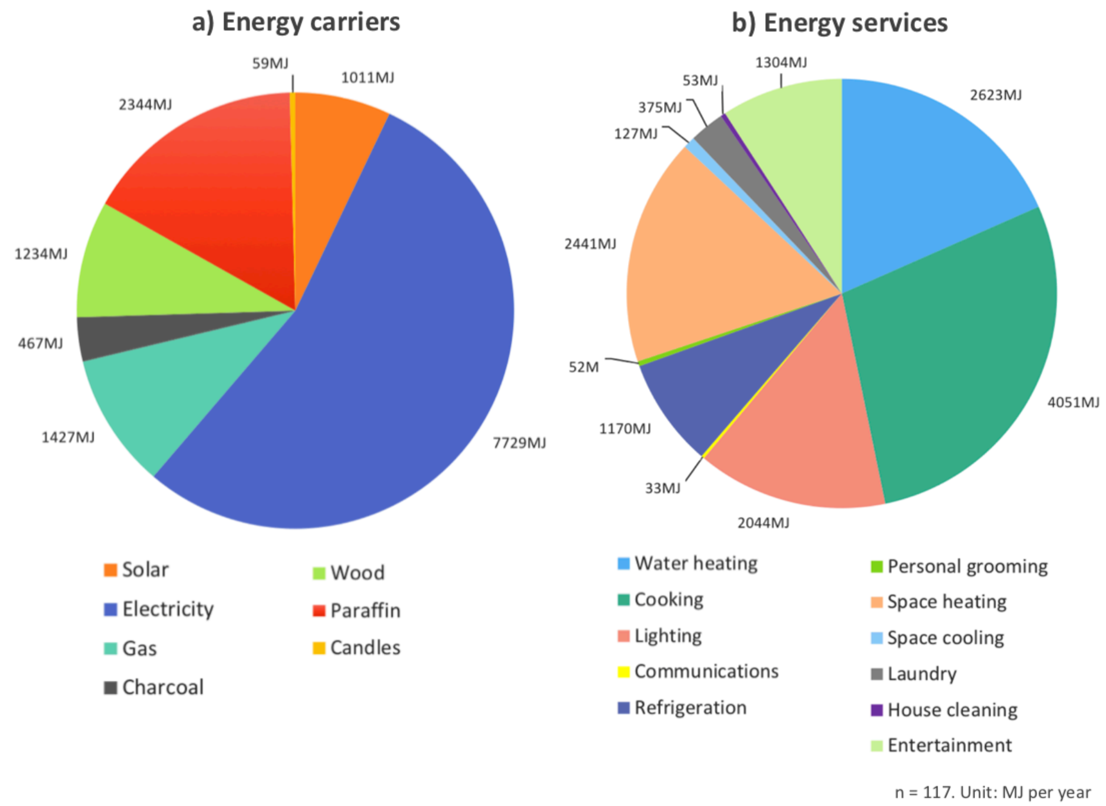

Figure 4.3: Average energy flows for low-income households: Carriers and services
Source: Author

By far, the most dominant energy carrier in the average low-income household is electricity at 7729MJ per year, which is 54% of total energy. This equates to 2147kWh per year, which is 179kWh per month. Following this is paraffin at 2344MJ per year, which is 17% of total energy. This equates to 62 litres of paraffin, which is 5 litres per month. Wood (9%) and gas (10%) contribute fairly equal shares of the total household's energy consumption. Interestingly, solar provides quite a significant portion of energy among low-income households (7%). This is solely attributed to the presence of solar water heaters in many of these households. While electricity remains the most dominant carrier, the average household includes a wide range of energy carriers, which is consistent with the literature that suggests low-income households typically access a broader spectrum of energy carriers.

Cooking is the most dominant service in this household group, consuming more than 4000MJ per year, which is 29% of total energy consumption as opposed to 19% for water heating. A reason for this is that many low-income households do not own geysers. This study categorised kettles under cooking rather than water heating, therefore water heating may be larger when considering that many low-income households use kettles to heat water for bathing. The reason for this was that for the majority of households, kettles are more frequently used for the service of cooking than for water heating, as it is used to boil water for making a range of different dishes as well as hot drinks, all of which this study chose to categorise as cooking. Water heating in this case was limited to the water needed to bathe.

A prominent finding is the significant proportion of the service of entertainment. When looking at the results in more detail, 109 of the 117 households own television sets, while only 34 own geysers. The previous section highlighted that using energy sources other than electricity for a specific service often increases the portion this service covers for total energy consumption. However, entertainment consists of only electric equipment, indicating that televisions, and even computers and music equipment, play an important role in low-income households.

Figure 4.4 is a Sankey diagram combining the carriers and services in order to visualise how energy flows into the households in the form of carriers, and through the household in the form of services. When considering that electricity contributes to all 11 of the services, it is easy to see why it is such a dominant energy carrier. Within each energy service, electricity is the most dominant contributor to that service with three notable exceptions. Nearly equal amounts of solar and electric energy contributes to water heating, indicating the importance of solar water heaters for low-income households in Cape Town. Interestingly, gas also contributes to a portion of water heating, indicating that these households sometimes own gas geysers.

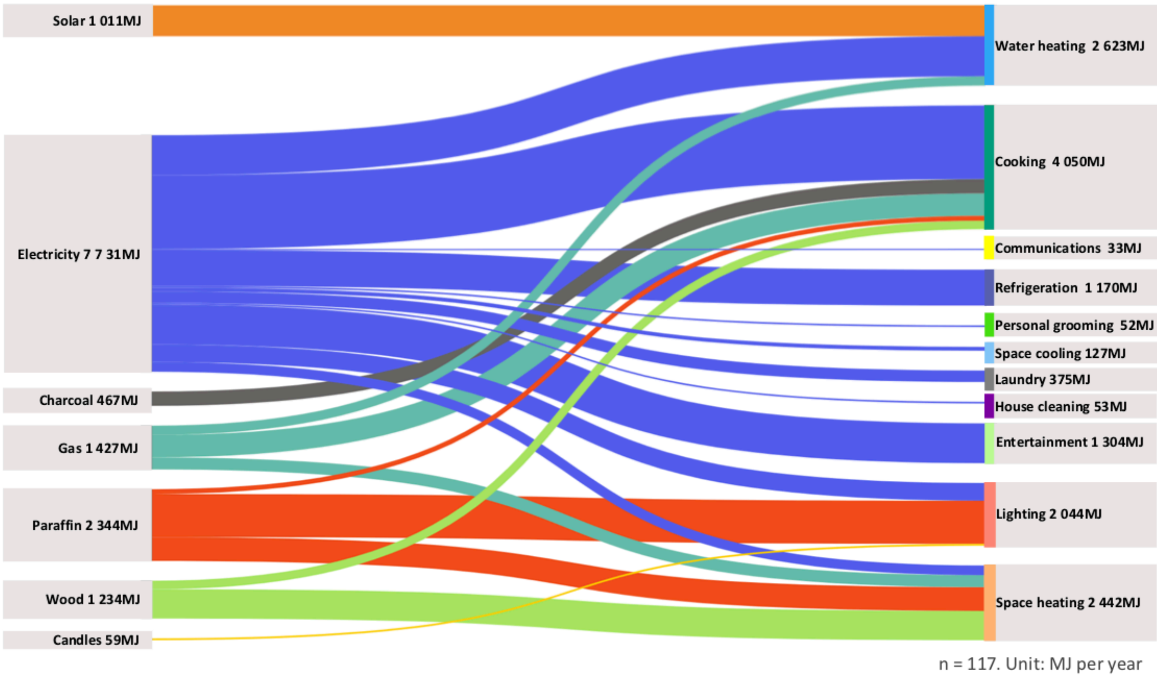

Figure 4.4: Average energy flows for low-income households: Sankey diagram
Source: Author

Lighting is largely fulfilled by paraffin instead of electric light bulbs. While this may seem like most of these households have paraffin lamps instead of electric light bulbs, it is really an indication of the vast difference in energy consumption between these two lighting sources. Almost all (113) households in this income group have electric light bulbs, while only 22 have paraffin lamps, mostly in addition to electric light bulbs. The other service where electricity is not the dominant carrier is space heating. Four different carriers contribute to space heating, which makes it the service with the second most diverse carrier list. Once again, electricity (electric heaters and air conditioning for heating) contributes the least amount of energy to space heating, closely followed by gas. In this case, it is because only eight households use gas heaters while 34 use electric heaters. 45 households use paraffin heaters during winter, which together with its lower efficiency, indicates why paraffin is such an important carrier for space heating. Wood is by far the largest contributor to space heating, which is interesting as only 10 of the low-income households studied indicated using a fireplace. This once again speaks to the efficiency of using wood for space heating. Considering the diverse carriers contributing to space heating and lighting, it is easy to understand why these two carriers are the second and third most dominant in the average household.

It is crucial to understand energy efficiency in order to understand the energy profile of low-income households. In order to move toward a more sustainable energy system, the intervention points for low-income households are therefore not around reducing energy consumption, but rather in changing energy carriers. This is also consistent with the literature. In Cape Town, a move away from wood, charcoal, and paraffin for cooking, lighting, and space heating could reduce overall energy consumption without compromising the comfort these households experience. Since wood is carbon neutral and charcoal and paraffin may seem a better option for the environment than fossil fuel-based energy sources like electricity. Electricity is much more affordable than its energy equivalent in paraffin or charcoal, while providing space heating, lighting, and cooking that is not as dangerous to the health of the residents than fuel- or biomass-based alternatives. Ideally, the city could use more renewable energy to power the electricity grid rather than demanding more 'sustainable' energy choices by residents of informal settlements. Similarly, in order to grant more residents access to hot water on demand, it is important to deploy solar water heaters rather than electric geysers. Solar is already a dominant hot water carrier and continuing this would increase access to hot water without increasing fossil fuel-based energy consumption.

4.2.4 Quantifying energy flows for low-middle-income households

Figure 4.5 is a representation of the energy flows into and through a low-middle-income household. The number of households represented in this group is 49.

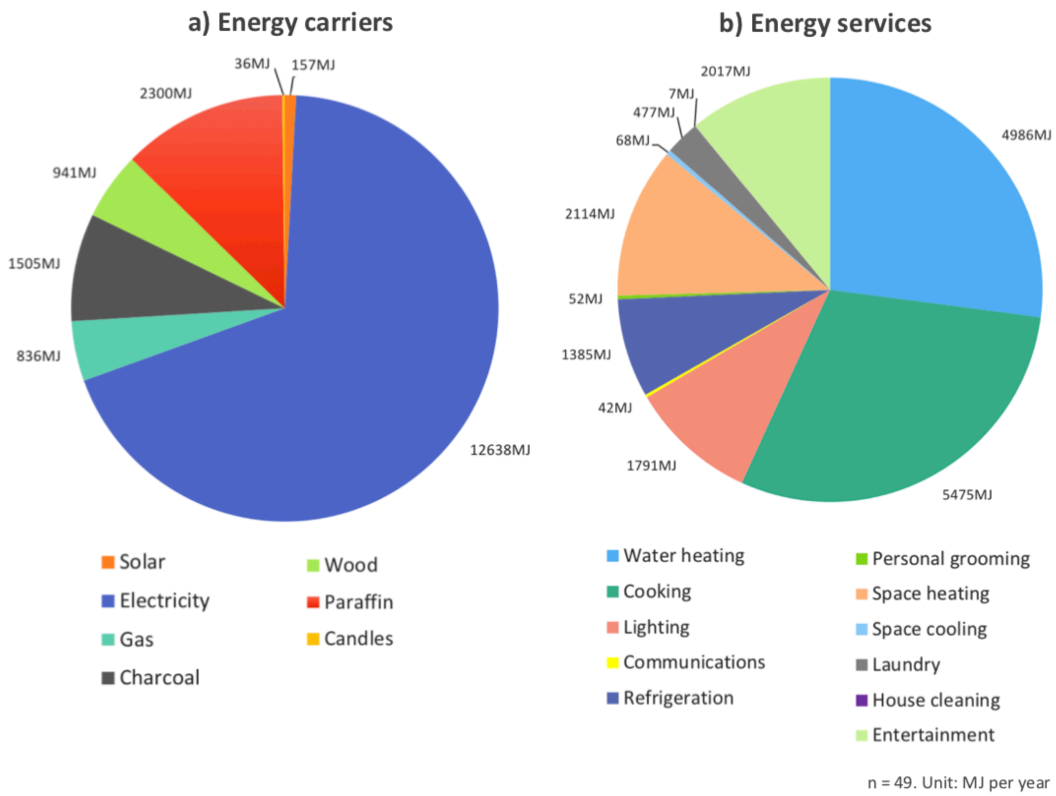

Figure 4.5: Average energy flows for low-middle-income households: Carriers and services
Source: Author

Figure 4.5(a) indicates that the most dominant energy carrier remains electricity with 12638MJ per year, which equates to 69% of the total energy consumption and 3511kWh per year, which is an average of 293kWh per month. This is significantly more than the average low-income household, which is consistent with the literature's argument that electricity consumption increases with income. The second most prominent carrier remains paraffin, this time with 2300MJ per year, which is 12% of total energy requirements, and 6 litres per year or an average of half a litre per month. Contrary to electricity, there is barely a difference between the amount of paraffin used in the average low-income household as opposed to the average low-middle-income household. Therefore, while access to energy clearly increases for this income group, residents depend less overall on paraffin, as it constitutes a smaller proportion of total energy requirements. Interestingly, charcoal plays an important role in the average low-middle-income household and fulfils 8% of total energy requirements. The presence of alternative energy carriers remains colourful, albeit less diverse, and shows a varied profile of energy carriers for this income group.

According to Figure 4.5(b), the most dominant energy service is once again cooking as opposed to water heating. Cooking contributes 30% to the total energy services while water heating contributes 27%. The difference between these services are smaller than in the average low-income household, but the fact remains that cooking is the most important service in the average low-middle-income household. For this income group, 24 out of the 49 households own geysers. To compare to the average low-income household, this translates into 49% of households with geysers in low-middle-income households as opposed to 29% of low-income households. While this is a significant increase, it remains concerning that less than half of households in this income group lack this basic means of energy access. Entertainment is once again an important energy service for the average low-middle-income household, contributing 2017MJ, or 11%, of the household's energy services. 48 out of the 49 households (98%) own television sets.

Considering Figure 4.6, which shows the Sankey diagram of how energy flows from carriers to services, it is interesting to note that solar water heaters play a much smaller role in water heating than with low-income households. This could mean that fewer of the low-middle-income households live in government-funded housing with pre-installed solar water heaters, or it could reflect the small sample size. Nonetheless, electricity plays a much more important role in heating water for the average low-middle-income household than in the average low-income household.

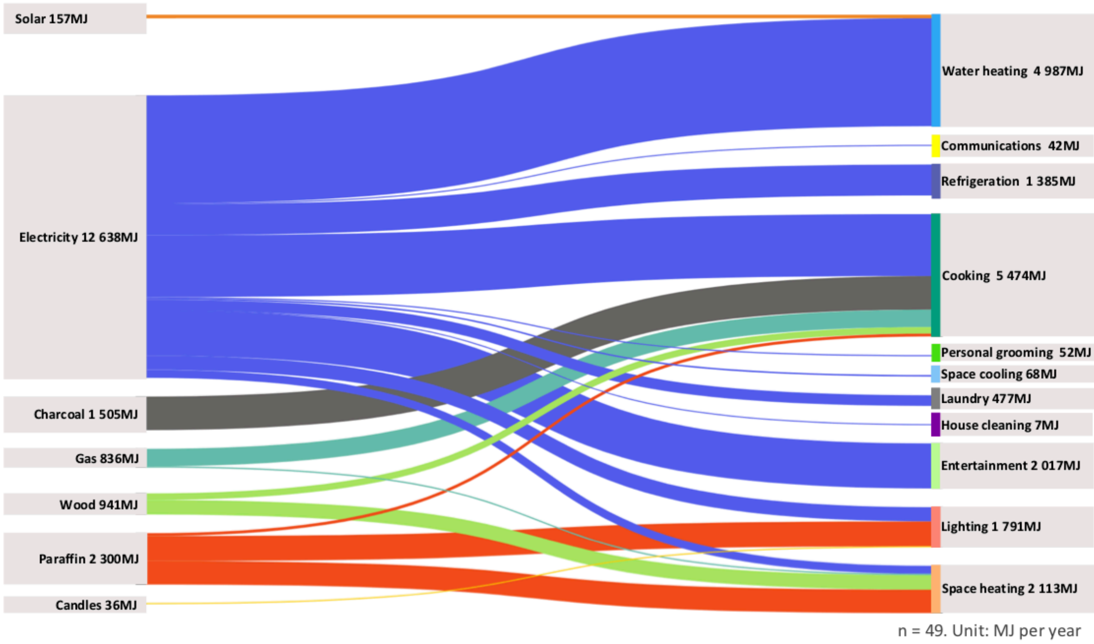

Figure 4.6: Average energy flows for low-middle-income households: Sankey diagram
Source: Author

Electricity is once again present for all services and became visibly more dominant overall. For services that have multiple carriers, electricity only dominates in the service of cooking. Interestingly, charcoal is the second most dominant carrier for cooking, as opposed to gas in the low-income group. Residents use an average of 4kg charcoal for cooking per month. Compared to the 64kWh electric cooking per month, the significance of charcoal seems to decrease slightly. This speaks to the inefficiency of cooking with charcoal. While paraffin is the most important energy source for lighting, it is much less significant than in low-income households. This may be why the entire service of lighting decreased with 253MJ, even though the households' income increased. Indeed, there is a decreased reliance on inefficient paraffin lamps and an increased reliance on light bulbs. 48 of the households in this group (98%) use electric light bulbs while only seven (14%) use paraffin lamps. For space heating, the reliance on wood decreased somewhat. Five households (11%) have fireplaces while 17 (35%) have paraffin heaters. Overall, the reliance on wood and paraffin for space heating and lighting has therefore decreased with the increase in income.

In order to aim for a more sustainable energy system, much of the same intervention points exist in the average low-middle-income household as in the average low-income household. Inefficient energy carriers like charcoal and paraffin increase overall energy flows and even though these carriers may be considered more sustainable, access to more electricity for cooking, space heating, and lighting may provide these households with a better opportunity to access sufficient energy. A further intervention point is water heating. Solar water heaters will undoubtedly make energy flows more sustainable; however, this group seems to fall mostly outside the national roll-out plan for solar water heaters, and since they are much more expensive than electric geysers, it is unlikely that these households would choose solar.

4.2.5 Quantifying energy flows for high-middle-income households

Figure 4.7 represents the energy flows into and through the average high-middle-income household in the sample.

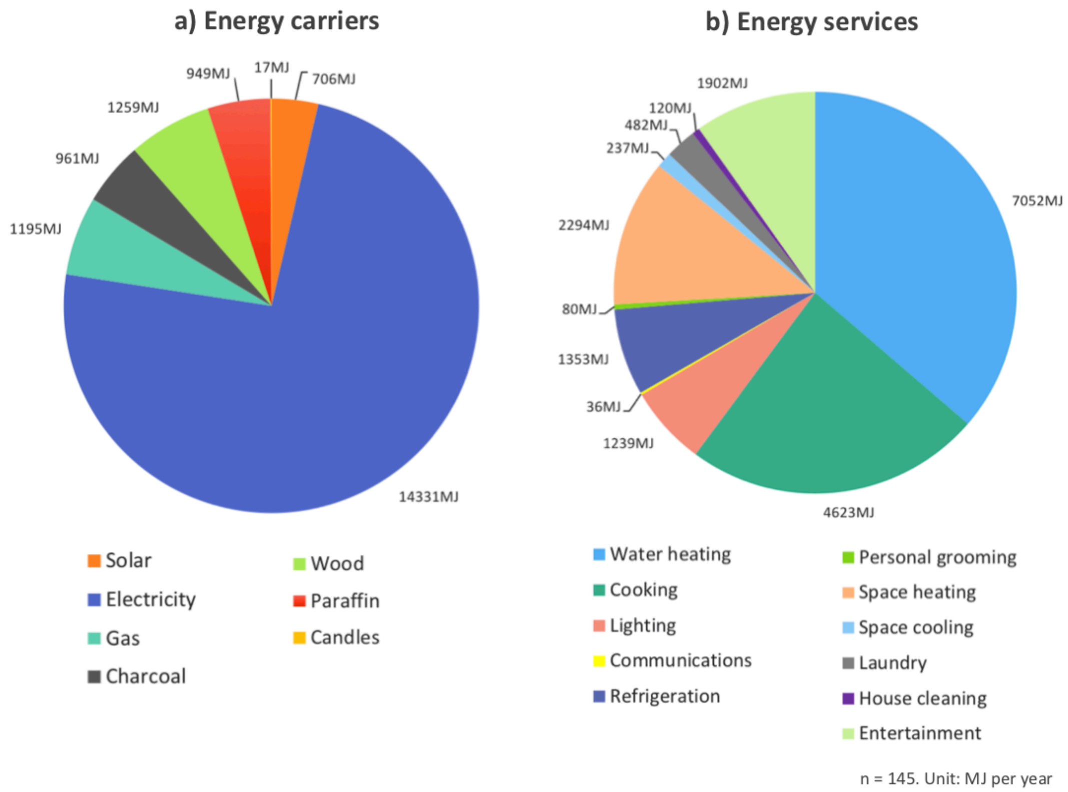

Figure 4.7: Average energy flows for high-middle-income households: Carriers and services
Source: Author

As expected, electricity is the dominant energy carrier, and both the total amount of the translated energy and the portion of total energy requirements met by electricity increased with an increase in income. Electricity here supplies 12331MJ per year, which is 74% of energy requirements, 3425kWh per year and 285kWh per month. Interestingly, this indicates an overall reduction in electricity consumed per month. For the first time, paraffin is not the second most dominant energy carrier. Paraffin contributes 949MJ per year (5%), which translates into 25 litres per year – only 2 litres per month. Wood (6%), gas (6%), and charcoal (5%) contribute a similar portion to the total energy requirements. Even though the presence of paraffin significantly decreased as households reach a higher income tier, it is interesting that paraffin still has a presence. The literature suggests that paraffin, often associated with low-income households, would not be present when households reach the higher income tiers. The overall energy profile remains diverse for this income group; however, electricity is clearly dominating.

According to Figure 4.7(a), for the first time, the dominant energy service is water heating at 36% followed by cooking at 24%. Therefore, while cooking remains a very important energy service, water heating overtakes it as the largest consumer of household energy. A much larger portion of this income group owns geysers, 93 out of 117, or 80%. Several households in this group also own more than one geyser, a finding that is very rare in the lower-income groups. Compared to the low-middle-income group, this is a significant increase. For the first time, the two smaller services of laundry and space cooling start taking up a larger portion of total energy requirements.

Very interesting is that cooking, lighting, refrigeration, and space heating all experience a decrease in the total energy requirements in Figure 4.7(b). This is not a decrease in the percentage attributed to each of these services, but the total amount of energy used to fulfil them. This could be attributed to a decrease in the average household size or a decrease in alternative energy carriers. Of particular importance is the decrease in entertainment between low-middle- and high-middle-income households. This service decreases by 1% with the rise in income. Since entertainment is only fulfilled by electricity, energy efficiency of carriers cannot be held responsible. Looking in more detail, only 83% of high-middle-income households own televisions compared to the 98% in the low-middle-income group.

Figure 4.8 provides a Sankey diagram of the average energy flows in the high-middle-income group. The energy carriers used to fulfil the services of cooking, lighting, and space heating remain equally diverse with an increase in income. Looking in more detail at the amount of each carrier contributing to the service might reveal, however, why some of the core energy services experienced a decrease in energy requirements. For cooking, a very small portion of paraffin now contributes to this service, only 33ml per month. Charcoal for cooking also decreased from 4kg to 3kg per month. Gas remained steady at 1kg per month and cooking with electricity decreased to 61kWh per month. Therefore, the decrease in less efficient carriers like charcoal and paraffin as well as an overall decrease in electric cooking caused the reduction in energy used for cooking.

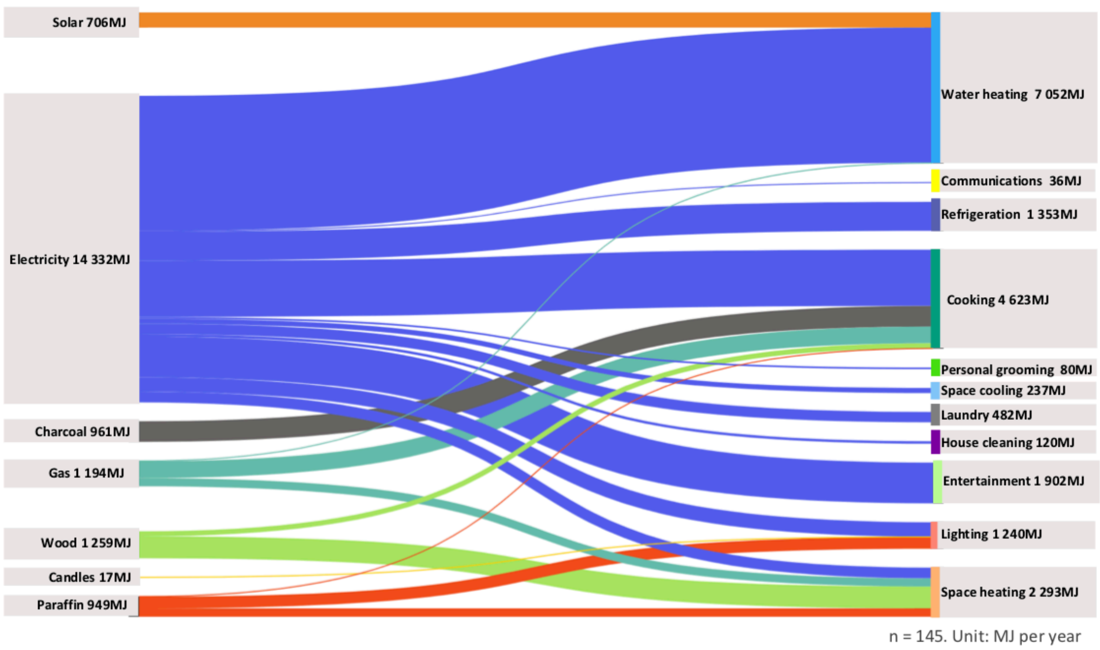

Figure 4.8: Average energy flows for high-middle-income households: Sankey diagram
Source: Author

For lighting, high-middle-income households use 1.2 litres of paraffin and 16kWh electricity per month while low-middle-income groups use on average 2.5 litres of paraffin and 11kWh of electricity per month. Low-middle-income households have an average of 8 lightbulbs per household, while high-middle-income households have an average of 10 light bulbs per household. Seeing as there is an increase in electric lighting, yet a decrease in overall energy required for lighting, the decrease in paraffin lamps is definitely the reason why this group uses less energy for lighting than the preceding one.

For space heating, the amount of paraffin used decreased significantly as income increased, which explains the decrease in total energy needed for space heating. Wood contributes the largest portion to space heating, with electricity, paraffin, and gas holding similar energy values. Since wood is an inefficient method for space heating, the overall decrease in energy for space heating might also be attributed to the level of insulation of the house. The literature suggests that a higher income household typically has better insulation and therefore requires less space heating energy. Comparing the insulation of an informal dwelling with that of a brick house supports this argument. It remains unclear why the total energy for refrigeration decreased with an increase in income, as refrigeration uses only electricity. Feedback from one of the enumerators suggests that many lower-income households run food-related businesses from home. This could explain the higher energy requirements for refrigeration in the two lower-income brackets as opposed to the high-middle-income bracket.

In order to achieve a more sustainable energy system, the intervention points for the high-middle-income group become slightly different from the two previous groups. While paraffin, wood, and charcoal remain present, their contribution to total energy requirements is so small that these would not be sufficient interventions. At this point, it becomes important to address the amount of electricity used by households. Water heating, for instance, requires a significant portion and is therefore perhaps the most feasible intervention point. A fairly small portion of water heating (10%) is currently fulfilled by solar water heaters, but it could be assumed that these residents invested their own money into this more sustainable form of water heating and that adopting more of these types of interventions may be possible should the appropriate incentive arise. Cooking is also a large consumer of electricity, making this an additional intervention point. Lastly, even though these services consume only a small portion of total electricity, interventions around frequency of space cooling and house cleaning would also reduce overall household energy consumption.

4.2.6 Quantifying energy flows for high-income households

Figure 4.9 represents the energy flows in and through high-income households.

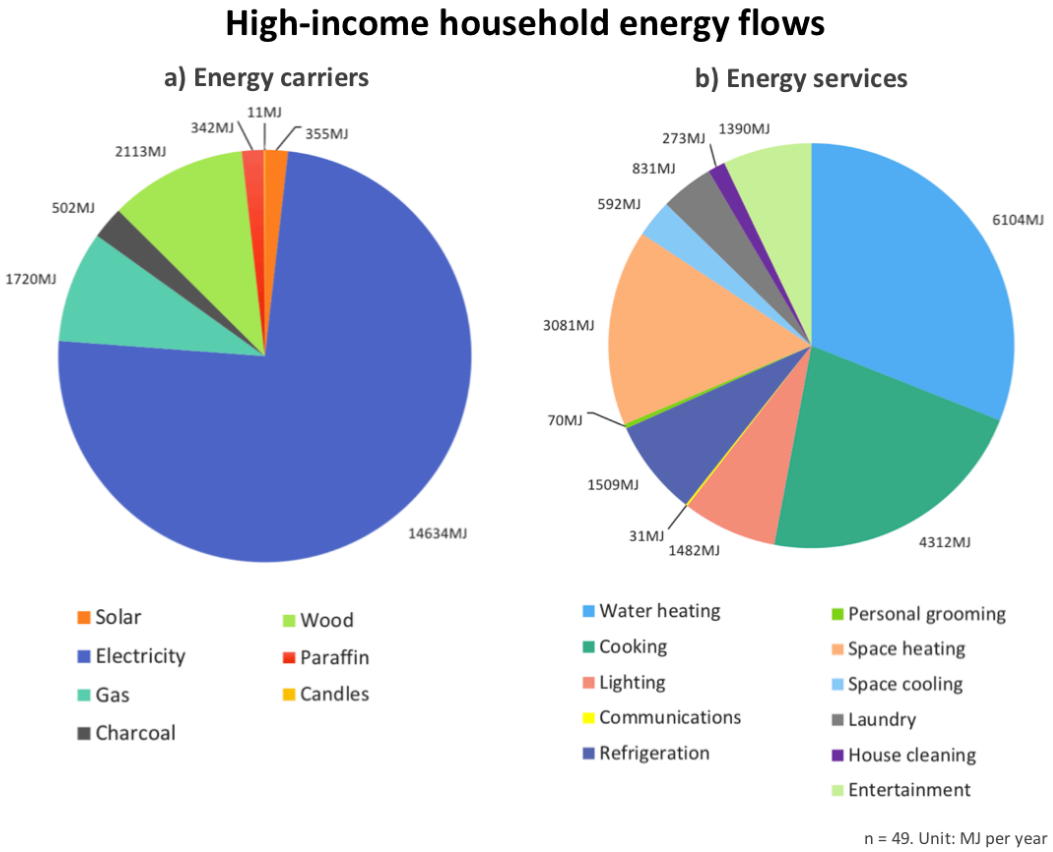

Figure 4.9: Average energy flows for high-income households: Carriers and services
Source: Author

Two interesting findings emerge from Figure 4.9(a), which depicts the distribution of carriers to meet total energy requirements. Firstly, while the percentage of electricity contributing to total energy requirements is the same as the high-middle-income group (74%), the total amount of electricity increased with income. Electricity contributes 14634MJ per year, which is 4065kWh per year and 339kWh per month. This is a fairly small amount considering the potential income earned in this group. A reason for this could be the small sample size for high-income households. Secondly, at 342MJ, or 9 litres per year, paraffin plays a small role in overall energy requirements, reaching only 2%. Even though the literature suggests that energy carriers become less diverse with an increase in income, this was not true for the current study. Consumption of paraffin may have decreased, but the same carriers remain present as income increases.

In Figure 4.9(b), water heating remains the most dominant energy service for high-income households, but it contributes a smaller portion, as well as a smaller amount of energy than the high-middle-income group. Water heating uses 6104MJ per year, which is 31% compared to the 36% in the high-middle-income group. A reason for this could be that the average high-income household size is two compared to three for a middle-income household. Cooking remains the second most dominant energy service ,and all the same energy services are dominant: lighting, refrigeration, and space heating. Energy required for lighting and refrigeration increased with income, but cooking decreased slightly. A notable increase in energy consumption is for space heating, which increased from 12% in the high-middle-income group to 16% in the high-income group. The total energy attributed to entertainment once again decreased with an increase in income. This is true despite the fact that 88% of high-income households own televisions, which is more than high-middle-income households, but still less than low-middle-income households. Interestingly, 96% own computers, which is the highest for all income groups. Both low- and high-income groups watch an average of six hours of television a day, so the only reason for the overall decrease in entertainment across the four groups is the decrease in the number of households that own televisions as income increases.

In the Sankey diagram of the high-income household (Figure 4.10), it is possible to see why the service of space heating increased so significantly. Wood is the most significant contributor to space heating in this income group. The same was true for the low-income group. However, the low-income group used an annual average of 52kg of wood, compared to 102kg of wood per year contributing to space heating in the high-income group. Even though electricity contributes a much larger portion to lighting than paraffin, overall lighting requirements increased, which means that high-income households potentially reside in bigger households requiring more electric lighting.

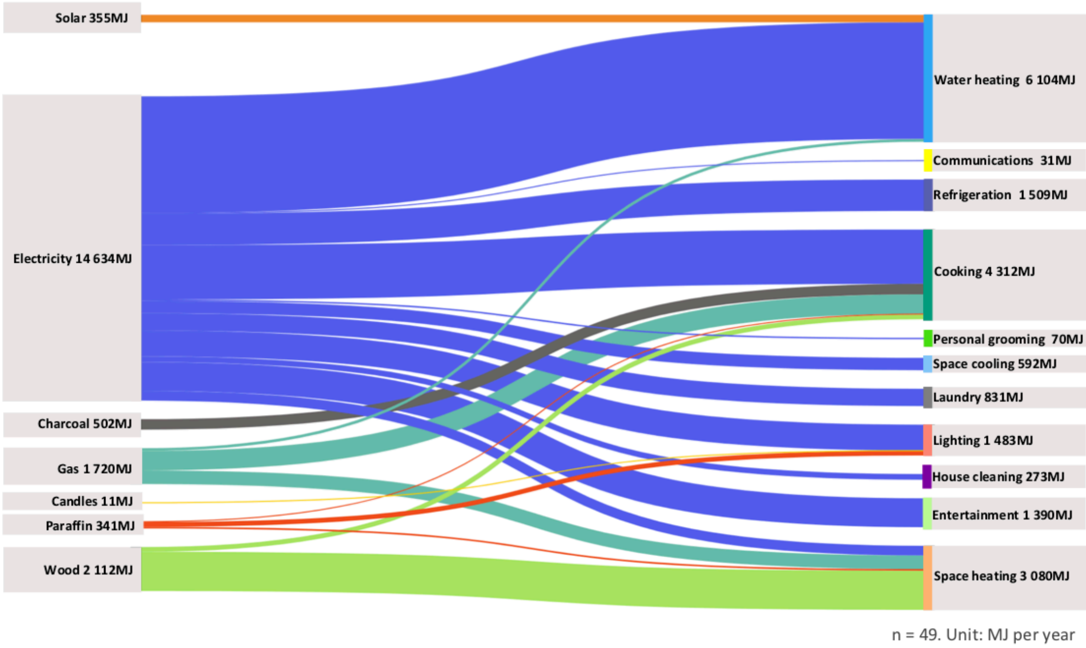

Figure 4.10: Average energy flows for high-income households: Sankey diagram
Source: Author

Only a very small portion of cooking and space heating is fulfilled by paraffin. That high-income households own paraffin appliances at all, remains interesting. A closer inspection reveals that the high-income households that consume paraffin are located in informal settlements, even though they reside in freestanding houses. These households may be in the habit of using paraffin heaters, ovens, and lights or they simply prefer them above electric alternatives. The portion of water heating supplied by solar in high-income households is lower than high-middle-income households, with 6% as opposed to 10%.

In order to make the energy system more sustainable, much of the same intervention points highlighted for high-middle-income households are relevant for high-income households. The two most prominent intervention points are for water heating and cooking, where electricity contributes a significant portion. Once again, the potential for solar water heaters is significant and there also exists potential for gas, especially if natural gas is an option. Entertainment and refrigeration contribute the next level of intervention points with the 'luxury' services, like laundry, house cleaning, and space cooling providing possible third-level intervention points. Overall, intervention points for high-income households exist more along reducing energy consumption than replacing carriers with more efficient alternatives.

4.3 Examining drivers of household energy consumption

This section relates energy services accessed by the four income groups to the energy ladder, in order to speak about drivers of energy consumption. This section then analyses the reported energy satisfaction of the four different income groups in order to gain further insight on what energy access means for Cape Town.

4.3.1 Energy services and the energy ladder

According to the energy ladder for Cape Town, households where the energy consumption is driven by satisfying subsistence has access only to the services of cooking, lighting, communications, space heating, refrigeration, water heating, and personal grooming. The services of space cooling, entertainment, laundry, and house cleaning signify a household's rise to the second tier, which is comfort, convenience, and cleanliness.

Figure 4.11 represents the energy services of low-income households and how these services translate into drivers of energy consumption. It also displays the total amount of energy consumed within this driver. This total is based on the amount of energy required for each service that feeds into the driver. This allows for comparison between the size of the income groups' drivers.

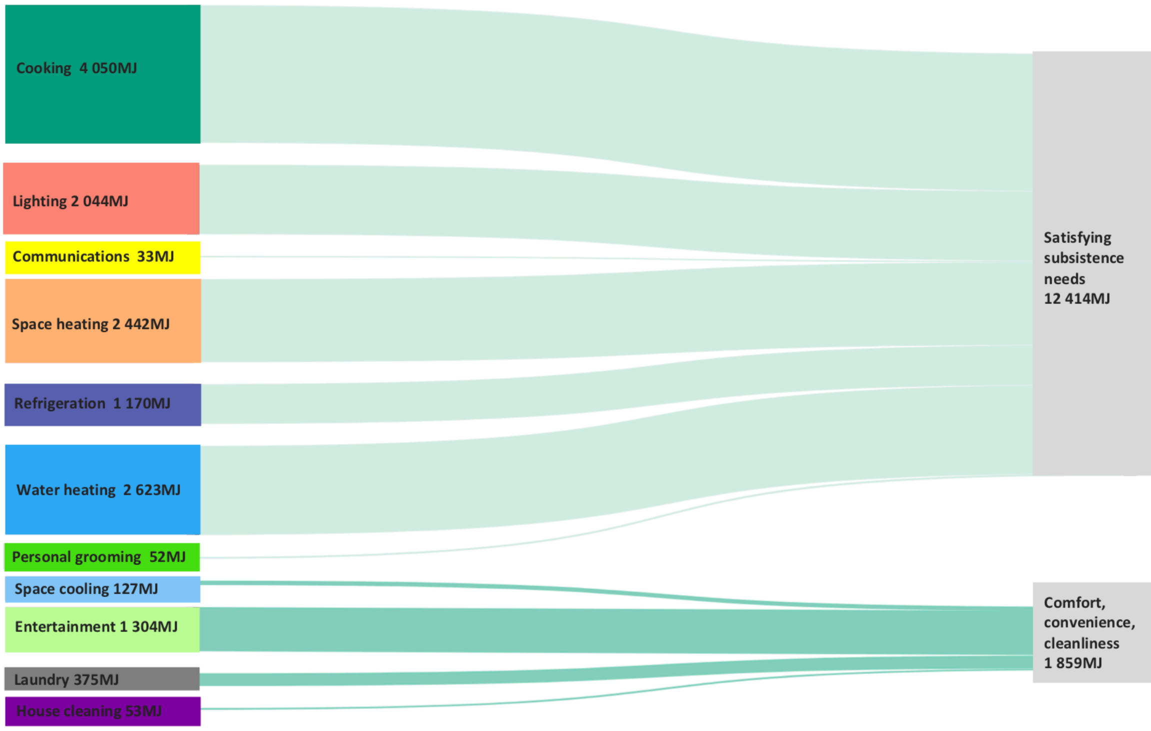

Figure 4.11: Low-income household energy drivers
Source: Author

In the average low-income household, the subsistence services are the most dominant. Communications only contributes a small portion because the energy consumption of this service is small in all income groups. Even though the services that contribute to the subsistence driver are dominant, it is important to note that the average low-income household is still able to access the services found in the comfort, convenience, and cleanliness driver.

The size of entertainment for this income group is notable, especially since this service is located in the second tier of the energy ladder. The majority (93%) of low-income households own television sets while 74% own laptops or desktop computers. It can be concluded that based on the dominant energy services, the low-income group is driven mostly by satisfying subsistence needs, but that it is also driven to a degree by comfort, convenience, and cleanliness.

Figure 4.12 is a representation of the energy services and their respective drivers for the average low-middle-income household. Even though the subsistence drivers are dominant, households are once again accessing all the services typically driven by comfort, convenience, and cleanliness. Entertainment once again plays a very important role. The increase in energy for the comfort, convenience, and cleanliness driver is 710MJ. This is why it is useful to quantify the services. It shows that there is a slight shift further up the energy ladder with an increase in income.

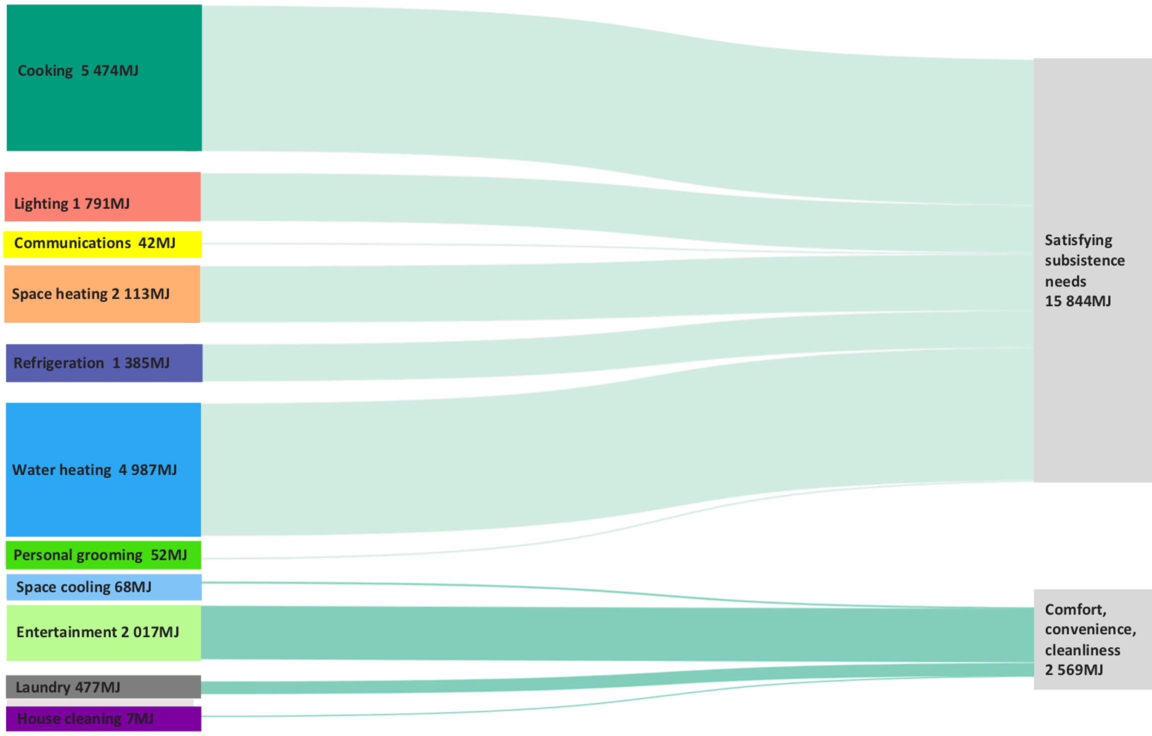

Figure 4.12: Low-middle-income household energy drivers

Source: Author

Judging by the energy increase in the second tier, it might be possible to classify this household type as sitting more firmly in the comfort, convenience, and cleanliness driver. However, comparing the energy flows of the average low-income and average low-middle-income households, there are no significant shifts that could signify a move up the energy ladder. This could mean that low-income households are showing unexpected results or that the low-middle-income household should remain as a dominantly subsistence-driven energy consumer. Looking at the representation of the energy ladder for the average high-middle-income household (Figure 4.13) might provide further insight.

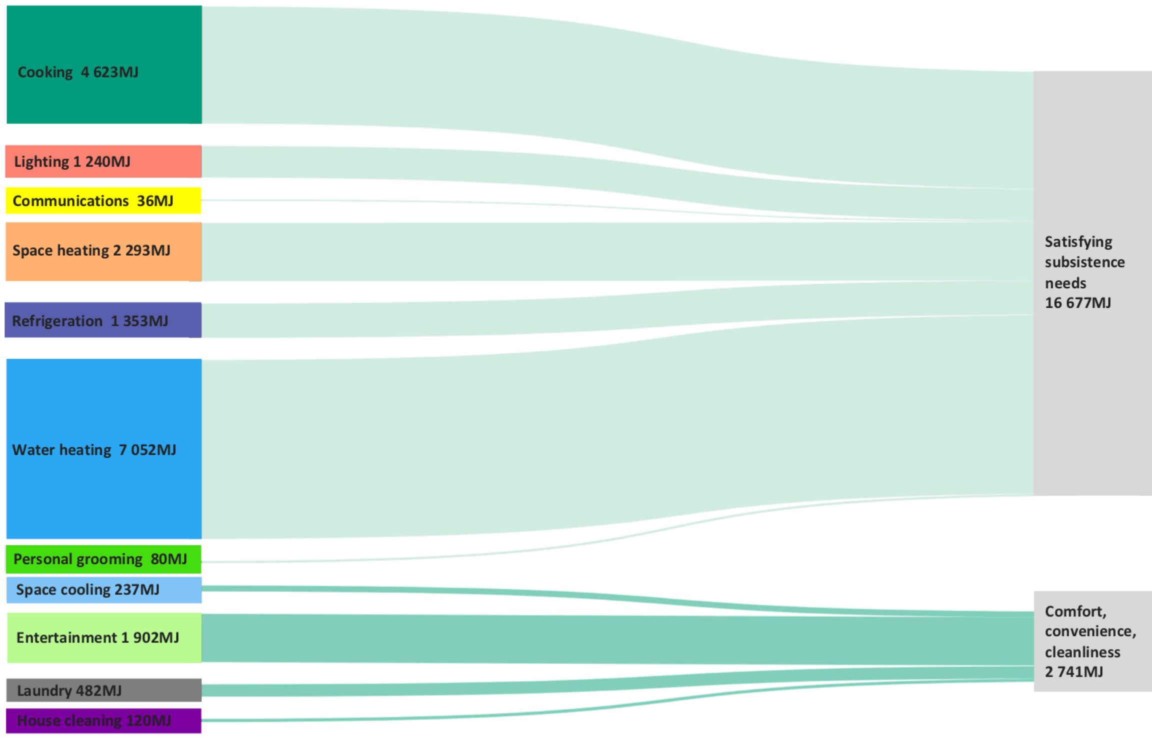

Figure 4.13: High-middle-income household energy drivers

Source: Author

The three services of space cooling, laundry, and house cleaning have clearly become more dominant in the average high-middle-income household. However, the change is not profound, and the entire driver remains small compared to the subsistence driver. Moreover, the service of entertainment reduced from the low-middle- to the high-middle-income group. This shows that the appliances in the comfort, convenience, and cleanliness driver consume less energy than those in the subsistence driver. Looking at the quantities, there is an increase of only 172MJ from low-middle to high-middle-income households for the second tier. Since the low-middle-income group is much closer to the high-middle-income group, it might mean that both the middle-income groups belong on the second tier; however, the results are non-conclusive, as the profiles remain very similar for all three income groups studied thus far.

Figure 4.14 is the representation of the energy ladder for the average high-income household. Once again, the same profile is present, with the further challenge that the service of entertainment has now reduced. The three remaining services have become slightly more prominent.

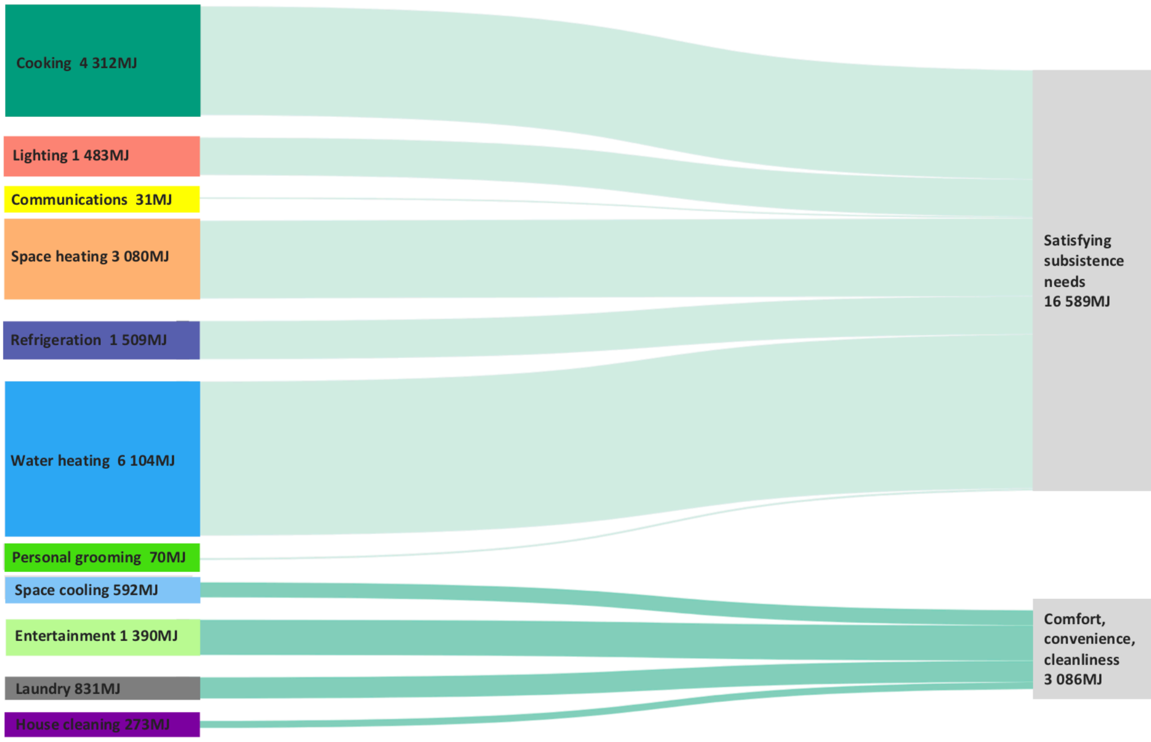

Figure 4.14: High-income household energy drivers

Source: Author

The overall increase in energy for the comfort, convenience, and cleanliness tier between high-middle-income and high-income is 345MJ, which is once again only a small increment. Therefore, while the high-income group should no doubt be a representation of these energy drivers, it is challenging to know how to categorise the other groups, as all the profiles are so similar, with a reduction in some of the services of the second tier. Especially considering that all the groups are clearly able to access all the services to some extent, it can only be concluded that Cape Town does not fit the typical profile for the energy ladder. This may be attributed to the unexpected findings around entertainment. It could mean that entertainment truly belongs in the lower tier, challenging the notion of what subsistence services could mean, and that the service of water heating, the only service that shows a real increase between the lower- and higher-income groups, should be moved to the second tier of the ladder.

4.3.2 Measuring energy satisfaction across income groups

Figure 4.15 summarises the results for the question about energy satisfaction. It is clear that the lower the household's income, the less satisfied the residents are with the energy they are currently accessing. The focus group revealed finances as the strongest theme for households dissatisfied with the amount of energy they are able to access. Residents are simply unable to purchase enough energy to meet their household needs. They often curb their energy consumption because of limited finances. Interestingly, this is not the case for everyone. The focus group revealed a second theme around finances, cost. Many residents feel that electricity and paraffin are too expensive, and even though they might be able to purchase enough to meet their household needs, they are dissatisfied with the cost of it. A third theme is energy cuts. Especially in informal settlements with unstable electricity connections, residents are dissatisfied with the unexpected energy cuts, and similar dissatisfaction is voiced across income groups when reflecting on past load-shedding disruptions. This influences recommendations for sustainability. Providing more electricity in order to move away from paraffin, wood, and charcoal in low-income households will not be possible if the electricity system cannot handle an increased load.

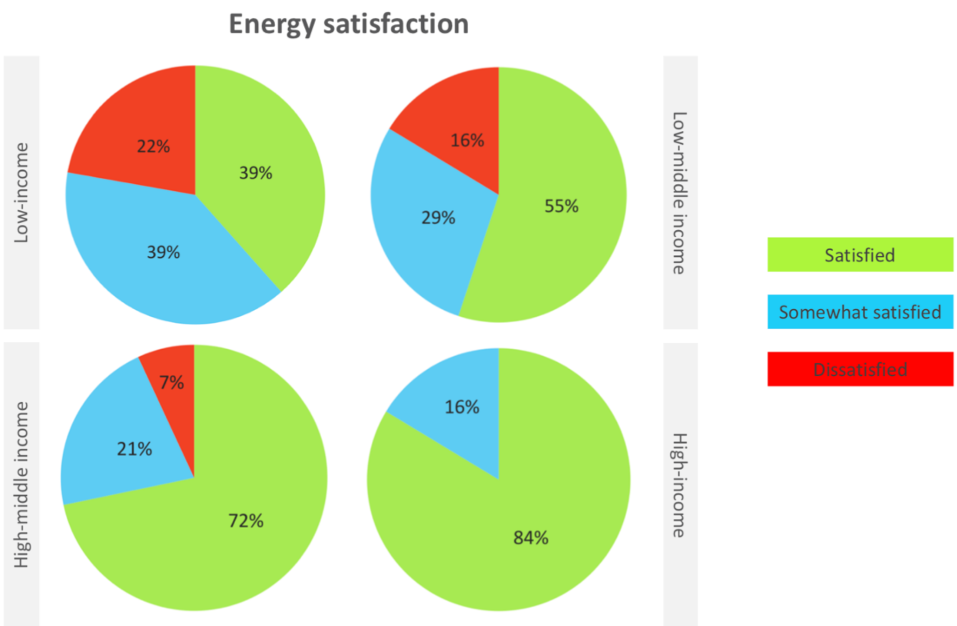

Figure 4.15: Energy satisfaction across income groups

Source: Author

It is interesting to see that 7% of the high-middle-income group remains dissatisfied, even though it could be expected that this group is able to purchase enough energy to satisfy their needs and that they have stable electricity grid connections. The theme of cost also arose in the energy audit interviews for these households. Residents are dissatisfied by the price of electricity, so even though they can purchase enough, they are not satisfied with their overall energy supply. In the high-income group, 16% of residents are somewhat satisfied, but none of them are completely dissatisfied.

A second theme that emerged from the energy audit interviews is renewable energy. For both higher-income groups, a prominent reason for lower satisfaction or complete dissatisfaction is stated as the city's lack of commitment to replacing fossil fuels with renewable energy sources to supply electricity to households. Therefore, while higher-income households can easily access sufficient energy, many have voiced that they would be more satisfied with the energy they consume in their households if they know that more renewable energy sources are used to meet the demand. The energy profile for these two groups revealed that residents seem reluctant to invest in solar water heaters. Therefore, while residents would like to make use of more renewable energy sources, they want the investment to come from the city. Residents do not seem motivated to invest their money into renewable energy for their own households.

The question of energy satisfaction and energy access informs our understanding of energy drivers, as it provides the perspective from Cape Town's residents instead of relying purely on the literature to provide insight into drivers of energy consumption. As the previous section revealed, the energy ladder may not be the most robust method for understanding energy access, as residents believed to access energy to meet subsistence needs are also accessing many of the energy services found in the driver of comfort, convenience, and cleanliness. Inquiring about energy satisfaction provides insight into the perspective of those surveyed. The following additional insights can therefore be added to a Cape Town specific understanding of energy drivers:

For lower-income households, whose energy behaviours are expected to be driven by satisfying subsistence needs, energy satisfaction also means the following:

- Having the financial means to purchase the needed amount of energy.
- Having access to energy carriers at a lower cost.
- Having a stable electricity grid that is able to handle a potential increase in load.

For middle- and high-income households expected to be driven by comfort, convenience, and cleanliness, energy satisfaction also means the following:

- Having access to energy carriers at a lower cost.
- Having the knowledge that more renewable energy sources supply electricity to the grid.

4.4 Summary

This chapter detailed the results of a household energy metabolism assessment in the city of Cape Town, focusing specifically on low-income, low-middle-income, high-middle-income, and high-income households in order to address the question of energy drivers and energy access. The study sample reached proved sufficient for achieving this.

Based on energy activity, this chapter presented an overall image of energy consumption, divided into energy carriers and energy services to account for energy flows in and through the household, based on monthly household income. Energy profiles based on average energy use for four different income groups allowed a more detailed analysis of carriers and services, as well as the interaction between the two.

Using the energy services for each group, it was possible to create representations for each group about the energy drivers they access and the applicability of this ladder to households in Cape Town. Diagrams depicting reported energy satisfaction provided a further opportunity to discuss energy access and what that means to residents of Cape Town. Chapter 5 concludes by summarising the key findings of this study, as related to the literature and the results.

Chapter 5 – Conclusion and recommendations

This study addressed various research gaps found in household energy metabolism assessments by reviewing the literature on urban metabolism, energy metabolism, and household energy consumption, and subsequently conducted such an assessment in the city of Cape Town.

The overall research objective of this study was to assess the energy metabolism of different households in Cape Town. This was achieved through the following specific sub-objectives:

1. To quantify household energy consumption and associated household activities.
2. To examine drivers of household energy consumption.

This study gathered household-level energy consumption data from 366 households across 56 suburbs in Cape Town by distributing household energy consumption surveys. These surveys asked residents about their monthly energy purchases as well as their usage habits of 44 different household appliances. These appliances were categorised in two ways: according to energy carriers and energy services. Enumerators were tasked with collecting data in informal settlements in order to increase the presence of low-income households.

The data provided the means to create an average energy consumption picture for four income groups: low-income, low-middle-income, high-middle-income, and high-income. Based on services accessed, it was possible to associate each income group with its placement on the energy ladder to determine what factors drive energy consumption in the household. In addition, respondents were asked about their energy satisfaction in order to create a better understanding of what energy access might mean in a city like Cape Town. Based on the findings, different intervention points were identified for each income group.

5.1 Key methodological findings

It is believed that this is the first study undertaken in the city of Cape Town that quantifies household energy carriers and services based on a questionnaire focusing on appliance use. The following methodological findings emerged:

- The method proved useful in providing rich data from individual households on energy consumption, which could be used to quantify household energy flows, namely carriers and services, according to income brackets and income groups. The appliance-based data allowed a unique opportunity to grapple with energy access and energy drivers based on the presence or absence of certain appliances in the household.
- Across income groups, there were inconsistencies between the amount of reported energy purchased and the energy equivalents of appliance usage. This could mean that respondents mis-reported their spending or the number of hours their household uses various appliances for, or it is a reflection on the method. Either the energy value used to quantify the reported usage was inaccurate, or the survey omitted crucial household appliances.
- Quantifying electricity consumption based on energy activity and appliance usage is simpler than quantifying alternative energy carriers, as these appliances have more variables to consider.
- Using enumerators to gather data to fill gaps in online survey responses proved useful, as it provided bottom-up, household-specific data for this group. In addition, it provided the chance to engage with the enumerators to gain feedback on the surveying process, as well as energy habits, purchases, and satisfaction of multiple household groups. Many enumerator surveys visited high-middle- and high-income households within the suburbs they surveyed, which speaks to the income and household variances found in suburbs that display low average incomes.
- Sankey diagrams proved particularly useful in analysing the relationship between carriers and services for the different income groups, as it visualised the household’s energy consumption in the form of flows. It also proved useful in linking the energy services with the energy ladder in order to visualise energy drivers.

- The bottom-up visualisation of household energy consumption patterns proves a useful tool for gaining insight, which can aid in policy-making.

5.2 Key empirical findings

Urban metabolism is a useful way to find intervention points for making resource flows in cities more sustainable. The literature argues that quantifying resource flows will reveal intervention points for making these flows more sustainable. Since household energy is one of the largest resource consumers in cities, a household energy metabolism assessment would reveal intervention points needed to reshape household energy consumption to move toward a more sustainable urban energy system.

Sustainability in the Global South, however, should go beyond quantification and reduction of flows to reshaping them to allow those households still without access to sufficient energy the means to access energy sustainably, while finding interventions to reshape energy consumption toward sustainability in households that are accessing energy in abundance.

Studies done so far around household energy consumption and household energy flows are mostly focused on reducing overall greenhouse gas emissions, which limits studies to energy outflows, thereby overlooking the study potential found in inflows and throughflows of household energy. Furthermore, these studies are mostly done at the city or national level and disaggregated to household level, which disregards the insights possible by studying different types of households and income groups. This bottom-up approach will also account for both energy inflows and throughflows to create a higher-resolution picture of household energy flows.

Energy flows into the house in the form of carriers and through the house in the form of services. Studying carriers is useful because a sustainable energy system may sometimes mean changing energy carrier instead of simply reducing the size of the flow. Studying services is useful because this allows an understanding of energy access, which is crucial when finding intervention points to move toward a more sustainable energy system. These services can be related to energy access by means of the energy ladder. The energy ladder looks at drivers of energy access based on income and the types of services accessed by households of each income group, thereby determining whether household energy consumption is driven by satisfying subsistence needs (lacking sufficient access) or by comfort, convenience, and cleanliness (accessing sufficient energy). The literature also recommends studying not only the system's flows in isolation, but addressing the interactions between them, therefore looking at how carriers transform into services and how the relationship between carriers and services changes depending on income or household size.

5.2.1 Key findings based on Objective 1

- When studying bracketed income groups, there does not appear to be a positive correlation between annual energy consumption and income. The variance in consumption within the income brackets is too large, which is a function of this surveying approach. Regardless, this finding does not correspond to the literature, which finds a positive correlation between the two.
- Solar water heaters play an important role for water heating in low-income households; up to half of total water heating requirements. This could be a reflection of the government's roll-out of low-pressure solar water heaters. Contrasting this, there is a very small presence of solar water heaters in high-middle- and high-income households, suggesting that this could be a clear intervention area, particularly given the proportion of energy directed towards water heating services in these households.
- Total energy consumption increases between low- and middle-income households, which corresponds to the literature, but consumption of certain services, for example cooking, space heating, and lighting, reduces as income increases, which does not correspond to the literature. This could be due to the use of less energy-dense carriers or more efficient use.
- In low- and low-middle-income households, the most prominent energy service is cooking, whereas the most prominent energy service in high-middle- and high-income households is water heating. This is because only

39% of this cohort own geysers, but all households have access to some means of cooking.

- As the literature also agrees, paraffin remains a very inefficient, expensive, and unsafe energy carrier, yet it is prevalent in especially low- and low-middle-income households. Paraffin is used for cooking, lighting, and space heating. Overall consumption of these three services routinely decrease as the portion provided by paraffin decreases.
- Electricity is the dominant energy carrier for all income groups, which means that in the areas of Cape Town studied, most households have access to electricity. This corresponds wholly to the literature.
- Even though the literature argues that in the Global South energy carriers are more diverse in low-income households and less diverse in higher-income households (with electricity as the main energy provider), in Cape Town, all seven energy carriers studied are present in all four income groups, albeit with differing portions of energy carriers. Even paraffin, often associated with low-income households, is present to some degree in all income groups.
- In low- and low-middle-income households, the presence of televisions and computers in households is more prominent than geysers; 39% of this cohort own geysers while 96% own television sets. This is inconsistent with the literature that classified water heating as one of the essential energy services, but entertainment belonging to higher-income groups. It shows that entertainment is a crucial service, especially in the lower-income households. It could also show a lack in access to desired water services in Cape Town.
- As household income increases from low- to middle-income, consumption of entertainment services increases; above this income group, however, consumption of entertainment services decreases. It can be suggested that higher-income groups choose to consume less electronic entertainment, or are doing so in manners not tracked by this study.
- It is important to remember that within each income group there exists a range of consumption levels, therefore the exact same may not be true for every household in the mentioned income group.

5.2.2 Key findings based on Objective 2

- The literature suggests that low-income household access only energy services associated with the driver of meeting subsistence needs; however, the average low- and low-middle-income household in Cape Town is able to access all 11 services studied, four of which are found in the second energy ladder tier, where energy consumption is driven by comfort, convenience, and cleanliness.
- The average high-middle- and high-income household accesses only between 1% and 3% more of the services in the second tier of the energy ladder than the average low- and low-middle-income household. This makes it difficult to categorise households on the energy ladder, especially considering that the service of entertainment (which falls in the second energy ladder tier) is more prominent in the average low- and low-middle-income household than it is in the average high-middle- and high-income household.
- The service of entertainment does not seem to belong in the second tier of the energy ladder and should be considered an essential service for households accessing energy to satisfy subsistence needs.
- Reported energy satisfaction increased with income, however, a dissatisfaction with energy was present in three of the four income groups, with only the high-income group showing no dissatisfaction.
- Studying energy access in Cape Town can be supplemented with understanding energy satisfaction. In low-income households, energy satisfaction can be achieved by i) lowering the cost of energy in order to allow all residents to access enough, and ii) providing a stable electricity grid that can handle the current load and a potential increase.
- In middle- and high-income households, improved energy satisfaction can be achieved by i) lowering the cost of electricity, and ii) supplementing the grid electricity with renewable energy sources.

5.3 Recommendations for sustainability

Based on the average energy profiles for the four different income groups, the following intervention points for moving toward a more sustainable energy system were identified:

- Installing solar water heaters across households will have direct impacts on energy use: it is an excellent way to increase access to water heating in low- and low-middle-income households without increasing the reliance on fossil fuel energy sources, as long as they receive the needed maintenance. Further, it decreases the energy footprint of middle-high and high-income groups, which show the largest proportion of energy directed towards water heating services. This should be a government priority, as access to water heating may be the biggest energy access gap in Cape Town, and it is a simple way to reduce energy impact.
- For the two lower-income groups, a shift in energy carrier is the first step towards reshaping these energy flows for sustainability. This will reduce overall energy consumption, as electricity is much more efficient than alternative energy carriers such as paraffin, wood, and charcoal. It is also more affordable. In winter, for example, the price of paraffin increases drastically. Seeing as paraffin is predominantly used for space heating, a shift from paraffin heaters to electric heaters will save residents money while reducing consumption. This will give residents the opportunity to access more of the services they desire. However, it requires electricity networks to be stable enough to carry an increased load.
- For high-middle- and high-income households, sustainability interventions revolve around reducing overall energy consumption, as alternative energy carriers do not play such a prominent role. The most dominant service to address is water heating, as this consumes the bulk of electricity in these homes. This will require a change in behaviour in reducing water heating activities or an investment in technology in the form of purchasing solar water heaters.
- While residents of the average high-middle- and high-income household are dissatisfied by the city's current commitment to including more renewable energy sources in the energy mix, they do not seem willing to make a personal investment toward solar water heaters, which would provide the most significant reduction in household energy consumption.

5.4 Limitations and recommendations for future research

The following aspects proved limiting to the study:

- The study excluded transport, yet if considered an extension of a household's energy activity, it is expected to be the largest energy consumer among middle- and high-income groups. Future studies could include transport as an extension of a household's energy activity.
- The study relied on self-reported energy purchases and activity. The challenge with this is that respondents may not recall the exact number of hours they spend using various appliances or the exact amount of energy carriers they purchase in a month.
- The study used the average of an income range, which made it difficult to analyse the correlation between income and energy consumption. Future studies can aim to collect data on exact income.
- Where household size was not stated, this study used an average household size for the income group in question. Future studies should pay careful attention that completing household size in the survey is compulsory.
- This study presented a wealth of data, which provides the basis for improvement to the method. Future studies could focus on increasing the accuracy of raw data gained from surveys as well as the proxies used for estimating consumption values from these.
- Since this is one of the first household energy metabolism studies in Cape Town, it would typically be considered a baseline study. Unfortunately, the local context challenges this approach. From 2015 to 2018, Cape Town experienced the worst drought in its history. Residents have drastically altered their water behaviours and some of these behaviours, for example taking shorter showers and doing laundry less often, may have affected the data collected for a situation without such a crisis. Since residents have become much more intentional about their water consumption, it may also be that they have become more intentional about their energy consumption too.
- The data collection was conducted during a single time in the year. While the survey asked questions around both summer and winter usage of, for example, space heating and space cooling, results were necessarily skewed toward current behaviour. The data collection was conducted from June to September, which means respondents were answering with the winter season in mind and relying on memory to reflect on summer behaviours.

Future studies could conduct research during both summer and winter months, in order to receive a better understanding of how energy consumption changes in temperate countries.

- Some households in informal settlements run businesses from their houses, which consume more energy than what a household would typically need. Future studies could make a separate category for such households so that they do not skew the answers.
- The query into energy access was at a very basic level and relied only on the energy ladder from the literature and participants' opinion on energy satisfaction, which, as the results show, can mean various different things depending on the context.
- This study omitted the high-income energy driver of conspicuous consumption, as it chose to focus mostly on low- and middle-income households. Future studies could include more detail on high-income households and how their energy consumption differs from the two other groups. This could be done by including more appliances and activities that may only be present in high-income households, including swimming pool pumps, heated towel rails, and accessing more than one energy service at a time, for example watching television while cooking.
- The sample size for high-income households was very small, which makes it challenging to compare all income groups. The income bracket for this cohort was also very large. There is opportunity for future studies to assess in detail the energy consumption patterns of high-income households only.
- This study does not explicitly differentiate between primary and secondary energy carriers, for example, electricity would be a secondary energy carrier with coal its primary carrier, while paraffin is a primary energy carrier used within the household. Future studies could therefore gain further insight by studying the efficiency of the coal equivalent for the electricity used in the household and comparing that to other primary carriers in the household, namely gas, paraffin, coal and wood.

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Appendix A: Household resource consumption survey demographic and energy questions

GENERAL HOUSEHOLD QUESTIONS

1. How did you receive this survey? **[REQUIRED]**
    - WWF Email subscription
    - Radio Neighbourhood association
    - Social Media
    - A friend sent it to me
    - Other
    - Visit from enumerator

2. Do you live in a gated community or security complex? **[REQUIRED]**
    - Yes
    - No

3. What type of home do you live in? **[REQUIRED]**
    - Freestanding house with a garden
    - Freestanding house without a garden
    - Semi-detached house with a garden
    - Semi-detached house without a garden
    - Cottage next to main house
    - Apartment Informal dwelling with a garden
    - Informal dwelling without a garden
    - Informal dwelling in a backyard
    - Dormitory / Hostel

4. Do you have an informal dwelling in your backyard? **[REQUIRED]**
    - No
    - 1 dwelling
    - 2 dwellings
    - 3+ dwellings

5. How long have you lived in this home? **[REQUIRED]**
    - Less than a year
    - 1-2 years
    - 3-5 years
    - More than 5 years

6. What race do you identify as? **[REQUIRED]**

- o Black
- o Coloured
- o White
- o Indian
- o Another Race:________________

7. How many people of each age and gender are in your household? (put **number of people** next to each category) **[REQUIRED]**

Female:

- _ 0 – 4 years old
- _ 5- 14 years old
- _ 15 – 24 years old
- _ 25 – 64 years old
- _ 65+ years old

Male:

- _ 0 – 4 years old
- _ 5- 14 years old
- _ 15 – 24 years old
- _ 25 – 64 years old
- _ 65+ years old

Another gender:

- _ 0 – 4 years old
- _ 5- 14 years old
- _ 15 – 24 years old
- _ 25 – 64 years old
- _ 65+ years old

8. Are all members of your household related? **[REQUIRED]**

- o Yes, we are all related
- o No, we share the household with non-related members
- o I am the only person living in my household

9. What is your household's total monthly income? **[REQUIRED]**

- o No income
- o R 1 - R 1 600

- R 1 601 - R 3 200
- R 3 201 - R 6 400
- R 6 401 - R 12 800
- R 12 801 - R 25 600
- R 25 601 - R 51 200
- R 51 201 - R 102 400
- R 102 401 - R 204 800
- More than R 204 801

10. What is the highest education level in your household? **[REQUIRED]**

- No Formal Education
- Primary School
- Secondary School
- Technical Certification
- Undergraduate Degree
- Postgraduate degree

11. How long does it take you to get to work? **[REQUIRED]**

- I don't travel to work
- 0 - 5 minutes
- 6 - 19 minutes
- 20 - 39 minutes
- 40 - 59 minutes
- 1 - 2 hours
- 2+ hours

12. Select each form of transport you typically use to get to work (select multiple) **[REQUIRED]**:

- ❑ I don't travel to work
- ❑ I walk
- ❑ Bicycle
- ❑ Motorbike / Scooter
- ❑ Minibus
- ❑ MyCiti Bus
- ❑ Other Bus
- ❑ Train
- ❑ Taxi / Uber
- ❑ Car (drive myself)

- ❑ Carpooling (driven by friend/family)

13. In which suburb do you live? **[REQUIRED]**

Answer:..

ENERGY QUESTIONS

14. Using your utility bill, please input how many kilowatt hours of electricity your household used as a daily average (see picture below): **[REQUIRED]**

ELECTRICITY (Period 12/04/2016 to 14/05/2016 - 33 Days) (Actual reading)

At [redacted]

Meter no: [redacted] / Consumption 993.000 kWh / Daily average 30.091 kWh

* Consumption charge: domestic

(1) 162.2950 kWh @ R 1.5430 (2) 216.3940 kWh @ R 1.5430

(3) 270.4910 kWh @ R 1.5430 (4) 343.8200 kWh @ R 1.8763

- ○ I don't have a bill with me
- ○ We use prepaid electricity
- ○ We pay our landlord for electricity
- ○ We don't use electricity
- ○ Daily average in kWh:__________

15. On average, how much money does your household spend on electricity per month? **[REQUIRED]**

- ○ We don't use electricity
- ○ Electricity is included in my rent
- ○ R0 - R49
- ○ R50 - R99
- ○ R100 - R199
- ○ R200 - R299
- ○ R300 - R399
- ○ R400 - R499
- ○ R500 - R599
- ○ R600 - R699
- ○ R700 - R799
- ○ R800 - R899
- ○ R900 - R999

- R1000 - R1199
- R1200 - R1399
- R1400 - R1599
- R1600 - R1799
- R1800 - R1999
- R2000 - R3999
- R4000 - R7999
- R8000 - R15999
- R16 000+

16. On average, how many bottles (9kg) of gas does your household use per month? **[REQUIRED]**

- We don't use gas
- Less than 1 bottle
- 1 - 2 bottles
- 3 - 4 bottles
- 5 - 6 bottles
- 7 - 8 bottles
- 9 - 10 bottles
- 10 + bottles

17. On average, how many bags (5kg) of charcoal does your household use per month? **[REQUIRED]**

- We don't use charcoal
- Less than 1 bag
- 1 - 2 bags
- 3 - 4 bags
- 5 - 9 bags
- 10 - 14 bags
- 15 - 19 bags
- 20 - 24 bags
- 25 - 29 bags
- 30 + bags

18. On average, how many big bags (12kg) of wood does your household use per month? **[REQUIRED]**

- We don't use wood
- Less than 1 bag
- 1 - 2 bags

- 3 - 4 bags
- 5 - 9 bags
- 10 - 14 bags
- 15 - 19 bags
- 20 - 24 bags
- 20+ bags

19. On average, how many litres of paraffin/kerosene does your household use per month? **[REQUIRED]**

- We don't use this
- Less than 1 litre
- 1 - 2 litres
- 3 - 4 litres
- 5 - 6 litres
- 7 - 8 litres
- 8 - 9 litres
- 10 - 14 litres
- 15 - 19 litres
- 20 - 24 litres
- 25 - 29 litres
- 30 + litres

20. On average, how many candles does your household use per month? **[REQUIRED]**

- We don't use this
- Less than 1
- 1 - 3 candles
- 4 - 6 candles
- 7 - 9 candles
- 10 - 14 candles
- 15 - 19 candles
- 20 - 29 candles
- 30 - 39 candles
- 40 - 59 candles
- 60 + candles

21. Does your household have solar PV panels? If yes, what is the size?

- We don't have solar panels
- Less than 1kWp
- 1 - 2 kWp

- 2 - 3kWp
- 3 - 4kWp
- 4 - 5kWp
- 5 - 6kWp
- 6 - 7kWp
- 7 - 8 kWp
- 8 - 9 kWp
- 9 - 10 kWp
- 10 - 12 kWp
- 12 - 15kWp
- 15 - 18kWp
- 18 - 20 kWp
- 20kWp+

22. What is the type, number and size of your geyser(s)/hot water cylinder(s) and how long are they switched on in summer and winter?

22.1 Electric geyser	**22.2** Solar water heater	**22.3** Gas geyser
Number of geysers: ○ 0 ○ 1 ○ 2 ○ 3+	Number of geysers: ○ 0 ○ 1 ○ 2 ○ 3+	Number of geysers: ○ 0 ○ 1 ○ 2 ○ 3+
Total capacity: ○ Don’t have this ○ Uncertain ○ 100l ○ 150l ○ 200l ○ 250l ○ 300l ○ 350l ○ 400l	Total capacity: ○ Don’t have this ○ Uncertain ○ 100l ○ 150l ○ 200l ○ 250l ○ 300l ○ 350l ○ 400l	Total capacity: ○ Don’t have this ○ Uncertain ○ 100l ○ 150l ○ 200l ○ 250l ○ 300l ○ 350l ○ 400l

Hours per day on in summer: ○ Don't have this ○ Never ○ Less than 1 hour ○ 1-2 hours ○ 2-5 hours ○ 5-8 hours ○ 8-10 hours ○ 10-12 hours ○ 12-15 hours ○ 15-18 hours ○ All day Hours per day on in winter: ○ Don't have this ○ Never ○ Less than 1 hour ○ 1-2 hours ○ 2-5 hours ○ 5-8 hours ○ 8-10 hours ○ 10-12 hours ○ 12-15 hours	Hours per day on in summer: ○ Don't have this ○ Never ○ Less than 1 hour ○ 1-2 hours ○ 2-5 hours ○ 5-8 hours ○ 8-10 hours ○ 10-12 hours ○ 12-15 hours ○ 15-18 hours ○ All day Hours per day on in winter: ○ Don't have this ○ Never ○ Less than 1 hour ○ 1-2 hours ○ 2-5 hours ○ 5-8 hours ○ 8-10 hours ○ 10-12 hours ○ 12-15 hours	Hours per day on in summer: ○ Don't have this ○ Never ○ Less than 1 hour ○ 1-2 hours ○ 2-5 hours ○ 5-8 hours ○ 8-10 hours ○ 10-12 hours ○ 12-15 hours ○ 15-18 hours ○ All day Hours per day on in winter: ○ Don't have this ○ Never ○ Less than 1 hour ○ 1-2 hours ○ 2-5 hours ○ 5-8 hours ○ 8-10 hours ○ 10-12 hours ○ 12-15 hours

○ 15-18 hours ○ All day	○ 15-18 hours ○ All day	○ 15-18 hours ○ All day

23. What is the type, number and energy source of your fridge(s)/freezer(s)?

23.1 Freestanding fridge	**23.2** Freestanding freezer	**23.3** Bar fridge	**23.4** Combination fridge/freezer
Number of fridges: ❑ 0 ❑ 1 ❑ 2 ❑ 3 ❑ 4 Energy source: ❑ Electric ❑ Gas ❑ Gas and electric	Number of fridges: ❑ 0 ❑ 1 ❑ 2 ❑ 3 ❑ 4 Energy source: ❑ Electric ❑ Gas ❑ Gas and electric	Number of fridges: ❑ 0 ❑ 1 ❑ 2 ❑ 3 ❑ 4 Energy source: ❑ Electric ❑ Gas ❑ Gas and electric	Number of fridges: ❑ 0 ❑ 1 ❑ 2 ❑ 3 ❑ 4 Energy source: ❑ Electric ❑ Gas ❑ Gas and electric

24. How many hours per week does your household spend cooking with the following?

Electric hob / stove:

- We don't use this for cooking
- Less than 1 hour
- 1-2 hours
- 2-5 hours
- 6-8 hours
- 9-12 hours

Gas hob / stove:

- We don't use this for cooking
- Less than 1 hour
- 1-2 hours
- 2-5 hours
- 6-8 hours
- 9-12 hours

Electric oven:

- We don't use this for cooking
- Less than 1 hour
- 1-2 hours
- 2-5 hours
- 6-8 hours
- 9-12 hours

Gas oven:

- We don't use this for cooking
- Less than 1 hour
- 1-2 hours
- 2-5 hours
- 6-8 hours
- 9-12 hours

Wood:

- We don't use this for cooking
- Less than 1 hour
- 1-2 hours
- 2-5 hours
- 6-8 hours
- 9-12 hours

Charcoal:

- We don't use this for cooking
- Less than 1 hour
- 1-2 hours
- 2-5 hours
- 6-8 hours
- 9-12 hours

Paraffin/Kerosene:

- We don’t use this for cooking
- Less than 1 hour
- 1-2 hours
- 2-5 hours
- 6-8 hours
- 9-12 hours

Gas braai:

- We don’t use this for cooking
- Less than 1 hour
- 1-2 hours
- 2-5 hours
- 6-8 hours
- 9-12 hours

25. How many electric lightbulbs do you have in the house? **[REQUIRED]**

- We don’t use this
- Less than 5 lightbulbs
- 5-9 lightbulbs
- 10-14 lightbulbs
- 15-19 lightbulbs
- 20-29 lightbulbs
- 30+ lightbulbs

26. How many of your lightbulbs are energy saving? **[REQUIRED]**

- We don't use electric lightbulbs
- None
- A few (10% - 20%)
- Quite a few (20% - 40%)
- About half (40% - 60%)
- Most of them (60% - 80%)
- Almost all of them (80% - 99%)
- All of them (100%)

27. On a typical day, how many of all the lightbulbs are switched on for five or more hours?

- We don't use electric lightbulbs

- None
- A few (10% - 20%)
- Quite a few (20% - 40%)
- About half (40% - 60%)
- Most of them (60% - 80%)
- Almost all of them (80% - 99%)
- All of them (100%)

28. How many hours per day does your household use the following lighting?

Paraffin/kerosene lamp(s):

- We don't use this
- 1 - 2 hours
- 3 - 5 hours
- 5 - 8 hours
- 8 - 12 hours
- 12+ hours

Candle(s):

- We don't use this
- 1 - 2 hours
- 3 - 5 hours
- 5 - 8 hours
- 8 - 12 hours
- 12+ hours

29. During winter, how many hours per day does your household use the following heating methods? **[REQUIRED]**

Fireplace:

- We don’t use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day
- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

Electric heater(s):

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day
- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

Gas heater(s):

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day
- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

Paraffin/kerosene heater(s):

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day
- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

Central heating:

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day
- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

Air conditioning:

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day
- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

Electric blanket:

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day
- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

30. During summer, how many hours per day does your household use the following cooling methods? **[REQUIRED]**

Air conditioning:

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day
- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

Fan(s):

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day

- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

Central heating:

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 2-4 hours per day
- 5-9 hours per day
- 5-9 hours per day
- 10-15 hours per day
- All day

31. How many loads and at what temperature do you use the following washing appliances?

31.1 Dishwasher	**31.2** Front loading washing machine	**31.3** Top loading washing machine	**31.4** Tumble dryer
Frequency of loads: ○ We never use this ○ 1 load per month ○ 1 load every 2 weeks ○ 1 load per week ○ 2-4 loads per week ○ 5-7 loads per week ○ 8-10 loads per week	Frequency of loads: ○ We never use this ○ 1 load per month ○ 1 load every 2 weeks ○ 1 load per week ○ 2-4 loads per week ○ 5-7 loads per week	Frequency of loads: ○ We never use this ○ 1 load per month ○ 1 load every 2 weeks ○ 1 load per week ○ 2-4 loads per week ○ 5-7 loads per week	Frequency of loads: ○ We never use this ○ 1 load per month ○ 1 load every 2 weeks ○ 1 load per week ○ 2-4 loads per week ○ 5-7 loads per week ○ 8-10 loads per week

○ More than 10 loads per week ○ We don't use this often Temperature: ○ We don't use this ○ Not applicable ○ 50°C and up ○ 20°C - 49°C ○ Cold	○ 8-10 loads per week ○ More than 10 loads per week ○ We don't use this often Temperature: ○ We don't use this ○ Not applicable ○ 50°C and up ○ 20°C - 49°C ○ Cold	○ 8-10 loads per week ○ More than 10 loads per week ○ We don't use this often Temperature: ○ We don't use this ○ Not applicable ○ 50°C and up ○ 20°C - 49°C ○ Cold	○ More than 10 loads per week ○ We don't use this often Temperature: ○ We don't use this ○ Not applicable ○ 50°C and up ○ 20°C - 49°C ○ Cold

32. How many hours per day does your household use the following entertainment appliances?

Television(s):

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 3-4 hours per day
- 5-7 hours per day
- 8-11 hours per day
- 12-14 hours per day
- 15-19 hours per day
- 20+ hours per day

Laptop(s) (charging)

- We don't use this

- Less than 1 hour per day
- 1-2 hours per day
- 3-4 hours per day
- 5-7 hours per day
- 8-11 hours per day
- 12-14 hours per day
- 15-19 hours per day
- 20+ hours per day

Desktop computer(s)

- We don’t use this
- Less than 1 hour per day
- 1-2 hours per day
- 3-4 hours per day
- 5-7 hours per day
- 8-11 hours per day
- 12-14 hours per day
- 15-19 hours per day
- 20+ hours per day

Mobile phone(s) (charging)

- We don’t use this
- Less than 1 hour per day
- 1-2 hours per day
- 3-4 hours per day
- 5-7 hours per day
- 8-11 hours per day
- 12-14 hours per day
- 15-19 hours per day
- 20+ hours per day

Tablet (charging)

- We don’t use this
- Less than 1 hour per day
- 1-2 hours per day
- 3-4 hours per day
- 5-7 hours per day
- 8-11 hours per day
- 12-14 hours per day

- 15-19 hours per day
- 20+ hours per day

Musical equipment / speakers

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 3-4 hours per day
- 5-7 hours per day
- 8-11 hours per day
- 12-14 hours per day
- 15-19 hours per day
- 20+ hours per day

Game console(s)

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 3-4 hours per day
- 5-7 hours per day
- 8-11 hours per day
- 12-14 hours per day
- 15-19 hours per day
- 20+ hours per day

Other electrical entertainment device(s)

- We don't use this
- Less than 1 hour per day
- 1-2 hours per day
- 3-4 hours per day
- 5-7 hours per day
- 8-11 hours per day
- 12-14 hours per day
- 15-19 hours per day
- 20+ hours per day

33. How many times does your household use the following electric appliances? (eg. if there are 2 in your household and you both use the kettle once a day, *Electric Kettle* is '2 times a day')

Electric Kettle:

- We don't use this
- Once a day
- 2-3 times a day
- 4-6 times a day
- Once a week
- 2 times a week
- 3 times a week
- 4 times a week
- 5 times a week
- 6 times a week
- Every 2 weeks
- Once a month
- Not very often

Coffee Machine:

- We don't use this
- Once a day
- 2-3 times a day
- 4-6 times a day
- Once a week
- 2 times a week
- 3 times a week
- 4 times a week
- 5 times a week
- 6 times a week
- Every 2 weeks
- Once a month
- Not very often

Toaster:

- We don't use this
- Once a day
- 2-3 times a day
- 4-6 times a day
- Once a week
- 2 times a week
- 3 times a week

- 4 times a week
- 5 times a week
- 6 times a week
- Every 2 weeks
- Once a month
- Not very often

Blender / Food Processor:

- We don't use this
- Once a day
- 2-3 times a day
- 4-6 times a day
- Once a week
- 2 times a week
- 3 times a week
- 4 times a week
- 5 times a week
- 6 times a week
- Every 2 weeks
- Once a month
- Not very often

Electric Shaver:

- We don't use this
- Once a day
- 2-3 times a day
- 4-6 times a day
- Once a week
- 2 times a week
- 3 times a week
- 4 times a week
- 5 times a week
- 6 times a week
- Every 2 weeks
- Once a month
- Not very often

Hairdryer:

- We don't use this

- Once a day
- 2-3 times a day
- 4-6 times a day
- Once a week
- 2 times a week
- 3 times a week
- 4 times a week
- 5 times a week
- 6 times a week
- Every 2 weeks
- Once a month
- Not very often

Hair Iron / Curler:

- We don’t use this
- Once a day
- 2-3 times a day
- 4-6 times a day
- Once a week
- 2 times a week
- 3 times a week
- 4 times a week
- 5 times a week
- 6 times a week
- Every 2 weeks
- Once a month
- Not very often

Other electrical device(s):

- We don’t use this
- Once a day
- 2-3 times a day
- 4-6 times a day
- Once a week
- 2 times a week
- 3 times a week
- 4 times a week
- 5 times a week
- 6 times a week

- Every 2 weeks
- Once a month
- Not very often

34. On average, how many minutes per day does your household use a microwave?

- We don't use a microwave
- Less than 1 minute a day
- 1 - 2 minutes a day
- 3 - 5 minutes a day
- 6 - 9 minutes a day
- 10 - 14 minutes a day
- 15 - 19 minutes a day
- 20 - 29 minutes a day
- 30 - 39 minutes a day
- 40 - 59 minutes a day
- 60 - 119 minutes a day
- 120 + minutes a day

35. Do the energy sources you currently have access to fulfil your energy requirements? (Ask them where they are on the line) **[REQUIRED]**

Yes-------------------------------------Somewhat-------------------------------------No

Appendix B: Details of enumerator meetings

Date: 19 August 2018

Place: University of Cape Town

Number of researchers present: 3

Number of enumerators present: 6

Purpose of the meeting:

- Introduce the study
- Meet the enumerators
- Discuss payment
- Outline responsibilities
- Work through the survey
- Address questions and queries

Date: 26 August 2018

Place: Isivivana Centre, Khayelitsha

Number of researchers present: 3

Number of enumerators present: 16

Purpose of the meeting:

- Meet new enumerators
- Sign confidentiality agreements
- Sign contracts
- Provide hard copies of surveys
- Distribute lanyards and ID cards
- Assign neighbourhoods
- Discuss the interpretation of questions
- Address questions and queries
- Set deadlines for data collection

Date: 29 September 2018

Place: 75 Harrington Street

Number of researchers present: 1

Number of enumerators present: 6

Purpose of the meeting:

- Provide enumerators access to computers and internet to upload hard copies
- Lead focus group on energy access

Appendix C: Household energy audits form

KITCHEN

Refrigeration

Appliance	**Type of fridge** (Bar fridge/fridge-freezer combo/freezer only/fridge only)	**Make**	**Litres**	**Energy rating** (A/A+/A++)
Fridge				

Dish washing

Appliance	**Make**	**Number of place settings**	**Energy rating** (A/A+/A++)	**Preferred cycle**
Dishwasher				

Cooking

Appliance	**Make**	**Size** (litres/cm)	**Energy source** (gas/electric)	**On average, how hot is the oven/hob when you use it?** (e.g. 25%, 60%, 75%, 90% of full heat)
Oven				
Stove/hob		Size not required		

Small appliances

Appliance	Make	Wattage (underneath or behind appliance)	Other (select one)
Kettle			Typically, how full is kettle when you boil it? (¼, ½, ¾)
Microwave			Size of microwave (litres/cm)
Toaster			How many slices does the toaster have? (2 or 4)
Coffee machine			Espresso machine or filter machine?
Blender			-
Food processor			-

ROOMS

Appliance	Make	Size (inches/cm)	Wattage (behind the TV)
Television			

Space heating

Appliance	Make	Wattage (behind/underneath)	Typical heat setting (e.g. 25%, 60%, 75%, 90% of full heat)
Electric heater			
Gas heater			
Central heating			

Space cooling

Appliance	Make	Wattage (behind/underneath appliance)	Typical setting (e.g. 25%, 60%, 75%, 90% of full)
Electric fan			
Air conditioning (including portable)			
Central cooling			

Computing

Appliance	Make	Wattage (on charger box or sticker on computer box)
Laptop charger		
Desktop computer		

WASHROOM

Laundry

Appliance	Make	Capacity wash (litres)	Capacity dry (litres)	Energy rating (A/A+/A++)	Preferred cycle
Washing machine					
Tumble dryer					

GARAGE/BATHROOM

Water heating

Appliance	Make	Litres	Energy source (gas/electric/solar)
Geyser			

ENERGY ACCESS QUESTIONS

Are you satisfied with the energy you're able to access? Why?

Are you satisfied with the quality of energy you use? Why?

Is there anything that bothers you about your energy supply?

Appendix D: Calculations for energy averages for appliances

Cooking							
Electric ovens	**Model**	**kWh per load**	**kW (x 2 loads per hour)**	**Total kW (x intensity)**		**Ave kWh/h**	
			2		**0,7**		
Bosch	VBD554FS0	1,2	2,40	1,68			Whirlpool
Bosch	HBN301E2Z	1	2	1,40			Whirlpool
Whirlpool	AKZ 6230 IX	0,9	1,80	1,26			Whirlpool
Whirlpool	AKP 288/NA	1,1	2,2	1,54			Whirlpool
Whirlpool	AKP 543 IX	0,91	1,82	1,27			Whirlpool
Whirlpool	AKP 742 IX	1,1	2,2	1,54			Whirlpool
Smeg		1,25	2,5	1,75			Smeg
Smeg		1,05	2,1	1,47			Smeg
Smeg		1,2	2,4	1,68		1,36	Smeg
Electric hobs	**Model**	**kW per element**	**kW (x 2 elements at a time)**	**Total kW (x intensity)**		**Ave kW/h**	
			2		**0,7**		
Bosch	NCM615A01	1,5	3		2,1		Bosch
	PKM975DK1						Bosch
Bosch	D	1,5	3		2,1		
Bosch	PKE645CA1E	1,2	2,4		1,68		Bosch
Bosch	PEE689CA1	2	4		2,8	2,17	Bosch

Gas ovens		kWh per load	kW (x 2 loads per hour)	Total kW (x intensity)	Ave kW	
			2	0,7		
Smeg	SFR9300X	1,15	2,3	1,61	1,61	Smeg

Gas hobs	Model	kW per element	kW (x 2 elements at a time)	Total kW (x intensity)	Ave kW	
			2	0,7		
Bosch	PRS9A6D70	1,9	2,52	2,52		Bosch
Bosch	PPP6A6B20	1,75	3,5	2,45		Bosch
Bosch	PSB3A6B20Z	1,75	3,5	2,45	2,47	Bosch

Toasters	Make	kW	Time (decimal of hour)	kWh per time (x intensity)	Ave kWh per time	
			0,043	0,7		
Philips	2 slice	0,95	0,04085	0,028595		Dion Wired
Defy	2 slice	0,8	0,0344	0,02408		Dion Wired
Bosch	2 slice	1	0,043	0,0301		Dion Wired
Defy	4 slice 2 press	1,6	0,0688	0,04816		Dion Wired
Russell Hobbs	4 slice 2 press	1,6	0,0688	0,04816		Dion Wired
DeLonghi	4 slice 2 press	1,8	0,0774	0,05418	0,04	Dion Wired

Smeg	4 slice 1 press	1,5	0,0645	0,04515			Dion Wired
Coffee machines	**Make**	**kW**	**Time (decimal of hour)**	**kWh per time (x intensity)**	**Ave kWh per time each**	**Ave kWh per time**	
			0,00556	**0,8**			
Espresso	DeLonghi	1,4	0,007784	0,00623			Dion Wired
Espresso	Espresto	1,5	0,00834	0,00667			Dion Wired
Espresso	Vida	1,2	0,006672	0,00534	0,01		Dion Wired
			0,25	0,8			
Filter	Russell Hobbs	1	0,25	0,2			Dion Wired
Filter	Bosch	1,1	0,275	0,22	0,21	0,11	Bosch
Blenders/food processors	**Make**	**kW**	**x Time (decimal of hour)**	**kWh per time (x intensity)**		**Ave kWh per time**	
			0,023	0,8			
Blender	Nutri Bullet	6	0,138	0,1104			Dion Wired
Blender	Nutri Bullet	9	0,207	0,1656			Dion Wired
Blender	Nutri Bullet	1,7	0,0391	0,03128			Dion Wired
Blender	Defy	0,6	0,0138	0,01104			Dion Wired
Blender	Russell Hobbs	1	0,023	0,0184		0,05	Dion Wired

Blender	Bosch	0,7	0,0161	0,01288			Dion Wired
Blender	Kenwood	0,8	0,0184	0,01472			Dion Wired
Food processor	Bosch	1,25	0,02875	0,023			Dion Wired
Food processor	Kenwood	1	0,023	0,0184			Dion Wired
Microwaves	**Make**	**Size**	**kW**	**kWh per time (x intensity)**		**Ave kW**	
				0,9			
Microwave	Hisence	30l	1,5	1,35			Dion Wired
Microwave	Defy	28l	1,45	1,305			Dion Wired
Microwave	Defy	34l	1,4	1,26			Dion Wired
Microwave	LG	42l	1,35	1,215			Dion Wired
Microwave	Samsung	40l	1,55	1,395			Dion Wired
Microwave	LG	42l	1,35	1,215			Dion Wired
Microwave	Samsung	45l	1,55	1,395			Dion Wired
Microwave	Kambrook	20l	0,7	0,63			Energy audits
Microwave	LG	20l	0,7	0,63		1,16	Energy audits
Paraffin stoves	**l/hour**	**1l of paraffin (kJ)**	**kJ/kWh**			**kWh/h**	
	0,36	37646	3600			3,76	
Wood cooking	**kg/h**	**Calorific value (kJ)**	**Efficiency**	**kJ/h**	**kJ/kWh**	**kWh/h**	
	6	16000	0,25	24000	3600	6,67	

Charcoal cooking	kg/h	Calorific value (kJ)	Efficiency	kJ/h	kJ/kWh	kWh/h
	2	30000	0,25	15000	3600	4,17
Gas braai	**kg/h**	**kJ/kg**	**kJ/h**	**kJ/kWh**		**kWh/h**
	0,53	49000	25970	3600		7,21

Lighting Paraffin lamps	Flat wick width (cm)	Lumens	Wattage	Intensity	Ave wattage	Source
Paraffin lamp						Various
		37				
	1	50	3,3	2,31		
	1,27	88	6	4,2		
	1,33	113	7,5	5,25		
	1,9	125	8,3	5,81		
	2,5	151	10	7		
	0,3				4,91	
Candles	**kWh/kg**	**kg/candle**	**kWh/candle**	**Candles/h**	**kWh**	
	11,67	0,075	0,875	0,1	0,088	Home experiments
Incandescent lightbulbs				**kW**		
				0,025		Various
				0,04	0,05	

			0,06		
			0,075		
Energy saving lightbulbs					
			0,005		Various
			0,007		
			0,011		
			0,015		
			0,029		
			0,023		
			0,03	0,01	

Communications				
Mobile phones	**Energy (kW)**	**x intensity (0,8)**	**Ave kW**	**Source**
Apple	0,005	0,004		
	0,004	0,0032	0,004	Apple
Tablet				
Apple	0,012	0,0096	0,01	Apple

Space heating				
Appliance	**Energy consumption**	**Intensity**	**Average**	**Data source**

Electric heaters					0,6		
Goldair				1	0,6		Home audit
Delonghi				2	1,2		Delonghi
Sansui				0,8	0,48		Russels
Russell Hobbs				1,8	1,08	0,79	Russel Hobbs
Gas heaters					**0,6**		
Alva					0,5		
Russell Hobbs				4,2	2,52		Russel Hobbs
Delonghi				4,2	2,52		Delonghi
Mellerware				4,2	2,52	2,52	Mellerware
Wood fireplace	**kg in 1 hour**	**Calorific value (J)**	**Efficiency**	**kJ/h**	**kWh/h**		
	6	16000	0,25	24000	6,666666667	6,67	Various

Refrigeration Make	Classification	Model	Code	Size	Energy kWh/24h	Average per day	Average per week	Data source
Combination fridge/freezer							**7**	
Hisence	Combination	Bottom Mounted	H359BME-WD	356l	0,91	0,81	5,70	Hisence
Hisence	Combination	Bottom Mounted	H410BS-WD	308l	0,827			Hisence
Hisence	Combination	Bottom Mounted	H390BI – WD	292l	0,972			Hisence
Hisence	Combination	Bottom Mounted	H300EMI	212l	0,6			Hisence
Hisence	Combination	Bottom Mounted	H420BMI – WD	320l	0,813			Hisence

Hisence	Combination	Bottom Mounted	H299BI	230l	0,857			Hisence
Hisence	Combination	Bottom Mounted	H340BI	264l	0,786			Hisence
Hisence	Combination	Bottom Mounted	H340BI – WD	263l	0,786			Hisence
Hisence	Combination	Bottom Mounted	H359BI	271l	0,912			Hisence
Hisence	Combination	Bottom Mounted	H360BME	170l	0,567			Hisence
Hisence	Combination	Bottom Mounted	H360BMI – WD	269l	0,909			Hisence
Hisence	Combination	Bottom Mounted	H359BME	271l	0,912			Hisence
Bosch	Combination			320l	0,796			Dion Wired
Hisence	Combination			320l	0,822			Dion Wired
Samsung	Combination			300l	0,749			Dion Wired
Side by side fridges								
Hisence	Side by side	Side by side	H600SME	436l	1,351	1,21	8,47	Hisence website
Hisence	Side by side	Side by side	H670SI	516l	1,129			Hisence website
Hisence	Side by side	Side by side	H670SMB-WD	512l	1,129			Hisence website
Hisence	Side by side	Side by side	H670SS	516l	1,129			Hisence website
Hisence	Side by side	Side by side	H700SI-IDL	535l	1,2			Hisence website
Hisence	Side by side			540l	1,123			Dion Wired
LG	Side by side			630l	1,205			Dion Wired

Samsung	Side by side			440l	1,178			Dion Wired
LG	Side by side			600l	1,2			Dion Wired
Samsung	Side by side			500l	1,178			Dion Wired
LG	Side by side			600l	1,266			Dion Wired
Smeg	Side by side			540l	1,26			Dion Wired
Samsung	Side by side			630l	1,384			Dion Wired
Freestanding fridges								
Hisence	Freestanding fridge	Single door	H310UI	235l	0,811			Hisence website
Hisence	Freestanding fridge	Single door	H420LI	320l	0,43			Hisence website
Bosch	Freestanding fridge			324l	0,301			Dion Wired
Whirlpool	Freestanding fridge			363l	0,312	0,4635	3,245	Dion Wired
Bar fridges								
Hisences	Bar Fridge			90l	0,31			Dion Wired
Samsung	Bar Fridge			200l	0,603			Dion Wired
Hisence	Freestanding fridge	Single door	H230RRE – WD	170l	0,44	0,451	3,157	Hisence website

Space cooling				
Appliance	**Energy consumption**	**Intensity**	**Average**	**Source**
Air conditioning	**kW**	**0,6**		
Goldair	3,48	2,088		Home audit
Defy	3,48	2,088		Makro
Defy	6,96	4,176		Defy
Goldair	2,61	1,566	2,48	Goldair
Fans	**kW**	**x intensity**		
		0,7	**Average**	
AIM	0,055	0,0385		Energy audits
AIM	0,055	0,0385		Energy audits
Logik	0,1	0,07	0,05	Energy audits

Entertainment						
Appliance	**Model**	**Size**	**Wattage**	**Intensity**	**Average**	**Source**
Televisions				**0,8**		
Samsung			0,145	0,116		Home audit
Panasonic		54cm	0,09	0,072		Home audit
			0,12	0,096	0,09	Home audit
Gaming consoles				**0,6**		
Playstation	PS4 Pro CUH-71XX		0,129	0,0774		PS website
Playstation	PS4 Pro CUH-70XX		0,126	0,0756		PS website
Playstation	PS4 CUH-20XX		0,079	0,0474	0,07	PS website

Playstation	PS4 CUH-21XX		0,075	0,045		PS website
Playstation	PS4 CUH-1116AB0XX		0,115	0,069		PS website
Playstation	PS4 CUH-12XX		0,098	0,0588		PS website
Playstation	PS3		0,076	0,0456		PS website
Xbox	Xbox One		0,105	0,063		Anandtech
Xbox	Xbox One X		0,172	0,1032		Anandtech
Music equipment				**0,6**		
Fender	Frontman 212R	Large	0,36	0,216		Home audit
Laney	Harcore max HCM65B	Medium	0,1	0,06		Home audit
Laney	LX12	Small	0,02	0,012		Home audit
Jensen			0,012	0,0072	0,07	Home audit

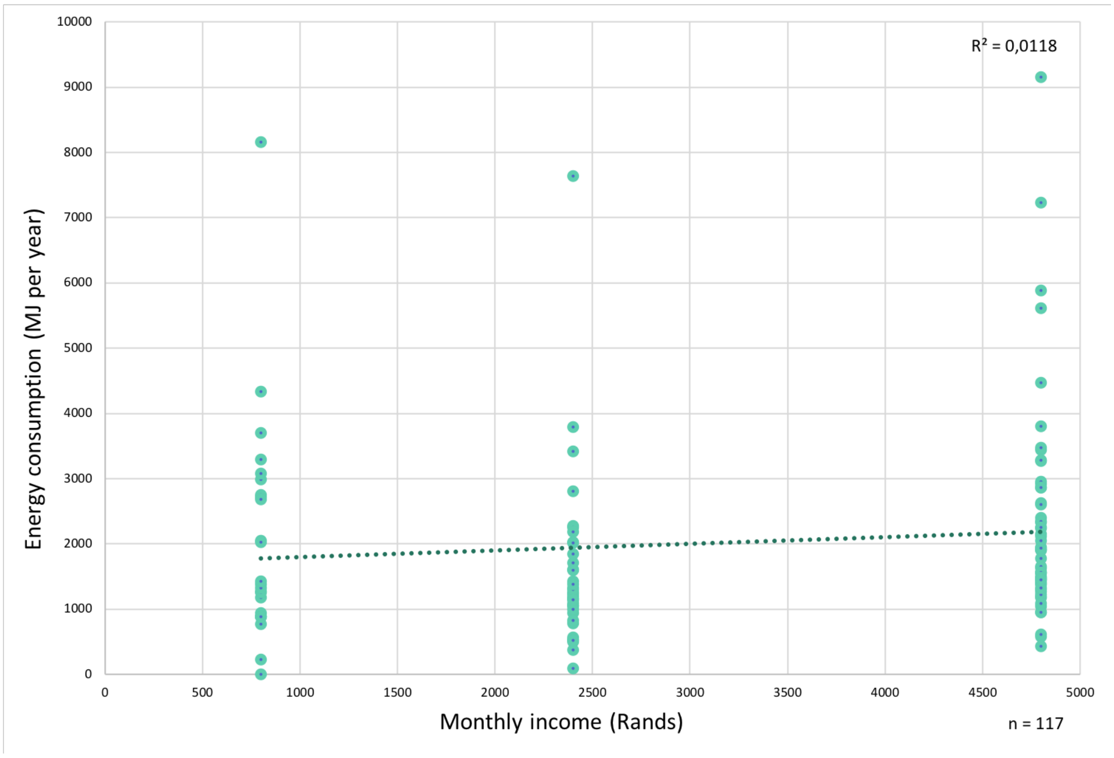
Computing					
Appliance	**Make**	**Wattage (max)**	**Intensity**	**Average**	**Source**
Desktop computers			**0,6**		
Apple	iMac Retina 5K, 27-inch 2017	0,217	0,1302		Apple
Apple	iMac Retina 4K, 21.5-inch 2017	0,161	0,0966		Apple
Apple	iMac 21.5-inch 2017	0,074	0,0444		Apple
Apple	iMac 27-inch 2014	0,288	0,1728		Apple
Apple	iMac 21.5-inch 2014	0,068	0,0408		Apple
Apple	iMac 21.5-inch 2013	0,136	0,0816		Apple
Apple	iMac 27-inch 2013	0,229	0,1374		Apple
Apple	iMac 21.5-inch 2009	0,241	0,1446		Apple
Apple	iMac 27-inch 2010	0,365	0,219		Apple
PC	Huntkey Green Power PSU	0,55	0,33	0,33	Computers Only

PC	FSP Hammer Full Modular	0,5	0,3		Computers Only
PC	Raidmax Semi Modular	0,73	0,438		Computers Only
PC	FSP Full Modular	0,65	0,39		Computers Only
PC	EVGA GQ Semi Modular	0,65	0,39		Computers Only
PC	Coolermaster	0,65	0,39		Computers Only
PC	Huge gaming	0,85	0,51		Computers Only
PC	Corsair	1,2	0,72		Evetech
PC	Mining PSU	1,6	0,96		Evetech
PC	Corsair	1	0,6		Evetech
PC	4 different ones	0,85	0,51		Evetech
PC	Antec and two others	0,75	0,45		Evetech
PC	Antec and two others	0,6	0,36		Evetech
PC	Antec	0,5	0,3		Evetech
PC	Office PC (10 different ones)	0,4	0,24		Evetech
Laptop chargers			**0,8**		
Apple	Macbook	0,029	0,0232		Apple
Apple	Macbook Air	0,045	0,036		Home audit
Apple	Macbook Pro	0,061	0,0488		Apple
Lenovo	V110 (windows 10 pro)	0,045	0,036		Evetech
Various	Gaming laptops	0,28	0,224		Evetech
Various	Core i7 laptops	0,28	0,224		Evetech
Various	Standard work laptops	0,135	0,108		Evetech
Various	Smaller laptops	0,045	0,036		Evetech
Asus		0,065	0,052	0,09	Energy audits

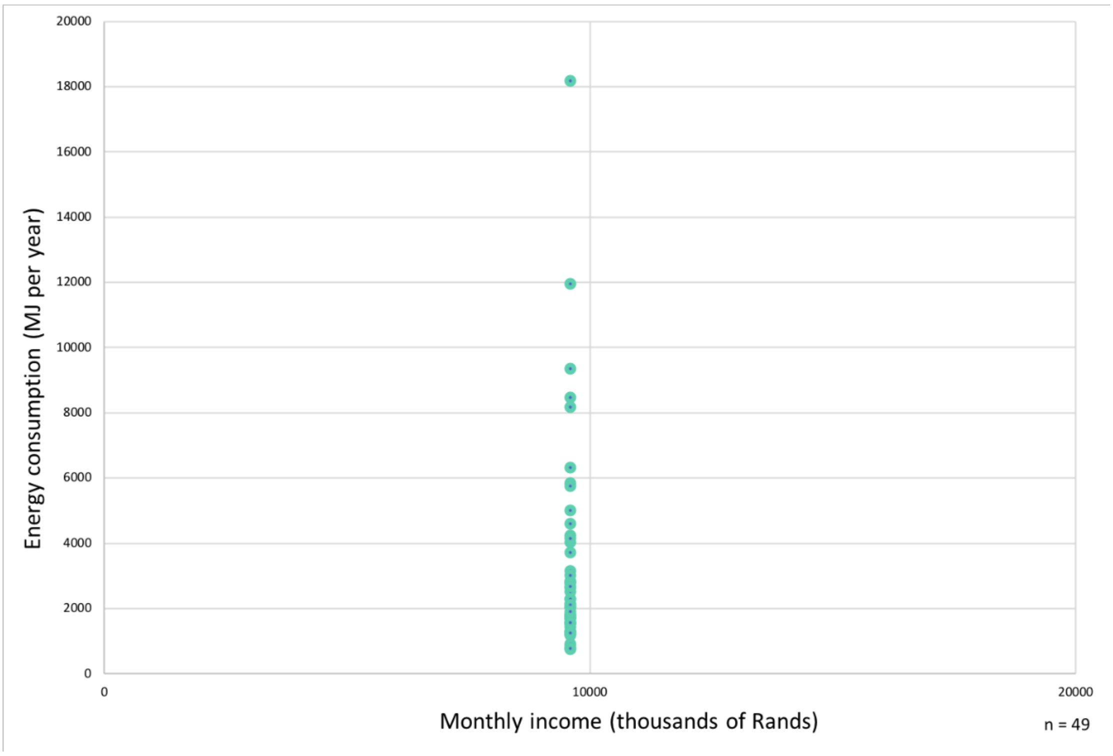
Personal grooming				
Appliance	Energy	x length of a session	Ave kWh per week	Data Source
Electric shaver	kW	8		
	0,006	0,048		Home audit
	0,002	0,016		Home audit
	0,035	0,28	0,115	Home audit
Hair curler/iron		**0,25**	**Ave kWh per time**	
	0,15	0,0375		Home audit
Taurus	0,04	0,01	0,024	Taurus
Hairdryer		**0,042**	**Ave kWh per time**	
	1,8	0,0756		Home audit
Carmen	2,2	0,0924		Carmen
Philips	2,1	0,0882		Philips
Russell Hobbs	2	0,084		Russell Hobbs
Russell Hobbs	1,8	0,0756		Russell Hobbs
Philips	2,1	0,0882	0,084	Philips

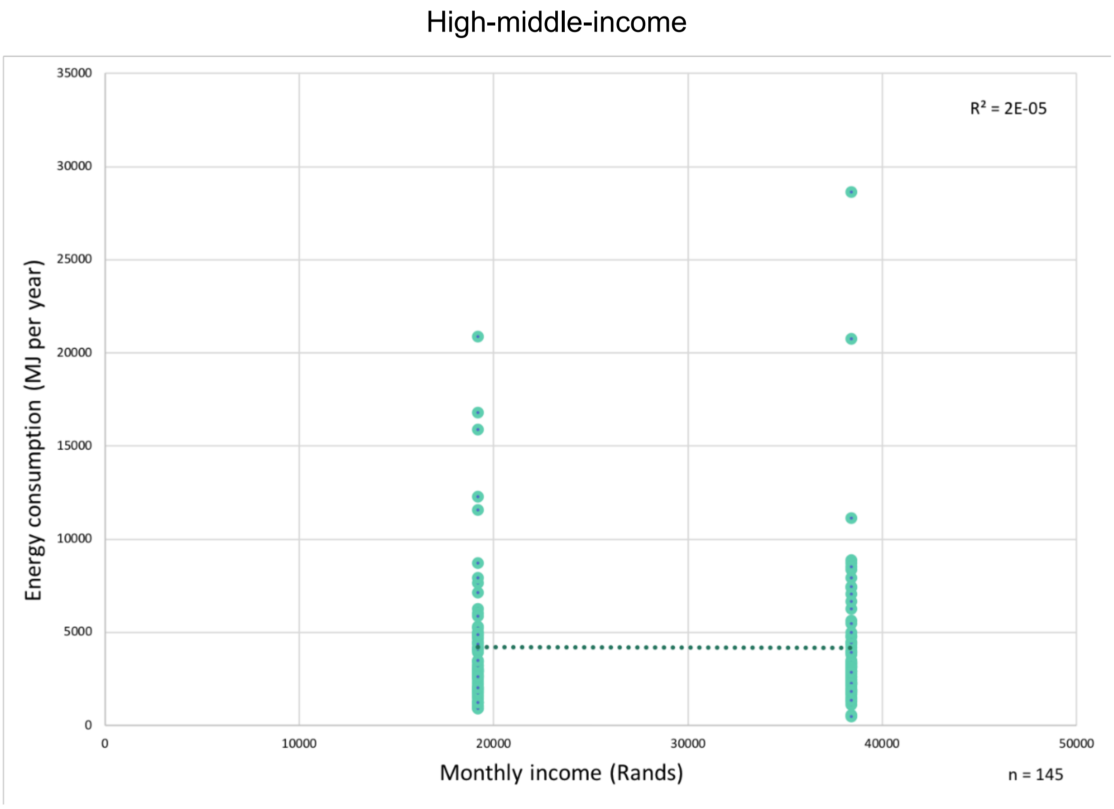
Appendix E: Correlation maps for four income groups

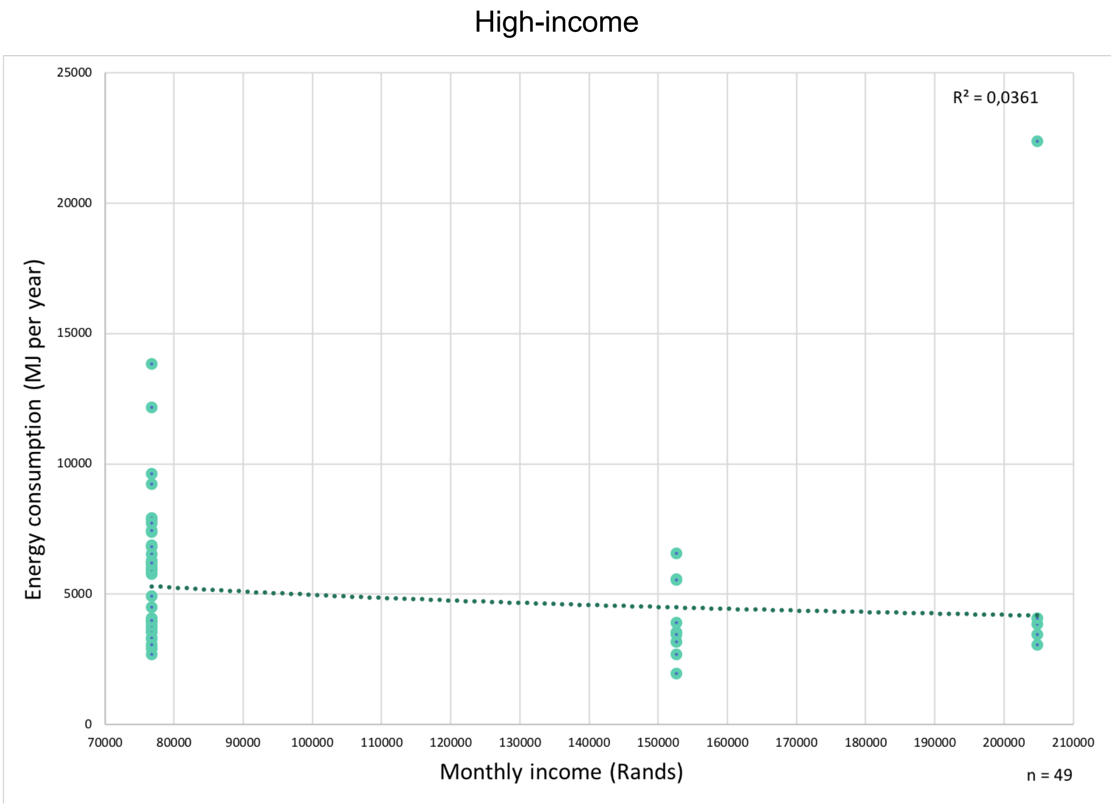
Low-income



Low-middle-income




High-middle-income
R² = 2E-05
35000
30000
25000
20000
15000
10000
5000
0
Energy consumption (MJ per year)
0
10000
20000
30000
40000
50000
Monthly income (Rands)
n = 145


High-income
R² = 0,0361
25000
20000
15000
10000
5000
0
Energy consumption (MJ per year)
70000
80000
90000
100000
110000
120000
130000
140000
150000
160000
170000
180000
190000
200000
210000
Monthly income (Rands)
n = 49