A system dynamics approach to understanding household energy-water urban nexus metabolism in Cape Town

by

Yumna Parker

Thesis presented in partial fulfilment of the requirements for the degree of Master of Philosophy in Sustainable Development in the Faculty of Economic and Management Sciences at Stellenbosch University

Supervisor: Prof Josephine Kaviti Musango

Mr Paul Klugman Currie

March 2021

Stellenbosch University https://scholar.sun.ac.za

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: March 2021

Copyright © 2021 Stellenbosch University
All rights reserved

Stellenbosch University https://scholar.sun.ac.za

Abstract

Energy and water are considered to be two of the most essential resources necessary to establish and maintain operations in urban cities. Patterns of energy and water consumption in urban metabolism studies have conventionally been examined independently rather than in their nexus at macro scales. Conducting the analysis in this way poses a problem, as energy and water use are interconnected in most networks of urban activities, and microscale households are an essential driver of water and energy consumption in a city. A system dynamics approach to household energy-water urban nexus metabolism is essential for understanding the dynamics and interrelationships between these two resources in order to identify high-leverage intervention points to improve sufficiency, efficiency and resource consumption. However, studies examining the energy-water urban nexus metabolism in Cape Town are lacking and of studies that have utilised system dynamics to address the nexus, none were conducted from an urban metabolism perspective at a household level. This study therefore assessed the household energy-water urban nexus metabolism of Cape Town to identify intervention points for energy and water savings. This was achieved by reviewing the literature to conceptualise the energy and water nexus flows in Cape Town households and develop a system dynamics model for the energy-water urban nexus metabolism in Cape Town households.

The literature revealed that energy and water in households are linked predominantly to water heating, which is used for household services and activities such as showering, bathing, dishwashing, cooking, laundry and swimming. The system dynamics model focused on municipal electricity and water, which captured the structure of the energy-water urban nexus of different identified households. As a part of the system dynamic modelling process, a dynamic hypothesis in the form of causal loop diagrams was created. From this, the quantitative model was developed to simulate results of electrical energy and water requirements for the different income levels identified in Cape Town.

Results show that personal hygiene is a high-leverage intervention point for energy and water savings across all household income groups. For low-income and low-middle-income households, bathing specifically showed the biggest nexus of electricity and water. In contrast, for high-middle-income and high-income households, showering showed the biggest nexus. To make energy and water requirements more sustainable, decision-makers' focus regarding minimising energy and water in their nexus could be on changing personal hygiene behaviour

Stellenbosch University https://scholar.sun.ac.za

and reshaping energy and water consumption patterns. In combination with functional behavioural changes, the installation of solar water heaters is recommended, as this would alleviate the electricity load required to heat water.

This research presents a methodological contribution through the utilisation of system dynamics to conceptualise and model the energy-water urban nexus metabolism at a household level in the city of Cape Town. However, a key finding was that the model was unable to capture smaller behaviours of the system, such as water temperatures. Therefore, it is recommended that future studies consider approaches that can include more detailed behavioural dynamics.

Stellenbosch University https://scholar.sun.ac.za

Opsomming

Energie en water word beskou as twee van die noodsaaklikste hulpbronne wat nodig is om bedrywighede in stedelike stede te vestig en in stand te hou. Patrone van energie- en waterverbruik in studies oor stedelike metabolisme word normaalweg onafhanklik eerder as op makroskaal in hulle neksus ondersoek. Daar is ’n probleem om die ontleding op hierdie manier uit te voer, aangesien energie- en watergebruik in die meeste stedelike-aktiwiteitsnetwerke verwant is, en mikroskaalhuishoudings ’n noodsaaklike aandrywer van water- en energieverbruik in ’n stad is. 'N Stelseldinamika-benadering tot huishoudelike energie-water stedelike nexus metabolisme is noodsaaklik vir die begrip van die dinamika en onderlinge verhoudings tussen hierdie twee hulpbronne ten einde hoë-hefboom intervensiepunte te identifiseer om voldoende, doeltreffendheid en hulpbronverbruik te verbeter. Daar is egter geen studies wat ondersoek instel na die energie-water stedelike nexus metabolisme in Kaapstad nie, en studies het gebruik gemaak van stelseldinamika om die nexus aan te spreek, maar niks is vanuit 'n stedelike metabolismeperspektief op huishoudelike vlak gedoen nie. Hierdie studie het dus die huishoudelike energie-water- stedelikeneksusmetabolisme van Kaapstad ondersoek om ingrypingspunte vir energie- en waterbesparings te identifiseer. Dit is gedoen deur die literatuur na te gaan om die energie- en waterneksusstrome in Kaapstad-huishoudings te konseptualiseer en om ’n stelseldinamikamodel vir die energie-waterneksus in Kaapstad-huishoudings te ontwikkel.

Die literatuur het getoon dat energie en water in huishoudings hoofsaaklik aan waterverhitting gekoppel is, wat vir huishoudelike dienste/aktiwiteite soos stort, bad, skottelgoed was, kosmaak, wasgoed was en swem gebruik word. Die stelseldinamikamodel fokus op munisipale elektrisiteit en water, wat die struktuur van die energie-water- stedelike neksus van verskillende huishoudings vaslê. ’n Dinamiese hipotese in die vorm van oorsaaklike lusdiagramme is as deel van die stelseldinamika-modelleringsproses geskep. Hieruit is die kwantitatiewe model ontwikkel om resultate van elektriese energie en watervereistes vir die verskillende inkomstevlakke wat in Kaapstad geïdentifiseer is, na te boots.

Resultate het getoon dat persoonlike higiëne ’n hoëvlak-ingrypingspunt vir energie- en waterbesparings regdeur al die huishoudelike-inkomstegroepe is. Vir lae-inkomste- en lae-middelinkomstehuishoudings het bad spesifiek die grootste neksus van elektrisiteit en water getoon. In teenstelling daarmee, het stort die grootste neksus vir hoë-middel- en hoë-

Stellenbosch University https://scholar.sun.ac.za

inkomstehuishoudings getoon. Om energie- en watervereistes meer volhoubaar te maak, kan besluitnemers se fokus rakende die beperking van energie en water in hulle neksus wees om persoonlikehigiëne-gedrag te verander en energie- en waterverbruikspatrone te hervorm. Gekombineer met funksionele gedragsveranderinge, word die installering van sonverwarmers vir water aanbeveel, aangesien dit die elektrisiteitslading wat vereis word om water warm te maak, sal verlig.

Die navorsing lewer ’n metodologiese bydrae deur die benutting van stelseldinamika om die energie-water- stedelikeneksusmetabolisme op huishoudelike vlak in die Stad Kaapstad te konseptualiseer. ’n Belangrike bevinding was egter dat die model nie die minder beduidende gedrag van die stelsel, soos watertemperature, kon vasvang nie. Daar word dus aanbeveel dat toekomstige studies metodes oorweeg wat meer gedetailleerde gedragsdinamika kan insluit.

Stellenbosch University https://scholar.sun.ac.za

Acknowledgements

Thank you to the following people, whose support and encouragement made this research possible:

- Prof Josephine Kaviti Musango, for her excellent supervision. I appreciate the patient guidance and encouragement of deeper thinking. Thank you for showing me the possibilities of system dynamics modelling.
- All the members of Team Mahali, who reinforced the idea that changes in the home, no matter how small, can make all the difference.
- The Sustainability Institute, for providing a platform that challenged my understanding of sustainability, which undoubtedly shaped my thinking.
- Beatrix and Monique for their continuous motivation and great administrative support throughout my MPhil journey.
- My friends and family, for their continued interest, enthusiasm and constant check-ins with my progress.
- My parents, for their unconditional support and encouragement to go further.

This research was funded by the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University. The study would not have been possible without this financial contribution.

Stellenbosch University https://scholar.sun.ac.za

Table of Contents

Stellenbosch University https://scholar.sun.ac.za

Stellenbosch University https://scholar.sun.ac.za

Stellenbosch University https://scholar.sun.ac.za

List of Figures

Stellenbosch University https://scholar.sun.ac.za

Stellenbosch University https://scholar.sun.ac.za

Stellenbosch University https://scholar.sun.ac.za

List of Tables

Stellenbosch University https://scholar.sun.ac.za

List of acronyms and abbreviations

CLD	Causal Loop Diagram
EWNEX model	Energy-Water Urban Nexus Metabolism model
HH	Household
kWh	Kilowatt-hour
OECD	Organisation for Economic Co-operation and Development
StatsSA	Statistics South Africa
uMAMA	Urban Modelling and Metabolism Assessment

Stellenbosch University https://scholar.sun.ac.za

Chapter 1 : Introduction

1.1 Background

The number of people living in urban regions worldwide is ever-increasing. As of 2014, 54% of the global population resides in urban areas, compared to 30% of the population in 1950 (Fan, Kong, Wang & Zhang, 2019; United Nations Department of Economic and Social Affairs, 2014). It is expected that 2,5 billion more people will reside in urban areas by 2050, bringing the total population close to 9,8 billion (Department of Economic and Social Affairs Population Division, 2017; Fan *et al.*, 2019; Radcliffe, 2018). Furthermore, it is expected that there will be 41 mega-cities by 2030, which will each contain more than 10 million citizens, increasing the density of these cities (Radcliffe, 2018; United Nations Department of Economic and Social Affairs, 2014).

The urbanisation rate is regarded as a modernisation assessment indicator for economic development, as it is considered one of the most influential social processes in all of human history (Fan *et al.*, 2019). The rapid urbanisation rate is expected to significantly increase the pressure on already limited resources (Dai, Wu, Han, Weinberg, Xie, Wu, Song, Jia, Xue & Yang, 2018; Hussien, Memon & Savic, 2017). Water crises are an increasingly growing future risk (Arouri, Nguyen & Youssef, 2015). Similarly, global energy demands are expected to grow by 40% by 2035(Dai *et al.*, 2018). Energy and water-saving are therefore two of the most important human behaviours that are necessary to satisfy basic needs, and any problems that inhibit the provision of these resources need to be addressed (Dai *et al.*, 2018).

The implementation of holistic, sustainable development strategies in modern urban planning continues to be one of the biggest urbanisation challenges, especially considering that patterns of energy and water in cities have generally been addressed independently (Fan *et al.*, 2019; Villarroel Walker, Beck, Hall, Dawson & Heidrich, 2014). However, energy and water use are extremely interconnected in networks of urban activities, not only due to their interdependence on each other, but also due to their interconnections in terms of production and consumption of products (Wang, Cao & Chen, 2017). Understanding energy and water in their nexus is vital for implementing sustainable management strategies for these resources.

Stellenbosch University https://scholar.sun.ac.za

Urban metabolism is a conceptual framework that examines resources entering, circulating, being consumed and exiting as flows within an urban system (Kennedy & Hoornweg, 2012). Understanding the energy-water nexus from an urban metabolism perspective is beneficial, as it can help to identify alternative sources and corresponding utilisation pathways within a system that would take economic viability and environmental sustainability into account (Fan *et al.*, 2019). Urban metabolism is a useful framework for understanding resource flows in cities (Currie & Musango, 2016; Currie, Musango & May, 2017; Kennedy & Hoornweg, 2012).

Due to increased pressure on resources as a result of rapid urbanisation, development and management planning in cities are looking towards more sustainable resource plans to avoid future scarcities (Radcliffe, 2018). Understanding resource flows in cities through an urban metabolism lens could provide sustainable resource management plans (Musango, Currie & Robinson, 2017), especially in areas where resources are already scarce, such as Cape Town, which has been experiencing both water and energy shortages in the past years (Musango & Currie, 2018). However, urban metabolism assessments are generally undertaken from a macro-city level, where policy changes and implementation are not easily effective due either to time, resource or infrastructural constraints. There is also a lack of research done at a micro household level, where policy changes are more easily implemented. Furthermore, there is limited empirical research on the interdependencies of resources such as energy and water flows and their nexus.

An expanding middle class, resulting in increased consumption, especially in African contexts, causes more direct pressure on resource limits (Currie, Musangso & May, 2017). Therefore, households are a vital driver of water and energy consumption, as they are able to regulate direct energy consumption directly, and regulate it indirectly by regulating grey energy consumption (Kenway, Scheidegger, Larsen, Lant & Bader, 2013).

Resource flows in cities and households alike are generally non-linear (Brunner, 2007). Therefore, an approach to understand the flows needs to compensate for this non-linearity. System dynamics is one of the appropriate approaches, based on non-linearity, cause and effects, delays, feedbacks, stocks and changes in stocks known as flows (Maani & Cavana, 2007; Sterman, 2000). Intervention points can be identified by using system dynamics in the household energy-water nexus, as the feedback structures provide better insights for future policies that address the consumption of energy and water.

Stellenbosch University https://scholar.sun.ac.za

This study therefore utilised system dynamics to address the knowledge gap of the household energy-water nexus in Cape Town. This research aims to provide a methodological contribution by developing a system dynamics model of the household energy-water nexus of Cape Town. The way in which energy and water resources are understood and tracked in urban households was critically reviewed. The study examined how urban metabolism can be used as a lens to understand multiple resource flows, specifically energy and water in their nexus, at a household level utilising a system dynamics approach.

1.2 Problem statement

Patterns of consumption in urban metabolism studies have conventionally been examined independently rather than in their nexus. This poses a problem, because energy and water use are interconnected in networks of urban activities, both in their interdependence, and in the production and consumption of products and services. An expanding population and therefore increased consumption, especially in African cities, causes direct pressure on resources. This makes households an important driver of water and energy consumption in a city. A system dynamics approach to household energy-water nexus metabolism is essential for understanding the dynamics and interrelationships between these two resources in order to identify high-leverage intervention points to improve sufficiency, efficiency and resource consumption.

1.3 Research objective

The overall objective of this study was to assess the household energy-water urban nexus metabolism of Cape Town in order to identify intervention points for energy and water savings. This was achieved through the following research sub-objectives:

1. To undertake a critical review of the energy-water urban nexus metabolism at a household level.
2. To develop a system dynamics model of the energy-water urban nexus metabolism of Cape Town households.

1.4 Rationale for the study

Cape Town is unique in that there are many existing studies on resource consumption, resource flows, resource access and resource sustainability (Currie *et al.*, 2017; Hoekman & Von Blottnitz, 2017). With harsh droughts and electricity load shedding a common occurrence in the city, it is becoming ever more important that the dynamics of these resources are understood. Previous studies have been conducted through urban bulk balance, urban material flow analysis, transport dynamics, as well as environmental pressure of material consumption (Currie *et al.*, 2017). The Urban Modelling and Metabolism Assessment (uMAMA) research team within the Centre for Complex Systems in Transitions aims to engage with multiple actors, including city decision-makers, scholars, residents, urban planners, design professionals and many more. Their goal is to increase the research of urban metabolism in African cities (Currie & Musango, 2016) and to investigate urban household metabolism. uMAMA aims to achieve this by developing a database that can support urban African research, assessing resource flows, analysing urban metabolism on an intercity scale, modelling system behaviours and scenarios, visualising resource flows as a policy tool, and telling stories in order to make the research more accessible (Currie & Musango, 2016). These transdisciplinary engagements seek to foster solutions that are sustainable not for the society, but rather with the society. Therefore, this research aims to build on a specific understanding of metabolism, namely energy and water studies conducted by Strydom, Musango and Currie (2019, 2020) and Currie, Musango and May (2017) respectively by utilising system dynamics to understand the energy-water nexus metabolism at a household level.

Understanding the dynamics of the consumption patterns and demands for energy and water resources, knowing the constraints of the resources as well as understanding the potential consequences of possible solutions can prove vital to the planning of the city's infrastructure to provide these resources (De Stercke, Mijic, Buytaert & Chaturvedi, 2018).

1.5 Scope of the study

The scope of the study was:

a. Limited to Cape Town's formal residential households.
b. Limited only to the energy-water nexus.
c. Focused only on direct municipal water and electricity consumption in households.

1.6 Research strategy

Figure 1.1 illustrates the research strategy for this study. It began with the literature review of the fields of urban metabolism and household energy-water nexus. From this, gaps in existing data were identified, and additional data collection occurred. Both the additional data and the

Stellenbosch University https://scholar.sun.ac.za

literature review were used to inform the system dynamics model. Lastly, the results from the model were analysed, and findings were related to the literature to compare.

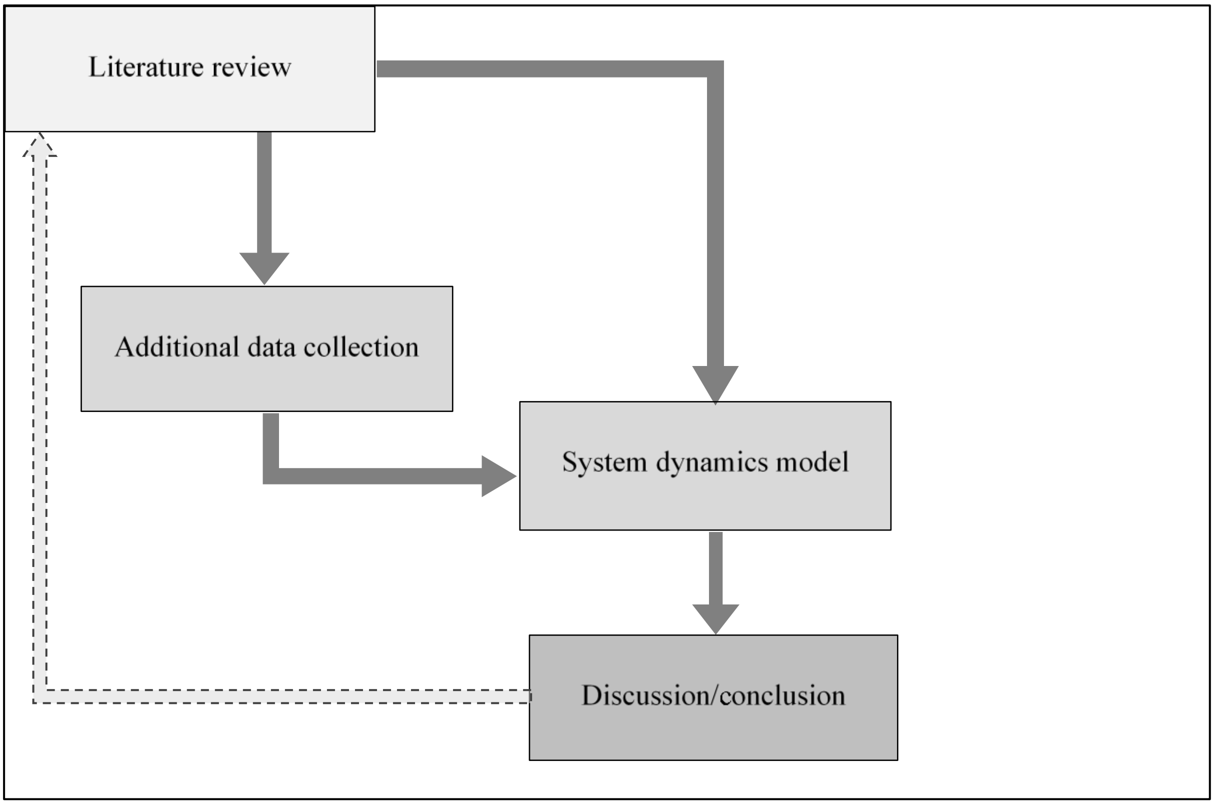

Figure 1.1: Research strategy
Source: Author

1.7 Chapter outline

Figure 1.2 illustrates the objectives of every chapter in relation to meeting the objective and sub-objectives of the research.

Stellenbosch University https://scholar.sun.ac.za

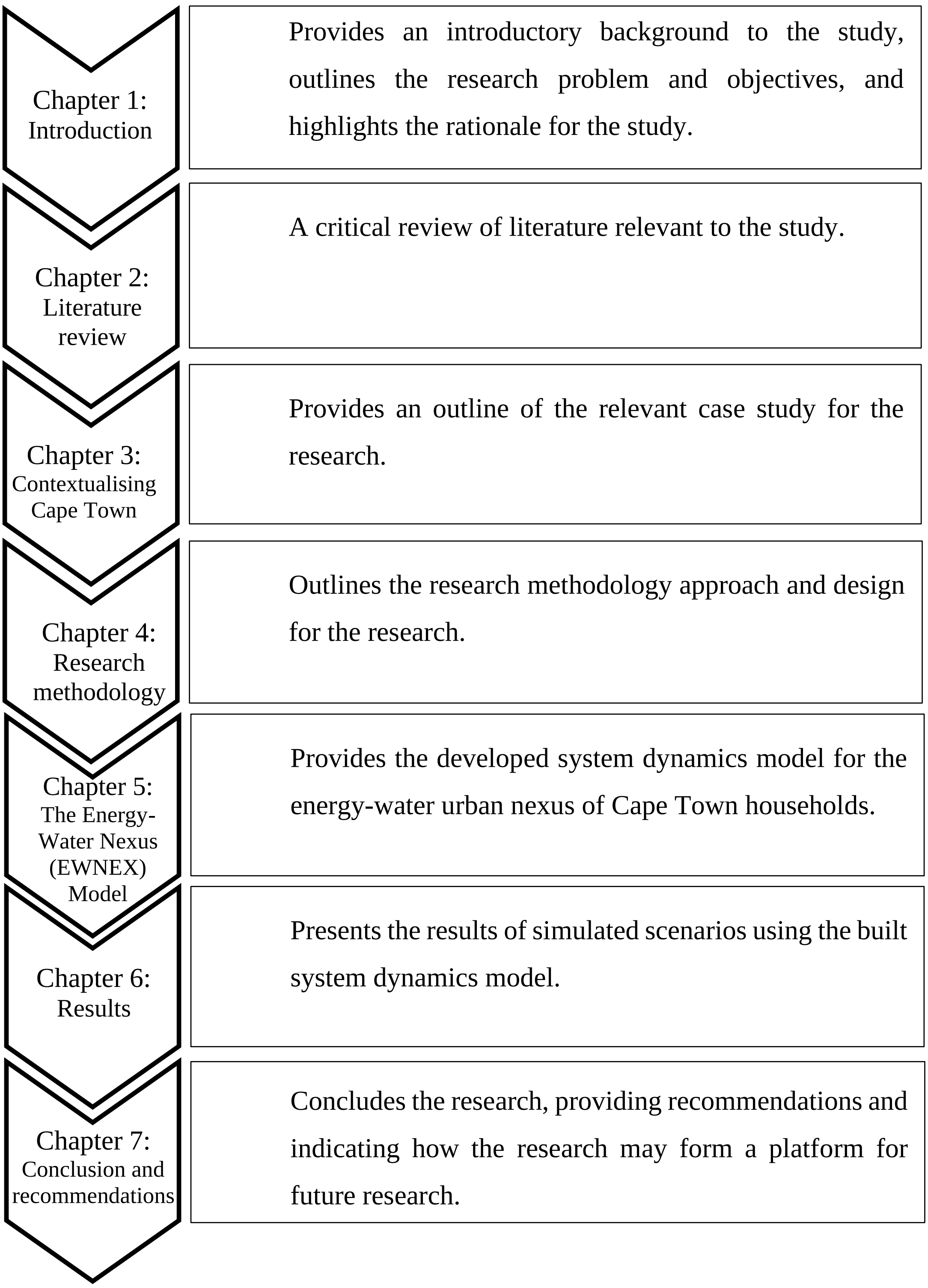

Figure 1.2: Chapter outline
Source: Author

Chapter 2 : Literature review

2.1 Introduction

The New Urban Agenda, which reached a point of understanding that cities are a critical point for solutions rather than a point of challenge, acknowledges that the global urban population is increasing, as is shown in Figure 2.1 (United Nations, 2017; United Nations Department of Economic and Social Affairs, 2014). Due to the majority of the world's population residing in urban spaces, it is critical to implement strategies for developing infrastructure to provide for basic resources such as energy and water (United Nations, 2017; United Nations Department of Economic and Social Affairs, 2014). People are drivers of change, and in these urban areas, population density is high. With a projected 9,8 billion people living in urban areas by 2050, cities can be seen as global nodes of energy and water resource consumption (Department of Economic and Social Affairs Population Division, 2017; Radcliffe, 2018; Swilling, Hajer, Baynes, Bergesen, Labbe, Musango, Ramaswami, Robinson, Salat & Sangown, 2018).

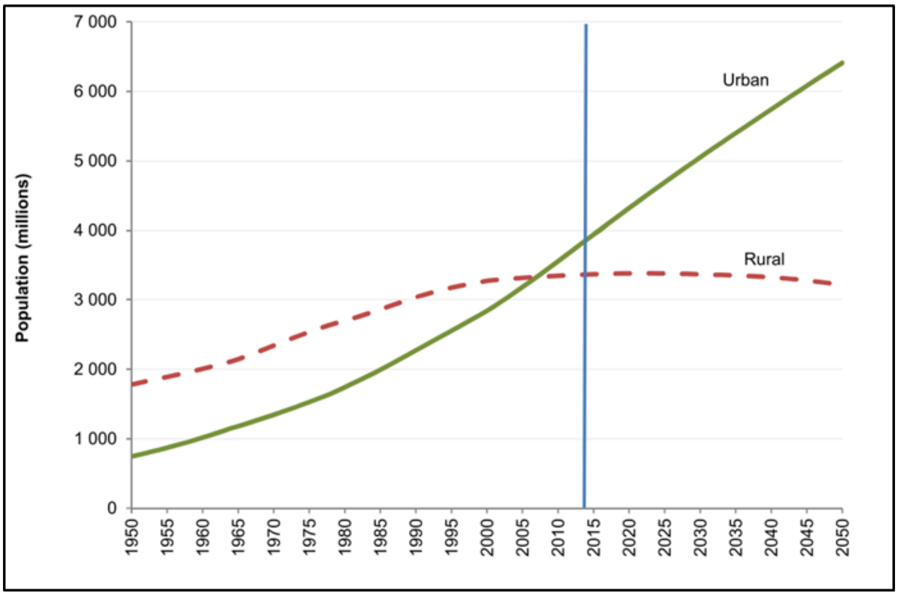

Figure 2.1: Global rural and urban populations between 1950 and 2050
Source: United Nations Department of Economic and Social Affairs (2014)

Human reliance on energy is expected to increase by 50% and on water by 40% by 2030 (Zhang, Zhang, Chang, Xu, Hao, Liang, Liu, Yang & Wang, 2019). As of 2016, two-thirds of the global population are located in areas that experience water scarcity for at least one month of the year (Mekonnen & Hoekstra, 2016). Practices that utilise and manage not only water but all resources, such as energy, are essential for cities to handle the projected urban population (Department of Economic and Social Affairs Population Division, 2017).

Stellenbosch University https://scholar.sun.ac.za

Cities are concentrated areas where human activities occur and represent an essential contact point between natural, social and economic systems (Zhang, Yang & Yu, 2015). Furthermore, cities are hubs of innovation, knowledge and creativity. As the populations of cities increase and cause pressure, more creative innovations are continuously created in order for cities to maintain essential functions (Swilling *et al.*, 2018; United Nations, 2015a, 2017; United Nations Department of Economic and Social Affairs, 2014). Lastly, with cities adopting specific indicator goals such as the Sustainable Development Goals and the New Urban Agenda, they are taking measurable steps towards combating challenges that the world faces. They are providing reduced effects of shocks and chronic stresses that affect a large number of people in a smaller area, compared to rural areas, through more sustainable and sound urban development (Swilling *et al.*, 2018; United Nations, 2015b, 2017).

Having established that cities are nodes of energy and water resource consumption with the need for developing practices for sustainable consumption, this chapter first explores how resources are understood and tracked utilising an urban metabolism perspective. According to the United Nations Environmental Programme (2018), urban metabolism can be introduced 'as a lens through which cities can be studied in order to understand major resource and energy flows and identify infrastructural investments that would enable cities to shift from linear metabolism towards more resource efficient urban metabolism' (Swilling *et al.*, 2018, p. 42).

Chapter 2 examines how urban metabolism can be used as a lens to understand multiple resource flows, specifically energy and water in their nexus. It further looks at how the energy-water nexus can be applied and understood at a household level. Lastly, the chapter addresses a systems approach to understanding the household energy-water urban nexus metabolism and provides some existing studies that have informed the development of this research. An array of different literature applicable to the intended research study was reviewed. Therefore, the chapter addresses the first objective of this study, which was to critically review the energy-water urban nexus metabolism at a household level.

2.2 Urban metabolism

Urban metabolism was first used as a concept by Karl Marx in 1883, in his critique of industrialisation in terms of describing exchanges between energy and material with nature and society (Zhang, 2013). However, Marx used it as a concept of social metabolism in order to

Stellenbosch University https://scholar.sun.ac.za

question the separation between the environment and humans that was becoming increasingly apparent (Wachsmuth, 2012; Zhang *et al.*, 2015). It was later, in 1965, that Abel Wolman redeveloped the term in response to the deteriorating quality of water and air in American cities (Kennedy, Cuddihy & Engel-yan, 2007; Zhang, 2013). Wolman was a water treatment expert and treated cities as organisms with equivalent metabolic processes (Zhang *et al.*, 2015). The term metabolism was initially used to define chemical changes within a living cell. As the term became more widespread in biochemistry, metabolism was used to describe the process of organic breakdown within an organism, and between organisms and their environments (Wachsmuth, 2012; Zhang *et al.*, 2015). In ecology, the definition of the metabolism of an ecosystem is considered to be the production (through photosynthesis) and consumption (by respiration) of organic matter that is often indicated as energy (Kennedy *et al.*, 2007).

2.2.1 Understanding the concept of urban metabolism

Cities are often viewed as non-cyclic linear chains, containing inputs, outputs and stocks of materials (Brunner, 2007). It is often that the input outweighs the output whereby an accumulation of stock will occur if not attributed to a population's growth (Bai, 2007). This means that cities are inherently and entirely dependent on the resources from which they receive their supply, which are usually external to the city itself. Most cities are service-based societies where consumer emissions are held at a higher level than production-related emissions (Brunner, 2007). Similar to the way in which a product can only be considered green if its environmental impact over its entire life cycle is less than that of a competing product, cities should be studied not only by the impacts of stocks, but by their overall impact, which includes the externalities of a city's inputs and outputs (Bai, 2007). Cities exchange energy and resources with their surrounding natural environment, and therefore it has been considered whether cities themselves are able to copy the same natural processes of its surrounding systems, and if insights gained from these systems are able to provide solutions towards mitigating environmental issues that plague these particular areas (Zhang *et al.*, 2015).

There are arguments that in order to mimic the efficiency and stability of natural systems there needs to be an understanding of the principles that underlie most urban processes from an ecological perspective (Zhang *et al.*, 2015). In this sense, cities are treated as an organism or ecosystem and are therefore studied in a manner similar to how natural organisms are studied in the ecological systems in which they occur (Zhang *et al.*, 2015). It is on this metaphor of cities as organisms or ecosystems that the idea of urban metabolism is based (Newell & Cousins, 2015).

Wachsmuth (2012) identified three different periods of urban metabolism situated within three different social science disciplines, which he regarded as the ‘three ecologies’. The first ecology follows Wolman’s understanding of the term from an industrial ecology perspective (Wachsmuth, 2012). Urban metabolism from an industrial ecology perspective spatially locates society in a city. However, it acknowledges nature as the source of natural resources or inputs and as the location for social waste. In this sense, there is movement only between a society sphere and a nature sphere (Figure 2.2(a)) (Wachsmuth, 2012).

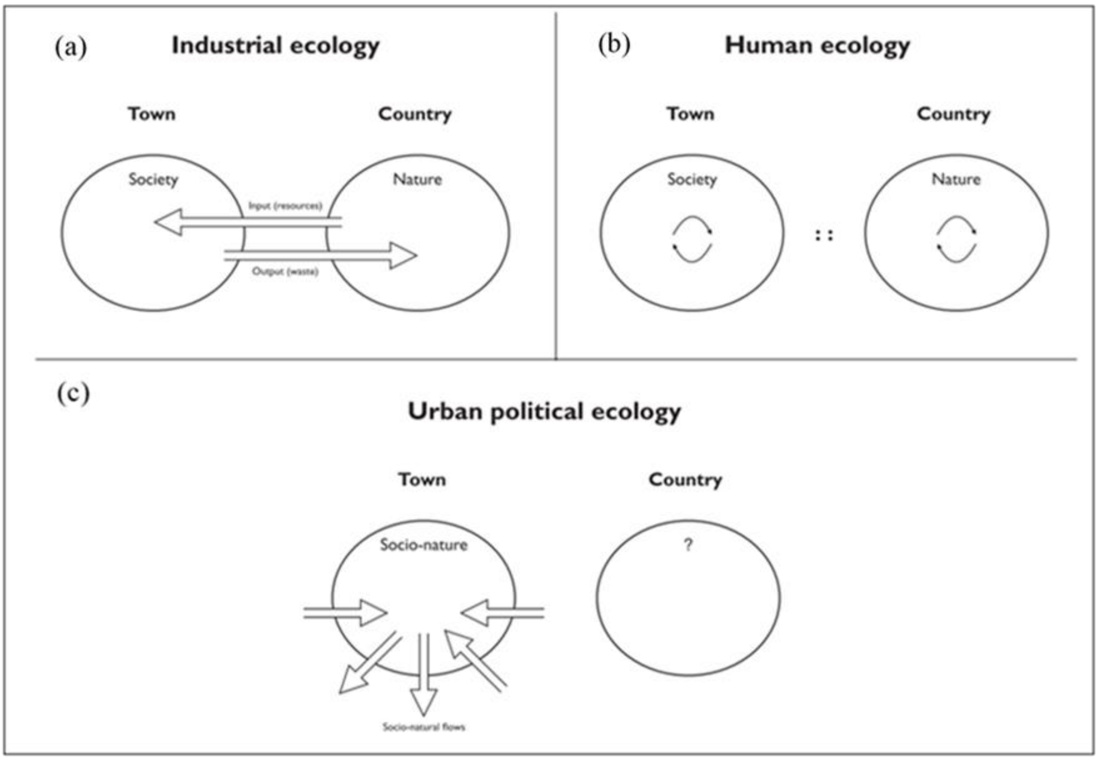

Figure 2.2: Different understandings of urban metabolism
Source: Adapted from Wachsmuth (2012)

In industrial ecology, urban metabolism is considered to be the ‘sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste’ (Kennedy *et al.*, 2007, p. 44). In this sense, urban metabolism quantifies material and energy fluxes in a city. Urban metabolism tracks flow entering a system or city, accounts the circulation to all users and tracks the flows, leaving the systems either as emissions or waste (Fan *et al.*, 2019). According to Currie and Musango (2016), urban metabolism is ‘the collection of complex sociotechnical and socioecological processes by which flows of materials, energy, people, and information shape the city, service the needs its populace, and impact the surrounding hinterland' (Currie & Musango, 2016, p. 1265). The inclusion of people and information in this definition expands the scope to one which considers the needs of citizens therefore addressing efficiency and equity (Strydom, 2019). This definition therefore provides a foundation in terms of contextualising flows within a city however, this study aims to understand specific physical resource flows in a city. The inputs, natural resources, outputs and waste of the city are tracked and measured. Figure 2.3 depicts a hypothetical city's boundary, its inflows, internal flows, outflows, storage (stocks) and production of resources.

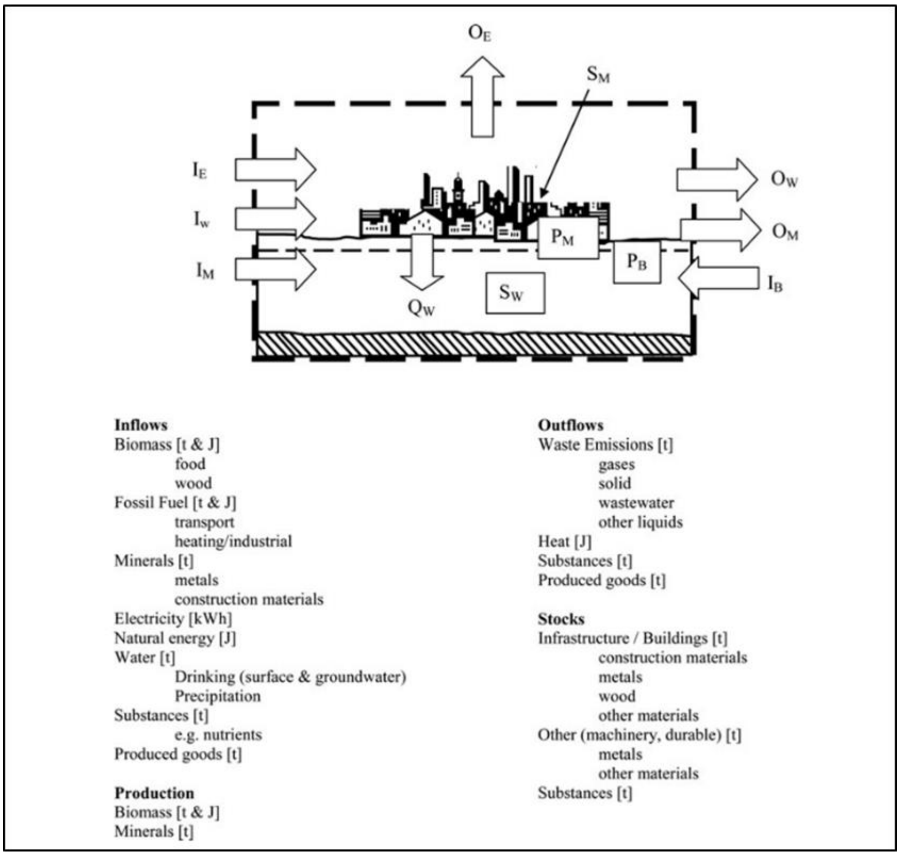

Figure 2.3: Urban city boundary with stocks and flows
Source: Kennedy & Hoornweg (2012)

Urban metabolism in industrial ecology gives nature a more significant role in understanding the metabolism of cities (Wachsmuth, 2012). This is of importance, as it shifts the ways that environmental problems and their solutions are approached. Rather than being social problems, environmental problems become technical problems. Therefore, if a problem arises between society and nature, solutions can be looked for in the city and are not isolated in nature (Wachsmuth, 2012).

Stellenbosch University https://scholar.sun.ac.za

The second of the three ecologies is human ecology, which was a dominant sociological understanding of a city where it was treated as an ecosystem similar to natural, external ecosystems, and urban metabolism was conceptualised to be a social change process internally in a city (Wachsmuth, 2012). In this sense, urban metabolism is seen as outside nature, as the study of the city is the study of society and nature being entirely separate from the city (Figure 2.2(b)) (Wachsmuth, 2012).

The last of the three ecologies is urban political ecology, which is shown in Figure 2.2(c), and sees the city not only as the site of urban metabolism, but rather as the product of it (Wachsmuth, 2012). Political ecology falls under Marxist ecology and uses metabolism to characterise the dynamic society-nature relationships that reorganise both physical and social environments into a socio-natural grouping (Newell & Cousins, 2015). Urban ecology uses the metaphor of metabolism to weaken the nature-society connection and expose uneven power relationships that shape urban spaces to create more democratic and sustainable forms of urban environmental policymaking and governance (Newell & Cousins, 2015).

Urban ecology applies ecological concepts when studying dynamics, and patterns of cities are described as open systems and establish metabolic interaction with cities and their environment (Bai & Heinz, 2011). In this sense, cities are deemed to be adaptive social-ecological systems, continually changing, dynamic and inherently complex, with these behaviours being shaped by both external and internal factors (Bai & Heinz, 2011). The idea that cities can be seen as ecosystems and the interaction between subsystems can be seen as the metabolism of the larger urban system, highlights the complexity of the system, as it recognises anthropic activity as an essential part of the ecosystem (Broto, Allen & Rapoport, 2012). This complex nature suggests an interconnection between all processes, and a change in one – even a small change – may have an overall effect on the metabolism of a city. In order to understand the dynamics of city flows in their entirety, they must be contextualised as a part of a larger, citywide metabolic configuration. Therefore, qualitative research and quantitative research methods should be used equally in order to provide a holistic view of a city and explain why events and processes unfold where and when they do (Schindler, 2017).

Metabolic analysis intends to track all flows coming in from other economies or ecosystems, their circulation in a city and leaving the city's boundary either as solid waste into the environment or as emissions (Fan *et al.*, 2019). Urban metabolism considers the mass balance

Stellenbosch University https://scholar.sun.ac.za

of all materials and has been used to analyse all types of urban materials such as energy, water and food, to name a few (Kenway, 2012).

The drive towards studying urban metabolism of cities is increasing. However, there is still an overall scarcity of city-level data. This is particularly true for cities situated in the Global South and African cities (Currie *et al.*, 2017). There appear to be challenges in finding representative data that allows for the modelling of a system and its effects on its environment (Beloin-Saint-Pierre, Rugani, Lasvaux, Mailhac, Popovici, Sibiude, Benetto & Schiopu, 2017). It is challenging to track informal, illegal, unregulated or decentralised systems that in most parts of the world include material flows and informal good flows (Currie *et al.*, 2017).

A comparison of the urban metabolism of different cities is also limited by the lack of a standardised examining method for urban metabolism (Currie & Musango, 2016; Currie *et al.*, 2017). Some studies, for example, indicate that the overall metabolism of some cities is increasing. Studies conducted between 1970 and 1990 show an increase in water and waste water flows. Hong Kong, Vienna and Hamburg have all become more material-intensive, and Sydney's energy input has increased (Kennedy *et al.*, 2007). However, at the same time other studies indicate that cities are also becoming increasingly more efficient (Kennedy *et al.*, 2007). Cities' metabolisms resulting from a metabolic input perspective are therefore not comparable from results that look at efficiency, as both may have different impacts on the city's waste output (Kennedy *et al.*, 2007). As such, the World Council on City Data (2015) has started a database for urban metabolism data and has collected data from cities such as Rio de Janeiro, Jakarta, Bangkok, Amman, Beijing, Cape Town and many more.

Furthermore, organisations such as Metabolism of Cities aim 'to collaborate on systematically improving the sustainability of cities, by creating and sharing urban metabolism knowledge and accelerating its implementation in policy and practice' (Metabolism of Cities, 2018). Metabolism of Cities has also launched a project called MultipliCity that strives to develop a global network that is able to maintain a hub that centralises, visualises and presents datasets for urban resource use and requirements online (Metabolism of Cities, 2018). This indicates that there is an interest in urban metabolism being used as a framework for sustainable city indicators, because as the global impact and cities themselves grow, it is becoming increasingly apparent that there is a critical need for a broad framework that captures material flows.

Stellenbosch University https://scholar.sun.ac.za

The urban metabolism framework and its methodology encapsulate this and are standardised, allow quick uptake by cities and are embedded in the academic literature that already exists (Kennedy & Hoornweg, 2012). Urban metabolic studies have the ability to identify intervention points required for reshaping resource systems needed for the sustainable growth and management of a growing city (Currie *et al.*, 2017). While the framework of urban metabolism has been adopted in studies concerning Cape Town and intervention points were identified, the matters identified all occur at a city level. Similarly, resource flows studied at a household level have mainly focused on water flows.

2.2.2 Urban metabolism assessment methods

There are many methods utilised to assess a city's resource flows. Urban metabolism is a topic of growing interest, and over the past 40 years it has been assessed with multiple different types of methods in more than 60 areas around the world (Beloin-Saint-Pierre *et al.*, 2017). This includes cities, territories, urban regions or neighbourhoods, most of which at least estimate the amount of impact of resource flows required by a sociotechnical or at least a socio-economic urban system (Hoekman & Von Blottnitz, 2017). The foundation of industrial ecology understanding of urban metabolism is based on the Law of the Conservation of Mass, which is that mass in chemical reactions are not created nor destroyed (Newell & Cousins, 2015). The methodologies that drive industrial ecology are based on this law that (Newell & Cousins, 2015). An industrial ecology understanding of urban metabolism assesses resources and energy in terms of stocks and flows. Therefore, the methods used to study urban metabolism can be through process analysis, accounting and assessment, a simulation model or optimisation and regulation (Zhang, 2013).

There are three main accounting methods of urban metabolism: material flow analysis, energy flow analysis and ecological footprint analysis. These are all based on the thermodynamic laws of conservation of energy and conservation of mass (Currie & Musango, 2016; Hoekman & Von Blottnitz, 2017; Musango *et al.*, 2017). All these methods measure the physical weight or volume of resource flows.

An economy-wide material flow analysis is the most commonly used urban metabolism method mainly due to its standardised methodology produced by the Statistical Office of the European Communities (EUROSTAT, 2001). Material flow analysis measures, within administrative boundaries, the overall magnitude of metabolic flows over a given period, and

Stellenbosch University https://scholar.sun.ac.za

accounts for resource extraction and imports as inputs, and changes of stock in the economy and emissions and waste as outputs to balance accounts (Musango *et al.*, 2017). It is from the comparison of the inputs and outputs from a city that characteristics are established. Younger cities often have larger inputs compared to outputs, but as the city matures, stocks are built up that add to waste flows as they break down, and the outputs begin to become more similar to the inputs and initiatives such as recycling will have more of an impact on the city (Musango *et al.*, 2017).

Energy flow analysis highlights the importance of energy when assessing the metabolism of a city. With energy flow analysis it is believed that material and energy flows should have equal status, and this method can represent the amount of work that the energy of a system is able to perform and is able to produce an analysis that is integrated and accounts for all flows in terms of energy (Zhang, 2013). However, a weakness of this method is the difficulty to evaluate the sustainability of a city based on different spatial units, as every energy transformation rate differs from flow to flow (Zhang, 2013).

Ecological footprint analysis combines the urban development demands with the ecological environment's supply in mind (Zhang, 2013). This method converts the resource consumption of a population into an indicator of how much land is required to sustain that population, combining the ecosystem's carrying capacity with socio-economic development demands (Musango *et al.*, 2017; Zhang, 2013). The drawback of the ecological footprint analysis is that it suggests that land can only be used for one particular aspect. Therefore, it is criticised for oversimplifying the measure of resource sustainability and is instead used generally in public campaigns for emphasising consumption patterns (Musango *et al.*, 2017).

While material flow analysis is used most often, others include substance flow analysis, bulk mass life cycle assessment, and combination and multiple hybrid methods (Currie & Musango, 2016). In industrial ecology, substance flow analysis has been used to study the metabolism of metals, such as those conducted in Stockholm (Hedbrant, 2001; Zhang *et al.*, 2015). Material flow analysis and substance flow analysis, although conceptually related, are different in the approach of analysis and estimation. Substance flow analysis traces the path followed by a particular unit and notes the changes in the flows along with different life cycles (Zhang *et al.*, 2015). Material flow analysis, on the other hand, looks at the quantity and state of data at different points of a life cycle (Zhang *et al.*, 2015). Therefore, material flow analysis requires

Stellenbosch University https://scholar.sun.ac.za

more data but can comprehensively estimate metabolic throughflow and can be used to compare cities (Zhang *et al.*, 2015). Furthermore, whereas most methods generally concern flows of only a single element or material, in some instances such as with material flow analysis, resources are lumped together, even though the linkages between multiple elements or materials are not identified or considered (Fan *et al.*, 2019).

Life cycle assessments consider a specific service or product and identify their impact. They evaluate the entire life cycle of the service or product from its extraction, processing, and consumption as well as its end use disposal (Musango *et al.*, 2017). This method is predominantly suited for approximating flows that are indirectly associated with material and products that have a low processing level, as the assessment can be time and resource-intensive (Musango *et al.*, 2017).

In addition, there are four main accounting methods for urban metabolism, namely ecological network analysis, process analysis, ecological dynamics and input-output analysis (Hoekman & Von Blottnitz, 2017). Process analysis delivers a life cycle account for the use of a resource as well as the environmental impacts associated with the extraction of the raw materials up to the final waste disposal (Zhang, 2013). The drawback of this analysis is that the results of the study may not be generalised to other similar areas (Zhang, 2013). Input-output analysis reveals how industries interact in order to produce gross domestic product by tracing the resources and products of purchases, while also depicting how the resources interact with urban activities by tracking sector-specific product resource flows (Musango *et al.*, 2017). However, input-output simulations are often rough due to the availability of limited data on material and energy flows, as all countries and provinces that interact with the urban space for that specific context would have to be quantified and considered as well (Zhang, 2013).

Ecological network analysis is based on input-output assessments in order to simulate an ecosystem's structural distribution components in order to define different trophic levels and complex interrelationships between them (Zhang, 2013). While based on input-output methods, ecological network analysis aims to simulate the energy and material flows of an ecosystem through a perspective that is more holistic by focusing on the total effect that one output has on another (Zhang, 2013). However, similar to input-output analysis, this method often lacks the data required to be simulated completely, and it is often difficult to refine sectors in a network due to the lack of flows among them in socio-economic systems (Zhang, 2013).

Stellenbosch University https://scholar.sun.ac.za

Lastly, ecological dynamics construct causal feedback relations in order to analyse the evolution and operation trends of urban metabolic systems over a specific time by combining elements of nature, economy and society (Zhang, 2013).

While several studies are conducting urban metabolism assessments, there have not been many that undertake simulation modelling, especially using system dynamics modelling. Furthermore, most research regarding urban metabolism studies involves large-scale studies and therefore lacks the insight required to address specific problems at more local-specific populations, activities or locations (Zhang *et al.*, 2015). However, studies conducted at a more advanced, more local level failed to consider dynamics that occur at a larger scale (Zhang *et al.*, 2015).

There is a frequent exchange of energy and materials between natural and socio-economic parts of an urban system, meaning that ideally there are three sections for intervention if a problem arises: social, economic and natural. However, this requires an understanding of all three based on their interactions and interdependence of each other (Zhang *et al.*, 2015).

2.3 Urban nexus

The Latin meaning of the term nexus is 'tying together' or 'something binding', and the Oxford Dictionary defines nexus as 'a connection over elements or a connected group' (Giampietro, 2018; Stevenson, 2010). These definitions emphasise the importance of the nature of binding in a nexus. Therefore, nexus in terms of resources is the connections that link or bind one resource to another. Figure 2.4 illustrates the conceptual model of a resource nexus by showing the connections between multiple resources. It shows where one resource is used in the process to produce another resource (solid line), or how a resource may be used as a substitute for another resource (dotted line) (Bleischwitz, Johnson & Dozler, 2014). For example, water is an integral resource for food production. However, energy is required to pump the water where it is needed, creating a water-food-energy nexus (Bleischwitz *et al.*, 2014). Similarly, in order to produce thermally produced electrical energy, water is required for the cooling stage of the electricity generation, and energy is needed to treat water for it to be used, creating an energy-water nexus.

Stellenbosch University https://scholar.sun.ac.za

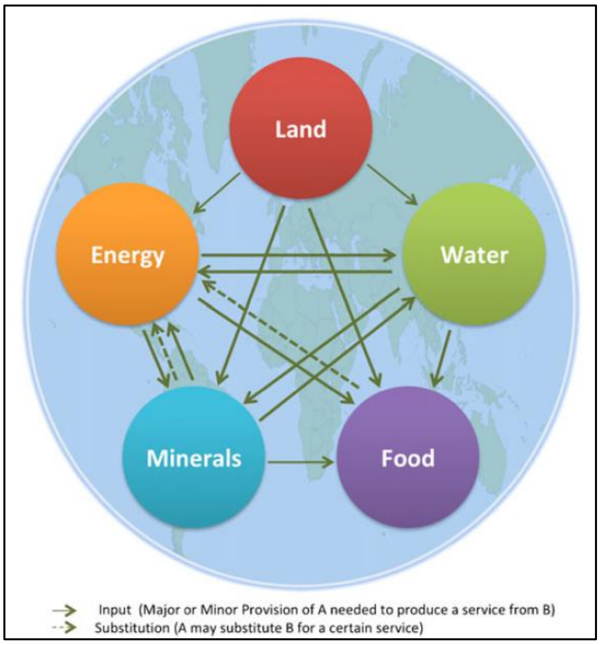

Figure 2.4: Resource nexus
Source: Bleischwitz *et al*. (2014)

However, with the increased use of the term 'resource nexus', the understanding and use of the term has become less defined with authors such as Cairns and Krzywoszynska (2016). They argue that the term has just become a buzzword that will produce conflicting accounts between disciplines, highlighting antagonisms and bringing about problems rather than solutions (Cairns & Krzywoszynska, 2016). While Liu, Hull, Godfray, Tilman, Gleick, Hoff, Pahl-Wostl, Xu, Chung, Sun & Li (2018) also echoed Cairns and Krzywoszynska (2016) opinion that nexus terminology can be overused, they argue that it is still extremely valuable to not retreat back into institutional and intellectual silos and highlight the advantages of the nexus approach (Liu *et al.*, 2018). Liu *et al.* (2018) illustrate (Figure 2.5) in how a nexus understanding of food, water and energy simultaneously achieve multiple Sustainable Development Goals. This indicates how a nexus approach can improve management, government and policy implementation to ensure that these goals are met. Generally, problems occurring within sustainability governance were technical problems arising in isolation and therefore dealt with through strategies that address the single, specific problem. This approach highlights the gap between structures in governance, as problems are dealt with individually, and the influence of other resources on the problem area is not considered or known. By considering how resources interact with each other for specific problems, it may be possible to mitigate unforeseen problems that could occur as a result of a solution to one. This is why nexus understanding of resources is essential (Chen & Chen, 2015).

Figure 2.5: Influence of food-water-energy nexus approach on achieving sustainable development goals.
Source: Liu et al. (2018)

Neoclassical economic principles form a foundational understanding of basic economic theory where technical innovation and human resourcefulness will always be able to find solutions to any problems relating to shortages of natural resources (Giampietro, 2018; Oosthuizen, 2016). Giampietro (2018) identified three main issues that are avoided with these neoclassical principles, namely (1) biophysical analysis used to check the viability and feasibility of potential solutions; (2) population growth; (3) political themes such as fairness and equity, especially significant in the contexts in the Global South. Furthermore Goodland & Ledec (1987) argue that neoclassical economic theories do not take sustainable development into account and that in order to account for environmental concerns, more research in the ecology-economics interface is required (Goodland & Ledec, 1987; Oosthuizen, 2016). Obeng-Odoom (2016) on the other hand suggests the approach to sustainability is emphasised with eco-technology and gadgetry for neoclassical economics, however this was deemed problematic

Stellenbosch University https://scholar.sun.ac.za

since more technology will generate more demand, therefore not considering the pressure exerted on nature (Obeng-Odoom, 2016). Georgescu-Roegen (1986) work on entropy law and the economic process is of note as it take into account that energy cannot be created therefore technology would require ‘a continuous supply of environmental low entropy’, which is limited (Georgescu-Roegen, 1986, p. 15). Neo-Malthusian is generally understood to be the advocacy for population control, but in terms of the resource nexus it addresses these issues on the basis of the acknowledgement that there are external limits to the growth of economic processes from a biophysical perspective (Giampietro, 2018). According to Bleischwitz *et al.* (2014), neo-Malthusian links demographic changes to environmental issues and resource scarcity, therefore it is with this understanding of nexus that this study takes into account the general trend of increasing population and increased urbanisation.

The concept of nexus was brought to international attention with the Bonn 2011 Nexus Conference, which occurred as a result of growing concern for the increasing demand for resources (Giampietro, 2018). The need for resources is one of the main problems that most papers on nexus, including this research, deal with. As background to the 2011 Nexus Conference, Hoff (2011) visually captured the water-food-energy nexus (Figure 2.6), and due to global trends of increased urbanisation, population growth and climate change, water was identified as a central role, as it was considered to be non-substitutional. In this sense, water acts as both a control and a state variable in the water-energy-food nexus (Hoff, 2011). The environment, society and the economy were seen as action fields where governance enables incentives that promote the security of these resources and that promote sustainable and equitable growth (Hoff, 2011).

Stellenbosch University https://scholar.sun.ac.za

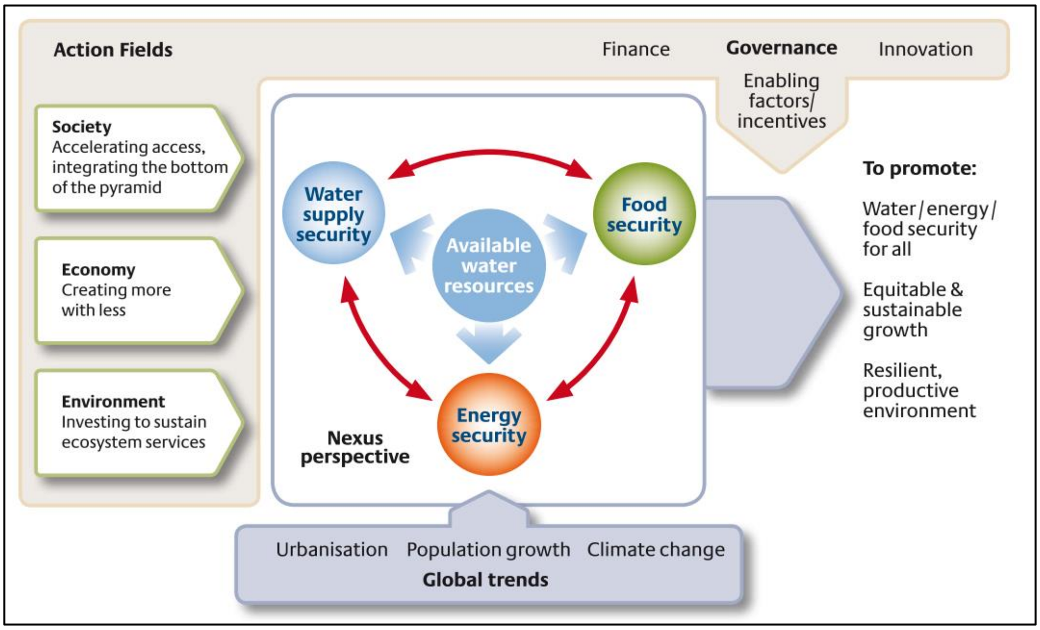

Figure 2.6: Water-food-energy security nexus
Source: Hoff (2011)

In terms of cities, a sustainable urban system needs to be able to achieve some form of mitigation of the human impact on the natural environment while still maintaining urban development (Chen & Chen, 2015). Because cities are complex and are considered the meeting point of natural, economic and social spheres, there needs to be a comprehensive understanding of how all the spheres impact and interact with each other to solve any problems arising in the city (Chen & Chen, 2015; Zhang *et al.*, 2015). The nexus understanding of resources in a city can improve quantitative connections between resources and act as a guide towards actions and policy implementation that could optimise the outcomes of not only one resource but of both (Chen & Chen, 2015; Dai *et al.*, 2018). While the concept of nexus thinking is generally accepted, there appears to be no concise understanding of nexus integration (Zhang *et al.*, 2019).

2.3.1 Urban nexus from an urban metabolism perspective

Giampietro (2018) uses the quantum physics term of 'entanglement' to describe the relationships of resource flows, where it is impossible to describe a particle independently from others, even when particles are separated, a quantum state must define the system as a whole that includes the distance of the separated particles. This explanation illustrates the need to conduct a holistic analysis of predicted patterns that are to be expected by individual metabolic

Stellenbosch University https://scholar.sun.ac.za

elements that belong to a larger system. While urban metabolism studies may be conducted on multiple flows, there is no apparent method that links the flows.

Unlike urban metabolism, urban nexus metabolism connects various materials where boundaries may be geographical, administrative, political or even technological (Fan *et al.*, 2019). Rather than focusing on an individual resource within an urban ecosystem, urban nexus metabolism uses more than the framework of urban metabolism by optimising the interlinkages within the entire urban system to identify high-intervention leverage points in order to maintain the sustainability of a city. Studying the link of different natural and socio-economic factors in urban ecosystems is extremely important. Cities that have designed their infrastructure and services in linear metabolism can now start to evolve into being more dynamic, with the intent of being more sustainable and having a lesser impact on nature (Chen & Chen, 2015).

Insight for sustainable urban development management and planning can be achieved by using urban metabolism as a base to define a more integrated and broad nexus system with multiple flows (Fan *et al.*, 2019). Nexus in terms of urban metabolism highlights connections and links between various resources and their intertwined conversion pathways through parallel production and consumption chains with regard to socio-economic sectors (Chen & Chen, 2015). Urban metabolism provides a general framework under which sustainable socio-economic development of cities can be defined. However, the integration of urban metabolism and nexus takes the next step towards sustainable management and planning. This process is vital when it comes to cities addressing challenges when facing rapid urbanisation and resource management.

2.3.2 Energy-water urban nexus metabolism

Water is one of the most precious resources, as it is essential for all basic functions of life. It should therefore not only be made available but also affordable to all (Ioannou & Laspidou, 2018). According to Kennedy *et al.* (2007), the largest component of urban metabolism is water. Water and energy are considered to be two of the world's most critical resources and as a result gained a lot of attention from both academia and the public. Therefore, it is crucial to have an in-depth understanding of the energy-water nexus in order to implement sustainable resource management.

While some may argue that the incorporation of food is essential when looking at sustainable resource management in the form of the energy-water-food nexus, this study is limited to only the energy-water nexus. The reason for this is the context of the case where drought and energy shortages are prevalent (Giampietro, 2018). Duan & Chen (2020) developed a basic framework for the energy-water nexus, which is illustrated in Figure 2.7. The framework is split into three main levels, or tiers, relating to the system boundary and object in the water and energy production and consumption cycle (Duan & Chen, 2020).

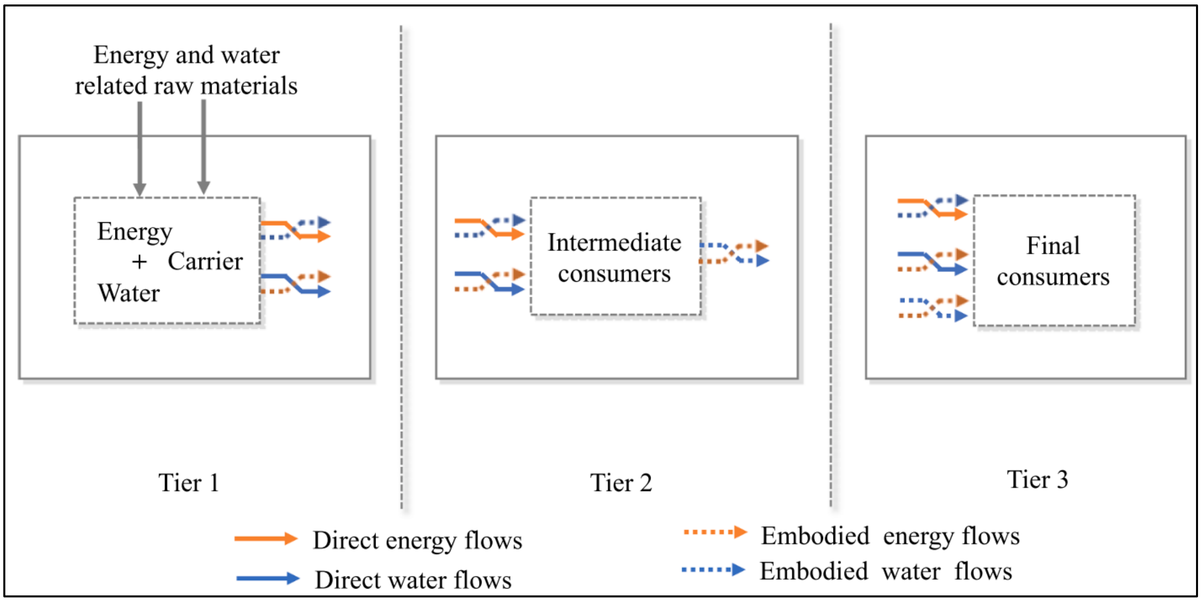

Figure 2.7: Basic energy-water nexus framework
Source: Duan & Chen (2020)

The first level is a quantified representation of the direct relationships between energy and water. It describes the basic nexus of the resources when primary energy is taken from the environment and the consumption of fresh water (Duan & Chen, 2020). Therefore energy-water nexus on this level includes water consumed or used for the production of one unit of energy carriers (fuel oil or electricity), and energy used for the production of one unit of water product. The second tier consists of the consumption of energy and water by intermediate consumers, such as industrial sectors. This second tier provides services and produces goods for final consumers' consumption (Duan & Chen, 2020). The last tier consists of the consumption of energy and water by final consumers, where the energy and water generated in the first two tiers flow into this tier of the final consumers where consuming and purchasing behaviours are considered (Duan & Chen, 2020).

Similarly, Hamiche, Stambouli and Flazi (2016) also categorised energy and water functions into three main sections: production, transportation and consumption. This categorisation

Stellenbosch University https://scholar.sun.ac.za

indicates that there is a general flow sequence when it comes to energy and water in urban spaces. Energy and water from the environment or hinterland, such as bulk water supply from dams, lakes or desalinisation plants and primary or secondary electricity generation, are placed in the ‘production’ category (Hamiche *et al.*, 2016). The category of ‘transportation’ consists of the distribution and transmission of water and energy, whether it is being stored or transferred (Hamiche *et al.*, 2016). ‘Consumption’ is close to the end-use, such as direct supply to residential, industry or retail, embedded generation or waste-water treatment (Hamiche *et al.*, 2016). This categorisation is also pertinent when one looks at the links between energy and water, for example, a ‘production’ link would be the use of recycled water to cool thermal power stations. Figure 2.8 visually illustrates some of the links between energy and water, with ‘production’ functions in blue, ‘transportation’ in orange and ‘consumption’ in green. While production, transportation and consumption read as a very linear process, the illustration of the links in Figure 2.8 visually emphasises that the links between water and energy functions are non-linear.

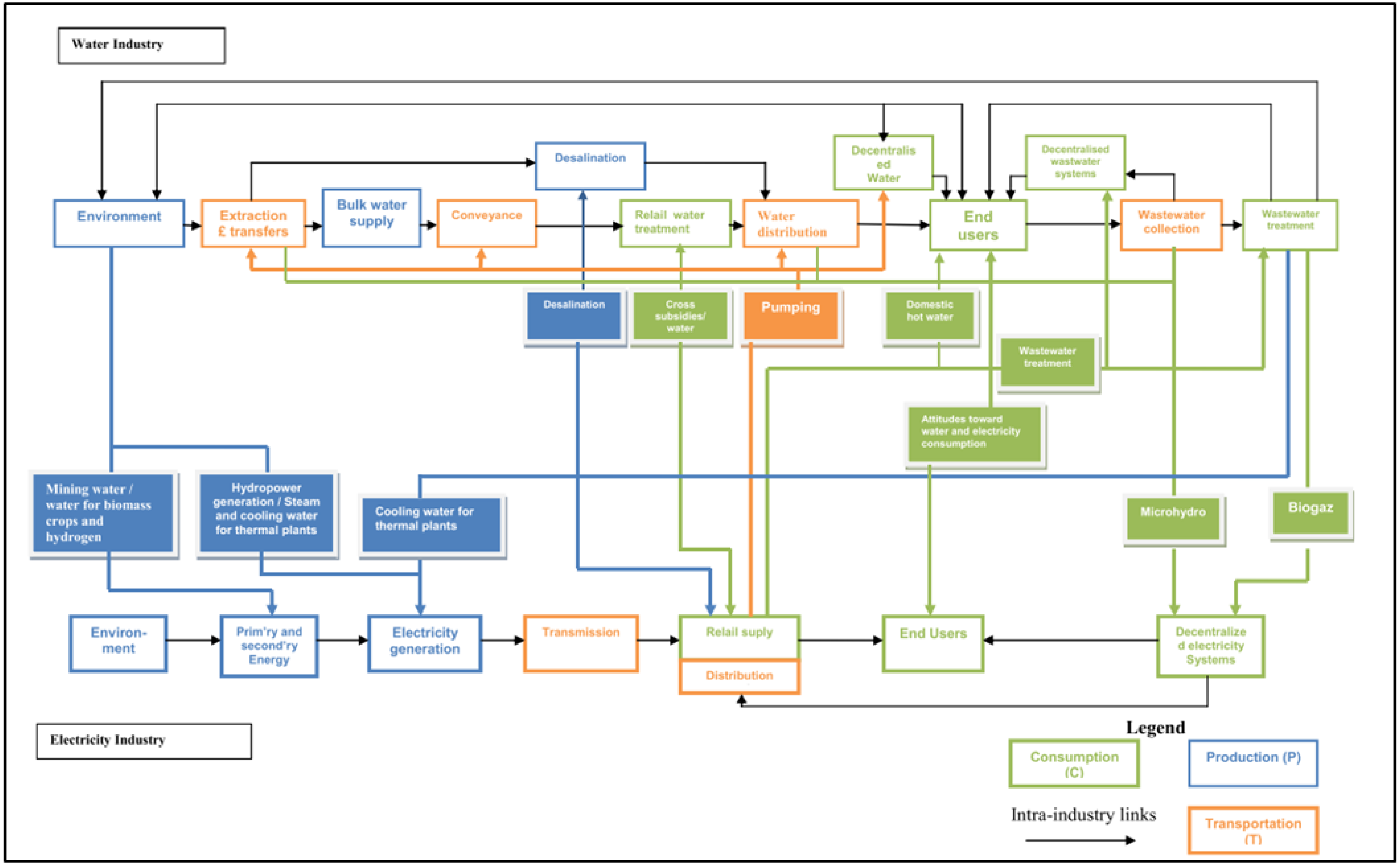

Figure 2.8: Energy and water 'production', 'transportation' and 'consumption' links
Source: Hamiche *et al.* (2016)

Stellenbosch University https://scholar.sun.ac.za

Within energy-water nexus studies, there are different facets to consider: environmental, social, technological, political and economic. The environment is generally the starting point for the energy-water nexus, as it is the source of all energy and water resources or the lack thereof in the case of droughts.

In drought-stricken Algeria, infrastructure and water and energy consumption have until recently been developed with little regard for the quantities of these finite resources in the area (Hamiche *et al.*, 2016). Both sectors are now responding to the drought in different ways, such as the sourcing of alternative water supplies and the installation of novel waste-water treatment technologies used for cooling coal-generated electricity powerplants (Hamiche *et al.*, 2016). Both innovations adopted may inevitably consume more energy in order to work, and the ultimate problem is which resource takes priority – the reduction of energy or the supply of water.

The societal dimension of the energy-water nexus acknowledges that any links that join energy and water have substantial value, the attitude towards the resources may reinforce the links between them if the perception of water and energy's value is linked to the consumption thereof (Hamiche *et al.*, 2016). If the perceived value is low, the tendency to conserve would be low, whereas if more value is placed, a tendency to conserve would be higher, therefore decreasing consumption. The technological dimension of the energy-water nexus refers to the physical infrastructure that links energy and water, such as waste-water treatment plants, water recycling, water extraction and desalination. These are all energy-intensive, as is the water needed for cooling thermal-generated electricity or hydropower (Hamiche *et al.*, 2016). The energy-water nexus political dimension is revealed through industrial policy reforms, for example, a lack of energy and water policies and regulations may result in increased energy use or the over-extraction of groundwater (Hamiche *et al.*, 2016). Lastly, the economic dimension of energy-water nexus addresses the regulatory arrangements, ownership and overall structure of both the water and the energy sectors (Hamiche *et al.*, 2016).

2.3.3 Energy-water urban nexus metabolism assessment methods

Zheng, Wang, Li, Zhang and Fan (2018) conducted an urban energy metabolism study between 2002 and 2010 at a regional and provincial level of the Jing-Jin-Ji urban agglomeration. The research analysed direct, indirect and integral processes of energy exchange and found that energy flows within the agglomeration changed in 2007 due to industrial restructuring,

Stellenbosch University https://scholar.sun.ac.za

indicating that industrial activity is a large driver of energy consumption (Zheng *et al.*, 2018). Zhang, Li and Zheng (2017) conducted an ecological network analysis of energy metabolism in the same area by constructing a sector network model representing energy flows and sectors as pathways and nodes. Energy flow processes were detailed, and energy consumption patterns were calculated on both regional and sectoral scales. The results also indicated that the largest energy consumption occurred from industrial activity, with Beijing being the dominant integrated energy consumer (Zhang *et al.*, 2017). However, these studies focused solely on energy and did not take any other material flows into account.

Similarly, urban metabolism has been used to understand water flows in Australia. Research by Renouf, Kenway, Lam, Weber, Roux, Serrao-Neumann, Choy and Morgan (2018) conducted an urban water metabolism evaluation to create water-sensitive interventions needed to achieve water-efficient performance objectives. In addition, a water mass balance was also examined in the area by Renouf, Serrao-Neumann, Kenway, Morgan and Low Choy (2017) to improve water resource management. However, just as the case of the Jing-Jin-Ji urban agglomeration, they focused on only one flow. Renouf *et al.* (2017) even suggest that the urban water balance should be overlain with energy and nutrient data to understand sustainable indicators for the extraction of resources and the diverse functions that every resource has. Similarly, with urban metabolism studies conducted in Cape Town, resource flows that were studied were studied in isolation of each other, indicating a gap not only in data but also understanding.

Within cities, energy and water systems are linked in multiple ways (De Stercke *et al.*, 2018). Water is required for the extraction, processing, transportation of energy and operation of thermal power plants (Ioannou & Laspidou, 2018). In turn, water needed for any form of human activity requires large amounts of energy, as energy is required for water purification processes, water pumping, waste-water pumping and pressurised water distribution systems (Ioannou & Laspidou, 2018). In this sense, water and energy are two of the most fundamental flows to form and maintain normal operations in all urban cities.

Cities' infrastructures are generally designed linearly, which may result in a high metabolic consumption of resources. Therefore an energy-water nexus from an urban metabolism perspective would be beneficial, as it would help identify alternative sources and corresponding

Stellenbosch University https://scholar.sun.ac.za

utilisation pathways within a system that would take economic viability as well as environmental sustainability into account (Fan *et al.*, 2019).

There are multiple methods to use to conduct nexus studies, specifically energy-water nexus studies, which are summarised in Table 2.1.

The first method is Energy Intensity, which is a top-down, bottom-up hybrid approach model, used mostly to quantify energy in water systems and requires no scenario function (Dai *et al.*, 2018). A municipal district in Northern California used the Energy Intensity method as an accounting method for the analysis of its water-energy nexus.

Jordan's framework used a developed systematic conceptual framework in order to bridge inter-organisational networks for planning and policymaking for energy and water (Dai *et al.*, 2018). There are three main linked components for this method. The first is an analysis component that is quantitative and that links energy and water in order to model sub-sectors within each sector (Dai *et al.*, 2018). The second component consists of a stakeholder analysis of both the energy and water sectors in order to identify all the organisations and key actors involved in the sectors (Dai *et al.*, 2018). The last component combines the results of the previous components in order to identify main stakeholders that can serve as a bridge between the water and energy sector for decision-making. While the Jordan framework is thorough, it was developed to be used predominantly in Middle Eastern and Northern African contexts due to the structuring of their governance of the water and energy sectors (Dai *et al.*, 2018). Therefore, it would not be suitable to use in other contexts.

Linkage analysis is able to detect both indirect and direct resource consumption and the roles that each plays within the economic sector (Dai *et al.*, 2018). This method is a quantitative method from an economic perspective that is derived from an input-output analysis.

The Multiregional Nexus Network is an integrated model that combines multiregional input-output analysis with ecological network analysis (Dai *et al.*, 2018). The ecological network analysis quantifies the relationships between economic sectors and the indirect and direct resource flows within sectors (Dai *et al.*, 2018). The multiregional input-output analysis, on the other hand, assesses indirect energy and water flows required to produce goods and services based on the interactions of different sectors (Dai *et al.*, 2018).

Table 2.1: Energy-water nexus assessment methods

Method	Model type	Developer and software	Geographical scale	Purpose	Nexus challenge level
Energy Intensity	Quantitative analysis model	No software	City level	Quantify energy flows in urban water systems	Understanding
Jordan's framework	Integrated model	No software	National level	Link decision-making to higher use efficiencies of water and energy in Jordan	Governing
Linkage analysis	Quantitative analysis model	No software	City level	Explore the structure and interconnection of both water and energy resources in cities	Understanding
Multiregional Nexus Network	Quantitative analysis model	No software	City and regional level	Explore the interconnections of energy consumption and water use for urban agglomerations	Understanding
System dynamics approach	Integrated model	No software	Global, regional, national, city and household level	Long-term regional water and energy resources management	Understanding
Urban Water Optioneering Tool	Quantitative analysis model	Online tool	City level	Quantify energy use in urban water supply systems	Understanding

Source: Adapted from Dai *et al.* (2018)

Stellenbosch University https://scholar.sun.ac.za

A system dynamics approach consists of a five-step process of problem articulation, dynamic hypothesis, formulation, testing and lastly, policy design and evaluation. This process includes a structure test, structure-orientated behaviour test, behaviour test and scenario evaluation and design (Sterman, 2000). System dynamics utilise long simulation periods in order to understand a long-term management option for both energy and water (Dai *et al.*, 2018). System dynamics models may contribute towards overcoming difficulties that may hinder the development and implementation of more holistic policies (Zhang, Chen, Li, Ding & Fu, 2018). Furthermore, it has the ability to analyse systems that are multisectoral at micro and macro level by generating causal feedback loops from the components of a particular system (Zhang *et al.*, 2018).

Lastly, the Urban Water Optioneering Tool assesses different interventions to reduce water demand, estimates energy required based on water appliances, evaluates waste volumes and runoff-beneficial use and evaluates the beneficial heat island effect (Dai *et al.*, 2018). While the Urban Water Optioneering Tool supports a historical time series, as with the Energy Intensity method, it has no scenario function (Dai *et al.*, 2018).

Understanding water and energy in terms of energy-water nexus metabolism provides not only a framework for understanding resource flows, but also the methods towards understanding the linkages between water and energy flows. That being said, Table 2.1 highlights a specific gap in the methods of the energy-water nexus, namely that the geographical scale at which all these methods are conducted is either national, regional or city level. While these levels are three of the four main macro-level scales at which the energy-water nexus is assessed (Figure 2.9), it indicates that detail at lower levels is either not considered or does not play as vital a role as those at the higher levels.

Stellenbosch University https://scholar.sun.ac.za

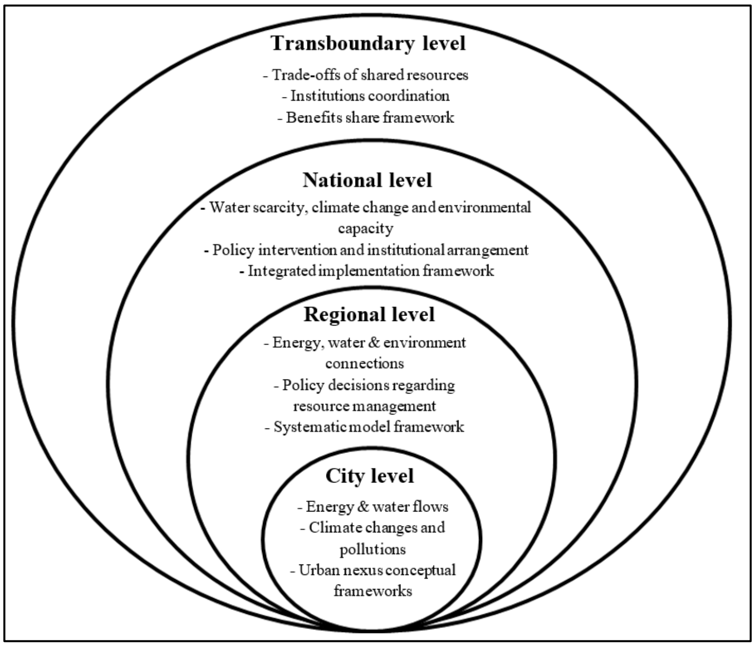

Figure 2.9: Focuses of macro-level energy-water nexus studies
Source: Adapted from Dai *et al.* (2018)

Energy-water urban nexus studies are looked at from a transboundary-level when governing authorities have to balance the needs of a particular local community with those of a different community within the same wider environment. An example of such a case would be two cities that fall within the same river basin or catchment area and are required to share their water resource.

Energy-water urban nexus studies conducted at a national level will generally be carried out when a policy needs to be implemented to tackle issues such as environmental capacity, water scarcity or irrigation pressure that affects a large area. These studies will be conducted even when resources are not always directly linked. Regional-level studies are performed generally around river basins where not only a city itself is concerned, but also the more extensive drainage areas are considered. This scale supports decision-making and policy by focusing on articulating interactions between energy, water and various actors, as well as the trade-off that may occur among them (Dai *et al.*, 2018).

City-level energy-water nexus studies are the most common of all the scales, as most studies consider cities to be the core systems for the energy-water nexus globally. At a city level, it is essential that energy-water urban studies are embedded in conceptual frameworks such as urban metabolism in order to not only take a systems approach to map water and energy urban flows, but to also connect them with environmental changes such as urban transition or pollution (Dai *et al.*, 2018). This indicates a need for the integration of nexus studies and urban metabolism studies to assess the energy-water urban nexus metabolism fully.

Dai *et al.* (2018) conducted a comprehensive review of 35 energy-water nexus case studies, which were all conducted at a macro-level scale. Figure 2.10 indicates how macro-level studies focus on access to energy and water management at different geographic scales and are more often than not on the resource availability of both water and energy systems. However, this knowledge is often fragmented, as it occurs over a large area consisting of multiple complex urban and rural systems. Micro-level studies, on the other hand, focus on specific economic sectors and access resource flows within them. This level of understanding provides more in-depth knowledge on the processes and dynamics of the energy-water nexus, and by not researching it at this level but rather at a broader level, entire economic sectors are overlooked and not understood because the detail is not understood.

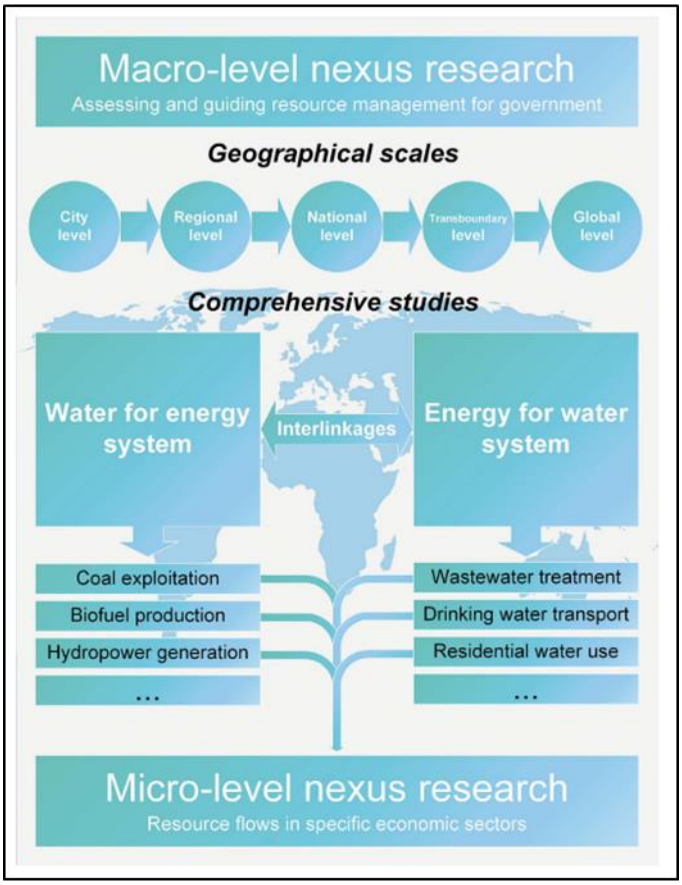

Figure 2.10: Macro-level energy-water nexus studies conceptual framework
Source: Dai *et al.* (2018)

Within cities there are various sectors and levels at which flows occur. The studies of Zheng *et al.* (2018) concluded that there were three main areas where the energy exchange of resources

Stellenbosch University https://scholar.sun.ac.za

was advantageous for both administrative divisions and geographic position, namely Hebei, Tianjin and Beijing. However, these exchanges were unable to be detected at a regional level. This indicates that the flows in an area can be understood differently, depending on the scale that the area is viewed from. The smaller scale means more detail in understanding the flows.

2.4 Household energy-water urban nexus metabolism

An urban population, especially in African contexts, causes more direct pressure on resource limits (Currie *et al.*, 2017). Large amounts of resources are consumed daily in order to meet the everyday demands of the inhabitants. A large proportion of water and energy consumption occurring in cities is attributed to daily household use (Hussien *et al.*, 2017).

In terms of the scale of energy-water urban nexus studies, households are the smallest level at which it may be studied (Barrera, Carreón & De Boer, 2018). While it could be argued that individual consumers are the smallest unit measurable, Biesiot and Noorman (1999) argue that individual activities are centred around the household. In this sense, households are considered the smallest social units consuming and changing a complex flow of energy and water.

The structural unit of the equivalent would therefore be the physical building or structure of a house, whereas the household refers instead to behavioural aspects of the group of individuals collectively living and performing activities in the house (Barrera *et al.*, 2018; Biesiot & Noorman, 1999). Therefore, this study considers households as the unit used to assess the energy-water nexus metabolism at a micro level. Harder, Dombi and Peters (2016) define household metabolism as ‘a concept that is concerned with the analysis of stocks and flows of energy, matter and information at a household scale’ (Harder *et al.*, 2016, p. 194). The term household energy-water nexus metabolism is therefore concerned with the analysis of the interconnected flows and stocks of energy and water at a household scale.

At a household level, energy and water present a high interdependency as a result of daily utilisation patterns. With just over 33% of consumed water needing to be preheated before use, energy demand associated with water use in residential areas is estimated to be more than that for waste-water treatment and water supply services (Fan *et al.*, 2019). Intervention measures that concern the amount of water used at this level will decrease not only the amount of water used, but also the amount of energy used (Chhipi-Shrestha, Hewage & Sadiq, 2017).

Stellenbosch University https://scholar.sun.ac.za

Households are essential drivers of water and energy consumption, as they are able to regulate direct energy consumption directly and indirectly by regulating grey energy consumption (Kenway *et al.*, 2013). Understanding resource flows at a household level provides more detail than understanding flows of resources in a city at a macro scale. While urban metabolic assessments of water and energy flows were conducted at a household level, those who studied the nexus of the resources at this level more often detailed how energy was used for water, and seldom the reverse (Chini, Schreiber, Barker & Stillwell, 2016; Hansen, 1994; Kenway *et al.*, 2013).

Kenway (2014) found that 50% of household energy was accounted for by water-related energy use such as showering, baths, dishwashers, electric kettles and washing clothes. The focus on energy for water rather than water for energy could be because, in households, energy is generally in the form of electricity, as water used for energy occurs at the macro-level production of energy, such as for hydroelectric power or for the cooling process of thermally generated power. Both of these will supply households with energy in the form of electricity. This focus on energy for water rather than water for energy in households was echoed in other studies, for example that of Liu *et al.* (2005), which studied the energy and water metabolisms of Chinese households. Similarly, Gerbens-Leenes (2016) also conducted a study of the energy and water metabolisms of Dutch households (Gerbens-Leenes, 2016; Liu *et al.*, 2005). Therefore, it is apt that the term 'energy-water' and not 'water-energy' is used when considering the household energy-water urban nexus metabolism, since in households it is energy used for water rather than water used for energy.

Liu, Wang and Yang (2005) visually depict household metabolism in Figure 2.11 and identify three main types of flows. Flows 1, 2 and 3 are the input flows of consumption in the household, and include materials, water and energy (Liu *et al.*, 2005). Flows 4, 5 and 6 are the output flows of household consumption, representing solid waste, air emission and water emission (Liu *et al.*, 2005). The last flows, flows 7, 8 and 9, represent the recycling processes of water, energy and materials (Liu *et al.*, 2005). For this study, Liu *et al.* (2005) considered only energy and water metabolism instead of taking all aspects of household metabolism into account, because consumption developments are closely linked to water and energy used (Liu *et al.*, 2005).

Stellenbosch University https://scholar.sun.ac.za

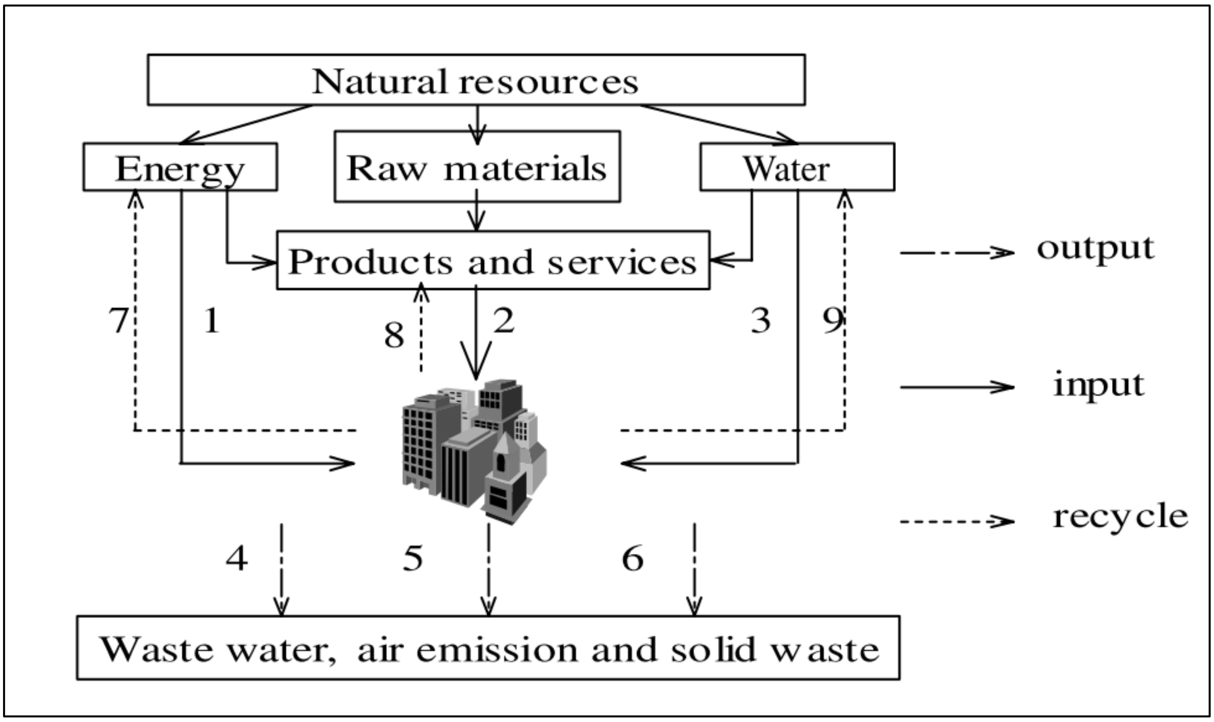

Figure 2.11: Model of household metabolism
Source: Liu, Wang & Yang (2005)

Alternatively, Harder *et al.* (2016) suggest that household metabolism can be analysed either as processes, pathways, products or layers. The rationale behind this is that flows can be calculated at different levels in the household itself. Flows can be calculated as layers of every resource entering and exiting the household, such as water or energy (Figure 2.12 (a)). Flows can also be quantified as products (Figure 2.12(b)), where fresh water may be considered an inflow and waste water considered an outflow (Harder *et al.*, 2016).

Stellenbosch University https://scholar.sun.ac.za

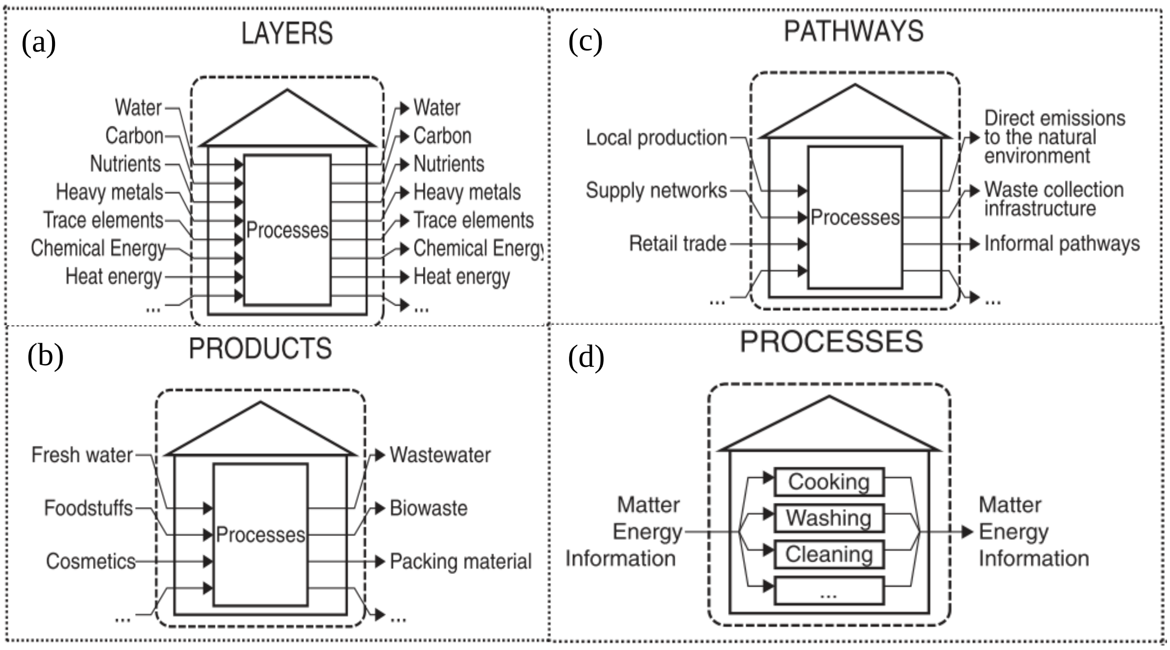

Figure 2.12: Analysis of household metabolism
Source: Adapted from Harder *et al.* (2016)

Alternatively, the pathway of flows can be quantified, for example, in Figure 2.12(c) supply network flows are quantified as inflows into households and outflows are waste, emissions and informal pathways (Harder *et al.*, 2016). Lastly, the processes of individual appliance groups, Figure 2.12(d), such as those used for washing, cleaning, cooking etc. can be quantified (Harder *et al.*, 2016). Flows quantified can be thought of in two main groups: those supplied through public mains and those that are not and either travel through waste collection schemes or retail trade (Harder *et al.*, 2016). Goods supplied through public mains are typically measured using sensors or meters, and at least one meter is required for every flow, which is often provided by utility companies for billing purposes (Harder *et al.*, 2016). However, more modern smart technologies have 15-minute sampling intervals, whereas energy and water bills usually consist only of monthly consumption (Harder *et al.*, 2016). While this type of data would prove beneficial for energy and water consumption, the nexus of the two resources cannot be analysed, and data on how the resources are used rather than how much would be more valuable. In this sense, individual data consumption for fixtures or appliances is required, and for this, there are two possible approaches.

The first is to place a meter at every appliance concerned. However, in practice this method is not realistic, as it requires a large number of meters and would be costly and unproductive with regard to installation time (Harder *et al.*, 2016). The second option would be to use

Stellenbosch University https://scholar.sun.ac.za

interpretations based on algorithms and pattern recognition of signals from single meters. This reduces the number of meters required, but errors may occur, as not all events for a given fixture may be classified correctly (Harder *et al.*, 2016). These forms of data only analyse flows from public mains. However, it cannot be assumed – especially in cities in the Global South – that energy and water resources are received exclusively from public mains for households, and resources not supplied through public mains need to be considered too. Quantifying consumption of these flows is more complicated, as supply and discharge occur via several different pathways. Still, the information is generally available to customers electronically, especially when it pertains to purchased goods (Harder *et al.*, 2016). Alternatively, data could be collected manually through household documentation (questionnaires or surveys), which provides the opportunity to identify all resource flows from both public mains and other flows. This would provide more insight into the nexus of energy and water consumption of households (Harder *et al.*, 2016).

Kenway *et al.* (2013) conducted a mathematical material flow analysis on households in Brisbane, Australia, and a system border with energy and water flows was defined for most common households in Australian cities (Kenway *et al.*, 2013). Figure 2.13 illustrates how the system was set up, with the main system encompassing 10 subsystems (in grey-shaded blocks). These subsystems are the ones that provide the household with services that are water-related, such as water for showering, bathing, washing machines, drinking, dishwashing, outdoor use, toilet flushing, kettles and laundry. The exception is the 'other energy use' subsystem, which consists of all other main household energy-using services that are non-water related (Kenway *et al.*, 2013). The energy and water from the 'supply subsystems' are what feeds into the 'service subsystems', and the waste water from the 'service subsystem' is released into the 'waste-water subsystem' (Kenway *et al.*, 2013). Tracking individual flows in this manner creates the ability to consider and assess the influence of changes on a subsystem level, such as changes in behaviours and environmental conditions, or the introduction of more efficient, smart technology systems (Kenway *et al.*, 2013).

Stellenbosch University https://scholar.sun.ac.za

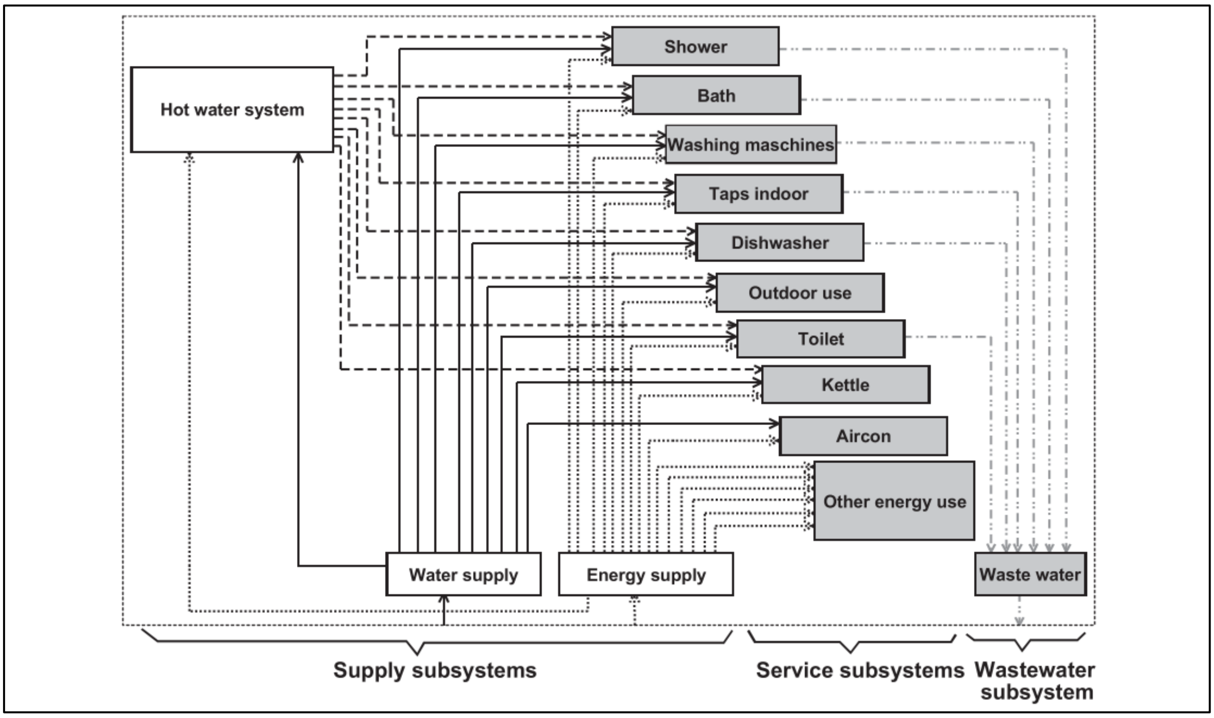

Figure 2.13: Household energy and water systems
Source: Kenway *et al.* (2013)

According to Liu *et al.* (2005), due to increasing urbanisation, residential water consumption is just as important as that of industrial sectors. The reason is that in China, between 1990 and 2000, while industrial-sector water consumption decreased from 72,18% to 48,6% of China's total water consumption, residential consumption increased by 16,46% from 26,18% to 42,64% (Liu *et al.*, 2005). These figures indicated that residential households became the main user of residential water consumption, as it exceeded that of the public sector (Liu *et al.*, 2005). Liu *et al.* (2005) described household energy consumption as the 'energy consumed in homes to meet the needs of family members', and found that the main usage of energy in a household was for cooking, cooling, heating, lighting and the operation of electrical appliances (Liu *et al.*, 2005, p. 333). It was found that heating and cooking required the largest amount of energy, consuming 68% and 11% of energy respectively, and cooling consumed the least, requiring 1% (Liu *et al.*, 2005).

While the figures may be outdated, the main uses of water in a Chinese household in a 2005 were attributed to cooking, bathing and toilet flushing (Figure 2.14). However, when compared to other countries such as Japan (Figure 2.15), America (Figure 2.16) and the Netherlands (Figure 2.17), it becomes apparent that Chinese households use considerably more water for cooking than these other countries. The reason could be the low popularisation of water-use equipment, as well as traditional diets (Liu *et al.*, 2005). This indicates that cultural and

Stellenbosch University https://scholar.sun.ac.za

traditional behaviours have an influence when it comes to water consumption patterns. It was expected that with the popularisation of water-use equipment such as washing machines, the water-use pattern of Chinese households will become increasingly more similar to that of other countries in the Global North (Liu *et al.*, 2005).

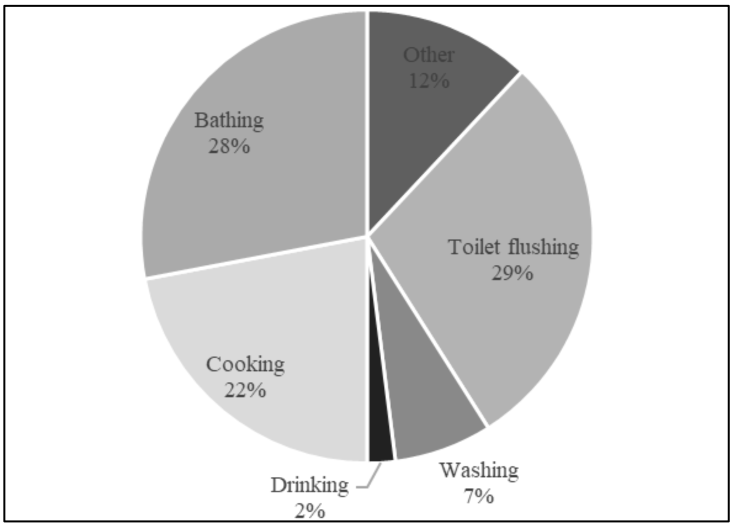

Figure 2.14: Average water consumption for Chinese households
Source: Adapted from Liu *et al.* (2005)

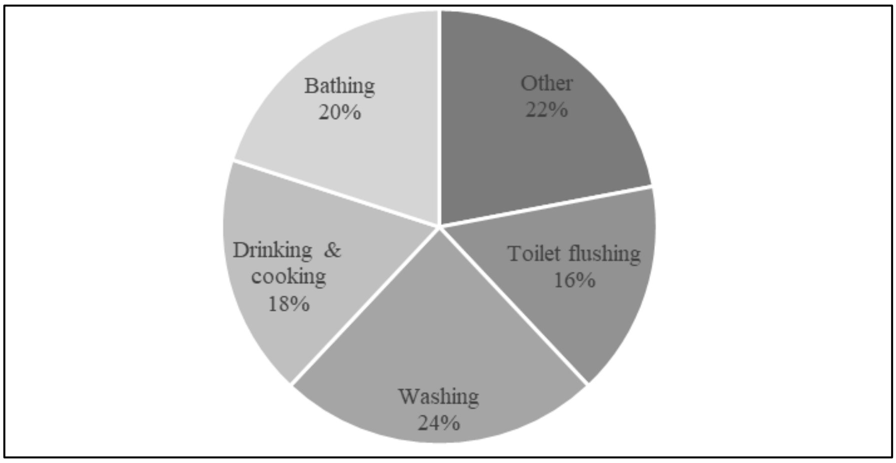

Figure 2.15: Average water consumption for Japanese households
Source: Adapted from Liu *et al.* (2005)

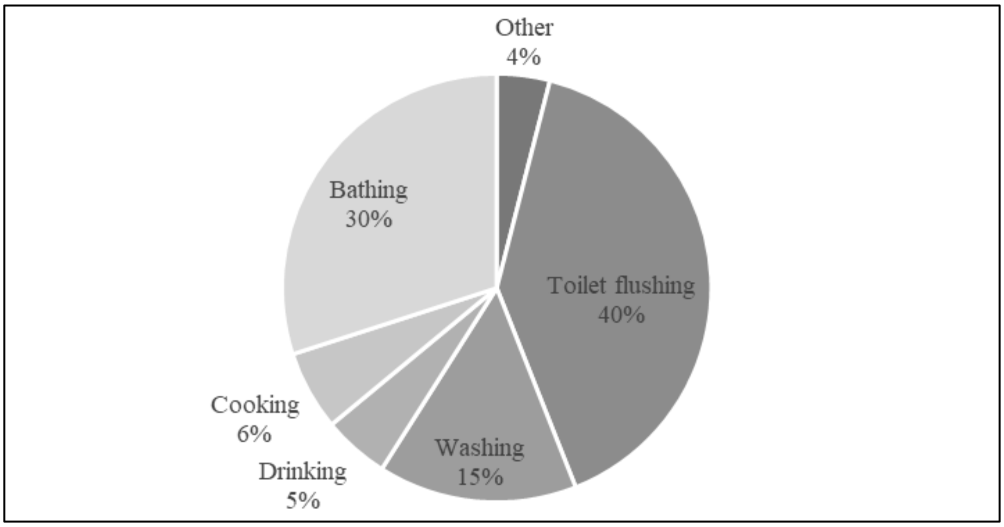

Figure 2.16: Average water consumption for American households
Source: Adapted from Liu *et al.* (2005)

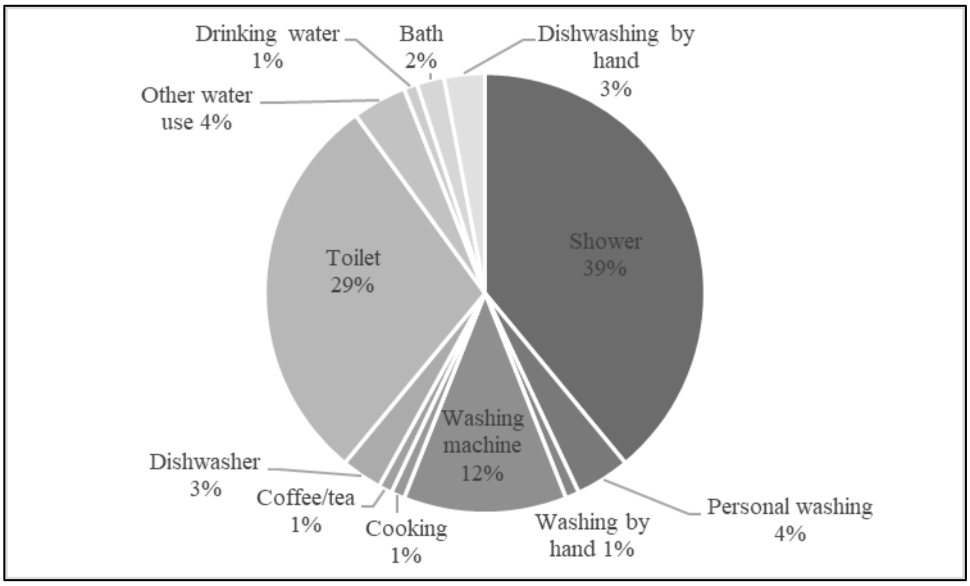

Figure 2.17: Average water consumption for Dutch households
Source: Adapted from Gerbens-Leenes (2016)

Two other studies conducted on households in the United States of America (US) had similar results: Sanders and Webber (2012) concluded that 75% of US households' energy requirement for water was used for water heating. Similarly, the study by Plappally and Lienhard (2012) supports that 72% of Californian households' energy is used for water heating (Gerbens-Leenes, 2016; Plappally & Lienhard, 2012; Sanders & Webber, 2012). Gerbens-Leenes (2016) had similar findings for Dutch households: 92% of energy relating to water use was used for the heating of water. Figure 2.18 shows that the three main requirements of energy needed for the household are 58% for showering, 9% for the dishwasher and 8% for the washing machine (Gerbens-Leenes, 2016). All of these require water to be heated. It is clear that human behaviour, especially in terms of showering, bathing and cleaning habits, plays an important role in consumption. Gerbens-Leenes (2016) concludes that water consumption in a household is dominated by human behaviour, and suggests that if less water is consumed for high energy-requiring activities such as showering, significant gains can be made for both water and energy (Gerbens-Leenes, 2016).

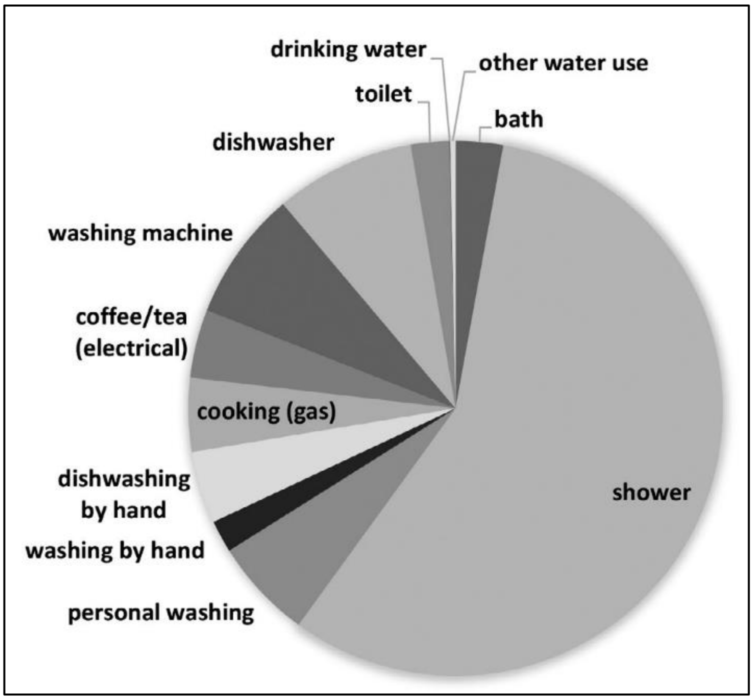

Figure 2.18: Dutch household energy for water requirement
Source: Gerbens-Leenes (2016)

The study further compared the energy for water to the total energy requirements per capita per year, which was 112 gigajoules (Gerbens-Leenes, 2016). This comparison showed that 9% of both total direct and indirect energy requirements of Dutch households was for energy for water, suggesting that by reducing the energy needed to meet the water demand, potential system gains could be made (Gerbens-Leenes, 2016).

Dietz, Gardner, Gilligan, Stern and Vandenbergh (2009) found that carbon emissions in the United States could be reduced by 7% through household behavioural changes, and identified this as the 'behavioural wedge'. Berman, Shwom and Cuite (2019) indicated that this 'behavioural wedge' could be applied to other resource consumption occurring at a household level (Berman *et al.*, 2019; Dietz *et al.*, 2009). For studies looking at behavioural determinants targeted for intervention, Steg and Vlek (2009) identified five main attributes for pro-environmental behaviour from an environmental psychology framework: moral and normative

Stellenbosch University https://scholar.sun.ac.za

concerns, contextual factors, costs and benefits, affects, and habit. Moral and normative concerns are value-focused, looking at the moral obligation of environmental concern (Berman *et al.*, 2019). Contextual factors include economic and political aspects regarding environmental concerns, for example, how the availability of certain products, the physical infrastructure or characteristic of a product affects attitudes and behaviour. The perceived costs and benefits are a direct link between behaviours and knowledge, where knowledge affects intention and individuals make decisions based on rational and reasoned costs and benefits (Berman *et al.*, 2019). Lastly, habit forms part of a behavioural determinant that goes further than rational decision-making and consumer reason.

Berman *et al.* (2019) indicated that social practice theory is able to provide a different theoretical framework for understanding consumption in a household by understanding life routines that are made up of practices that are established in habit, context and society, such as showering, doing laundry and cooking. This perspective of understanding the collective social arrangement of practices from broad cultural groups might provide better insight into consumption behaviours that are often overlooked (Berman *et al.*, 2019; Hargreaves, 2011; Røpke, 2009).

While households in cities cannot be independently sustainable, they are able to quickly adapt to being responsible partners towards achieving an overall greater sustainability (Perrone, Murphy & Hornberger, 2011). In terms of policy for implementing sustainable resource management and change, it is easier – and often cheaper – to implement at a smaller micro-household scale (Kenway, 2012). At a household level, the impact of user behaviour, household income, seasonal changes and appliance efficiency can be understood in terms of its effects on future resource demand (Hussien *et al.*, 2017).

Household energy-water urban nexus metabolism refers to the linkages between energy and water flows at household level. As was previously mentioned, there are multiple methods in which nexus studies, and specifically energy-water nexus studies, can be conducted. However, this research focuses on system dynamics as a method towards understanding the energy-water nexus metabolism at a household level.

As was discussed previously, the Energy Intensity method, the Jordan framework, the Multiregional Nexus Network and the Urban Water Optioneering Tool methods for analysing

Stellenbosch University https://scholar.sun.ac.za

energy-water urban nexus metabolism are inappropriate for this research. A system dynamics method would be the most appropriate method for understanding household energy-water urban nexus metabolism. While all the other methods of energy-water nexus explore the structure, interconnections and links of the nexus, system dynamics takes it a step further. It uses both quantitative and qualitative data to look for long-term management of energy and water.

2.5 System dynamics in household energy-water urban nexus metabolism

System dynamics is an approach used to understand and help provide possible solutions to an articulated problem (Maani & Cavana, 2007). System dynamics models are used to focus on a specific identified issue or concern by analysing feedback relationships between various constituents that are time-dependent (Jetha, Pransky & Hettinger, 2016; Sterman, 2002). While system dynamics modelling originated from the management and engineering sciences, its applications have proved to be of great benefit in many other sectors. By using system dynamics to approach the energy-water nexus, feedbacks in the nexus at a household level can be identified, and as a result of these feedback structures, high-leverage points may be found, which provide better insight for future policies that address consumption of energy and water on a household level.

2.5.1 System dynamics process

The modelling process is set out by defined steps that facilitate five main phases (Maani & Cavana, 2007; Sterman, 2000). This process combines both qualitative and quantitative modelling. The first two phases consist of the qualitative modelling, namely the initial structuring of the problem and then the dynamic hypothesis, which includes the modelling of causal loops. The quantitative modelling follows with the formulation of the model, followed by testing in the form of scenario planning, and then by evaluation and policy design, which then informs the articulated problem (Figure 2.19) (Hoad & Kunc, 2017; Maani & Cavana, 2007; Sterman, 2000).

Stellenbosch University https://scholar.sun.ac.za

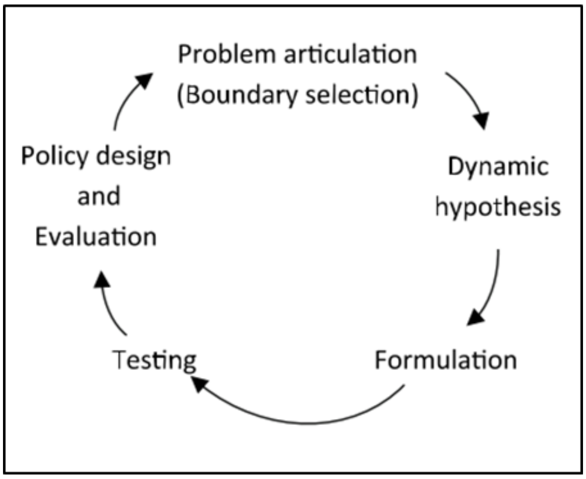

Figure 2.19: System dynamics process
Source: Sterman (2000)

Problem articulation

The first phase of the modelling process is problem articulation, which aims to highlight the importance of the purpose of the study. This phase deals with the problem that is being addressed – what the real problem is, and not just the symptom of the problem. It is considered to be the most important step in a modelling study, as it will not only set out a clear purpose for the model, but also allow for questions that query the usefulness of the model for the problem (Sterman, 2000). Four levels of thinking can be used when a problem is beginning to be identified. These four levels aim to answer the what, why, how and in what, of the problem in order to articulate it in the best way. Figure 2.20 represents these four levels as an iceberg, where the events of the what are only the tip of the iceberg and a deeper level of thinking would be why particular patterns occur (Maani & Cavana, 2007).

Taking a step further would be to understand how systemic structures that may cause the problem to occur are in place, and the most profound level is understanding the mental models within which the problem occurs. These mental models reflect the values or beliefs and assumptions that are personally held and underlie all the reasonings behind everything that is done (Maani & Cavana, 2007). In this phase, the problem is not only identified and articulated, but the main stakeholders involved or affected by the problem are also identified (Maani & Cavana, 2007).

When modelling, it is impossible to model everything. Therefore, when articulating the problem, it is crucial to set boundaries. Knowing what to cut out stems from a strong

Stellenbosch University https://scholar.sun.ac.za

understanding of the problem, its stakeholders and what is wanted from the modelling process (Sterman, 2000). Once the boundaries and assumptions of the problem have been articulated, a reference mode can be created. A reference model is usually a graph that shows how the problem developed over time and how this behaviour might develop in the future. In order to do so, important variables and concepts and a time horizon that would be considered important for designing policies that could solve the problem need to be defined and identified (Sterman, 2000). The time horizon should be far back enough to show the emergence and behaviour of the problem. It should be set far enough in the future that if policies are set in place, a difference in behaviour could be noted. This is often aligned with targets of other national or international policies that involve the problem (Sterman, 2000).

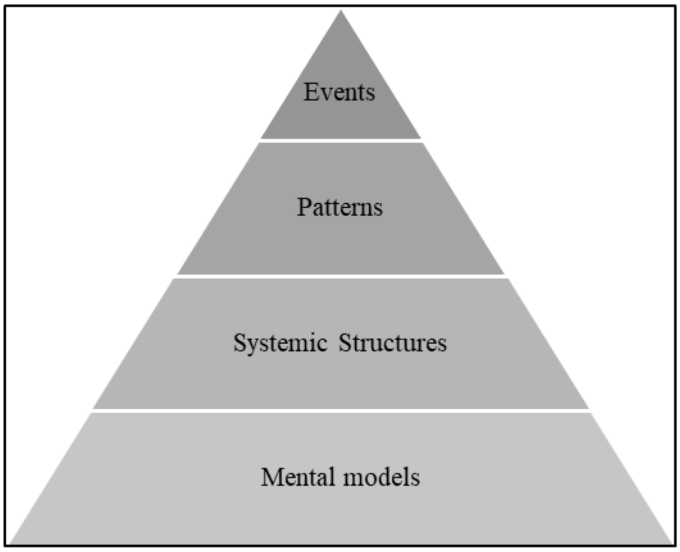

Figure 2.20: Four levels of thinking
Source: Adapted from Maani & Cavana (2007)

Dynamic hypothesis

The second phase of the process is dynamic hypothesis, which is used to account for the problem's behaviour. The dynamic nature of the problem will be characterised in terms of feedbacks and stock and flow structures that underlie the system (Sterman, 2000). In most cases, different actors will have different opinions on the source of the problems based on each of their individual mental models; the dynamic hypothesis should capture them all (Sterman, 2000). The dynamic hypothesis should include a model boundary chart that lists all the variables that are endogenous, exogenous and excluded from the model (Sterman, 2000). The boundary chart serves as a visual representation of the limitations of the model as it states the variables that it includes and excludes, providing transparency.

Causal loop diagrams (CLD) are beneficial tools to visually present feedback structures of a system (Sterman, 2000). CLDs are able to visually demonstrate the hypothesis about the dynamic cause while capturing the mental models of the individuals involved and still being able to communicate the important structural feedbacks of the articulated problem (Sterman, 2000). A CLD contains variables that are connected with arrows that indicate the causal influences between the variables (Sterman, 2000). These arrows are known as causal links, and the casual influence is known as the polarity, which can be either negative (-) or positive (+) to indicate the change in variables. A positive polarity (+) indicates that a change in one variable will have the same change effect on the variable to which it has a causal link. In contrast, a negative (-) polarity indicates that it will have an opposite change effect. For example, Figure 2.21 illustrates a CLD of 'Birth rate', 'Population' and 'Death rate'. The polarity between 'Birth rate' and 'Population' is positive, meaning if 'Birth rate' increases, 'Population' will also increase.

Similarly, if 'Birth rate' decreases, 'Population' will also decrease. However, the polarity between 'Death rate' and 'Population' is negative, meaning that an increase in 'Death rate' means a decrease in 'Population'.

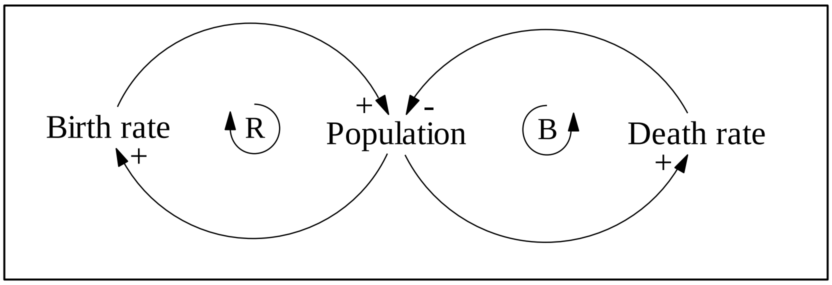

Figure 2.21: Causal loop diagram notation
Source: Adapted from Sterman (2000)

The rest of the modelling process will test the dynamic hypothesis.

Model formulation

Model formulation is the third phase of system dynamics modelling. It is the point at which a conceptual hypothesis is translated into a quantitative model with parameters, equations and initial conditions (Sterman, 2000). Model formulation generates insight into the problem before it is even simulated, as it can help recognise vague concepts (Sterman, 2000). This phase of formulation aids in identifying flaws in perceived formulations and aims to improve the overall understanding of the system (Sterman, 2000).

Stellenbosch University https://scholar.sun.ac.za

Model testing

Model testing does not begin only once the model has been completely developed. It begins when the first equation is formulated. Each formula and units of every equation need to be tested as they are built during the formulation phase (Sterman, 2000). A part of testing also includes comparing the models' actual behaviour with the simulated models' behaviour and identifying that all variables match real-world concepts (Sterman, 2000). Models should be tested in extreme conditions to test how they deal with shocks, but also to identify if the model has any flaws (Sterman, 2000).

Policy design and evaluation

The last phase of system dynamics modelling is policy design and evaluation. Once the integrity of the model has been tested, it can be used as insight in order to evaluate and design policies that may be able to improve the articulated problem (Sterman, 2000).

2.5.2 Application of the energy-water urban nexus metabolism using system dynamics

System dynamics was used by Dhungel and Fiedler (2014) as an approach towards understanding the water demand of the small university town of Pullman in Washington, USA. The study looked at water demand in single-family households and in residential households, and the developed model projected an overall increase in water demand for the households over a period of 25 years. Another study used system dynamics modelling to understand the interactions of the aspects that govern the quality and quantity of water, as well as the effects they have on economic conditions. However, this study occurred at a transboundary level of the US-Mexico border region that falls within the Rio Grande/Rio Bravo Water Basin (Duran-Encalada, Paucar-Caceres, Bandala & Wright, 2017).

Multiple studies have been conducted of energy flows at a household level. Dyner, Smith and Peña (1995) used system dynamics to simulate the substitution of inefficient household appliances with more efficient ones and developed a causal loop for the energy dynamics of residential homes. Similarly, Davis and Durbach (2010) used system dynamics to identify high-leverage intervention points in order to reduce energy in a household, and developed a stock and flow model to simulate this. However, it was concluded that there is no single, definitive

Stellenbosch University https://scholar.sun.ac.za

model for household consumption that exists, as there is more that needs to be learned about the factors that drive household behaviours beyond just energy (Davis & Durbach, 2010).

While there have been studies on the energy-water nexus using system dynamics, there are limited studies that have examined the energy-water nexus from an urban metabolism perspective (Chhipi-Shrestha *et al.*, 2017; Hussien *et al.*, 2017; De Stercke *et al.*, 2018). For instance, Chhipi-Shrestha *et al.* (2017) developed a system dynamics model for the water-energy-carbon nexus to analyse this nexus in neighbourhoods in Canada. From the research it was found that in residential areas, the highest energy consumption was for indoor hot-water use. Therefore water-based interventions such as water-efficient fixtures would have a significant effect not only on water saving, but also on energy saving (Chhipi-Shrestha *et al.*, 2017). Hussien *et al.* (2017) developed a system dynamics model too, but for the water-energy-food nexus at a household level. While there are many studies that have been conducted on the energy-water nexus, such as those conducted by Kenway (2014) and Radcliffe (2018) in Australia, these have not utilised system dynamics as a way of understanding the nexus (Kenway, 2014; Radcliffe, 2018).

Stercke *et al.* (2018) modelled the water-energy interactions with respect to London's residential sector and integrated end-use interactions of the nexus as well. This study focused on end-use interactions, as it found that the energy-water nexus was generally understood to be the energy required to supply water to citizens. The focus was more on water for energy and less on energy for water, with almost no literature considering end-use (De Stercke *et al.*, 2018). The system dynamics model that tested the influence of urban energy-water end-use interaction in London was derived from a causal loop diagram that detailed the qualitative representation of the system structure (De Stercke *et al.*, 2018).

The studies by De Stercke *et al.* (2018) concluded that end-use interactions have a large effect on the energy-water nexus system, and in order to comply with climate change mitigation strategies and water availability constraints, decarbonisation of electricity and the electrification of heating is vital (De Stercke *et al.*, 2018). These researchers suggest that the model, or at least the concept, should be expanded to emerging cities where water stress is dire and the end-uses differ because storage is required on a local level to cope with sporadic water supplies. The City of Cape Town would be a prime example of such a city. However, studies examining the energy-water urban nexus metabolism using system dynamics at a household

Stellenbosch University https://scholar.sun.ac.za

level in Cape Town are lacking. Furthermore, whereas all the aforementioned studies utilised system dynamics in order to address the energy-water nexus, none were conducted from an urban metabolism perspective at a household level.

System dynamics modelling provides an understanding of the indirect impacts of a city – it provides an integrated approach to the understanding of how the dynamics of urban infrastructure works and the service delivery that is required (Currie *et al.*, 2017; Dai *et al.*, 2018). System dynamics allows for new plans for sustainable management and development to be made within the existing constraints of urban infrastructures, as opposed to creating a completely new system. When new infrastructure is implemented, it is set out in a way that has an understanding of the dynamics of the current system and laid in an anticipatory manner with respect to a city's existing structures (Currie *et al.*, 2017).

2.6 Summary

This chapter reviewed literature relevant to the research objectives of this study. Urban metabolism laid the foundation of the conceptual framework that was developed throughout this chapter, as it dealt with how resources are consumed, used and expelled in a city.

Urban metabolism is generally understood to be a single resource flow in an urban space. It indicates that there is a gap on which urban metabolic studies are concentrating, as resource flows seldom occur independently, but rather interact with other resource flows. This interaction between resource flows is known as the nexus, and while the concept of nexus thinking is generally accepted, there appear to be multiple methods for understanding and applying nexus integration. Therefore, insight into sustainable urban development management and planning can be achieved by using urban metabolism as a base to define a more integrated and broader nexus system with multiple flows.

Energy-water nexus is of particular interest as in urban metabolism water is considered to be one of the largest flows in a city, and energy is the flow that has the biggest interaction with this flow. Furthermore, water and energy are two of the most fundamental flows to form and maintain operations in developing and developed cities. An energy-water nexus from an urban metabolism perspective would therefore be beneficial, as it would help identify alternative sources and corresponding utilisation pathways within a system that would take economic viability and environmental sustainability into account. The studies of energy-water nexus

Stellenbosch University https://scholar.sun.ac.za

metabolism mainly appear to occur at a macro scale. However, important drivers of energy and water consumption are private households that are able to regulate energy and water directly. Understanding resource flows at a household level provides more detail in understanding flows of water and energy in a city at a micro scale.

A system dynamics approach towards understanding and analysing the energy-water nexus metabolism at a household level was deemed most appropriate for this study. While there have been studies that have looked at using system dynamics to understand different types of nexus, as far as the author can establish, there have been no extensive studies examining the energy-water urban nexus metabolism using system dynamics at a household level in Cape Town.

The next chapter discusses the context of the case study for this research of the City of Cape Town.

Stellenbosch University https://scholar.sun.ac.za

Chapter 3 : Contextualising Cape Town

3.1 Introduction

When considering the interdependencies of energy and water, the City of Cape Town in South Africa proves to be a case study of specific interest, as the city experiences both episodic droughts and electricity cuts. In 2017 Cape Town became infamous internationally for being one of the first major global cities to almost have no running municipal water. The City Council named the imminent day where Cape Town's taps would run dry as 'Day Zero' which is when storage water levels reach 13,5%, and there would be no supply of municipal water (Madonsela, Koop, VanLeeuwen & Carden, 2019). In an attempt to curb water usage, water restrictions in Cape Town were imposed between November 2016 and February 2018, ranging from Level 3 to Level 6B in an attempt to avoid 'Day Zero' (Booysen, Visser & Burger, 2019).

While Cape Town is prone to recurring droughts and, as a result, water shortages, it also has challenges with regard to energy, particularly in terms of electricity supply. South Africa began nation-wide load shedding in 2007 when the demand for electricity outstripped supply (City of Cape Town, 2015; Niselow, 2019). In November 2014, South Africa in its entirety began controlled load shedding, mainly in order to invest in maintenance and upgrades on existing infrastructure while waiting for Medupi and Kusile, which are new-generation coal-fired power stations, to come online. Load shedding was suspended in May of 2016 (City of Cape Town, 2015; Niselow, 2019). Due to unlawful strikes over wages, in June 2018 load shedding was once again initiated, and it has been implemented sporadically since then for various reasons (Niselow, 2019).

These energy and water crises highlight the need for sustainable resource management and practices in order to sustain the demand for a growing population. This chapter looks at the context of Cape Town and examines the energy and water metabolic flows, and specifically the available data on these flows at a household level.

3.2 Description of Cape Town

Cape Town is located at the south-western point of Africa. It is one of South Africa's eight metropolitan municipalities and is officially recognised as the City of Cape Town. However, for the purpose of this study, the name Cape Town was used. Situated in the Western Cape province, Cape Town accounts for 63,8% of the population of the province (StatsSA, 2016a). Figure 3.1 illustrates the population distribution of the Western Cape by local municipality, of which there are 25 (StatsSA, 2016a). Cape Town's population is the second largest in South Africa after the city of Johannesburg and has a population of 4 005 016 people according to the 2016 census (StatsSA, 2016a). According to Ewing and Mammon (2010), between 2001 and 2006 Cape Town's population increased from 2,994 million citizens to 3,239 million at an annual rate of 1,6%. This was the same growth rate observed between 2011 and 2016 (StatsSA, 2016a).

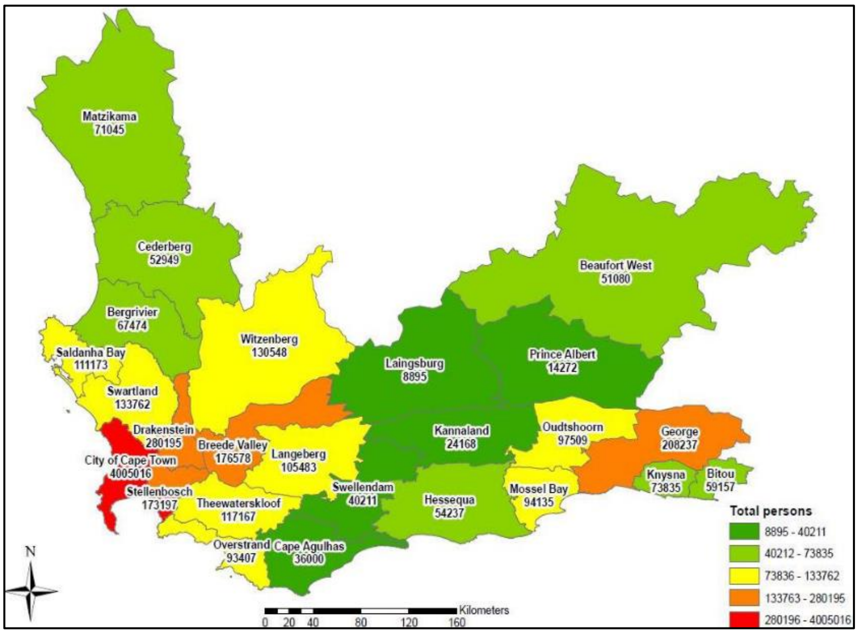

Figure 3.1: Western Cape population distribution by local municipality
Source: StatsSA (2016a)

The injustices of the previous apartheid regime are still very much present in Cape Town, especially regarding its spatial layout, which still contains distinct zones in terms of income class, race and population density (Hoekman & Von Blottnitz, 2017). The administrative area of 2 461 km^2 is demarcated into 190 suburbs and an estimated 378 informal settlements (Currie *et al.*, 2017). In its 2016 census, Stats SA recorded the number of households in Cape Town to be 1 264 949 households, with an average household size of 3,2 persons.

For the purpose of the census Stats SA defined a household as 'a group of persons who live together, and provide for themselves jointly with food and other essentials for living, or a person who lives alone' (StatsSA, 2016a,b). However, it is estimated that informal settlements account for 13% of Cape Town's population and an overall 21% of Cape Town households live in informal dwellings (Currie *et al.*, 2017). It is difficult to track informal, unregulated or

Stellenbosch University https://scholar.sun.ac.za

decentralised systems, which in most of the world include food flows, material flows and informal good flows, but especially so in Cape Town with regard to water flows. Therefore, this research will focus only on formal households (Currie *et al.*, 2017). Unlike conventional urban areas where the central business district is the densest, Cape Town finds its most densely populated areas on the periphery, where most of the informal settlements and apartheid legacy townships are found (Currie *et al*., 2017).

3.3 Cape Town's metabolism

Multiple metabolic assessments have been conducted on Cape Town's water metabolism. Hoekman and Von Blottnitz (2017) conducted an economy-wide material flow analysis study on biomass, construction materials and fossil fuel flows. Furthermore, Gasson (2002) conducted an ecological footprint study on Cape Town, looking at unsustainable resource use and planning implications. Currie *et al.* (2017) conducted a basic urban metabolism assessment on Cape Town, focusing on the resource consumption of water, energy, materials, food, solid waste, and flows of people in terms of housing and transportation. From this study, high-leverage intervention points that could reshape the resource systems were speculated and summarised in Table 3.1 (Currie *et al.*, 2017).

Stellenbosch University https://scholar.sun.ac.za

Table 3.1: Speculative high-leverage intervention points identified for different flows in Cape Town

Flow	*Intervention options for improving*	
	Internal sustainability	Relational sustainability
Water	Improved access to clean water and sanitation will improve health, productivity and lifestyle among the underserviced.	Water reuse, either through grey-water application or tertiary waste-water treatment, will reduce reliance on water catchments for raw water and improve resilience to drought.
Energy	Improved access to safe and clean energy will improve productivity and lifestyle among the underserviced.	Locally augmenting the electricity grid with renewable electricity will reduce the embodied carbon and water footprint.
Food	Promoting urban agriculture will improve local resilience and can be used as a nutrition literacy tool if coupled with public space development.	Reclamation of nutrients from waste-water systems and organic solid waste to enrich soils will reduce the need for imported fertilisers.
Solid waste	Changing the valuation of waste streams enables a shift from a landfill-based waste management system. Facilitating industrial symbiosis between industries improves the efficacy of waste products.	Effective waste management systems will reduce biophysical damage caused by leakage.
Housing	Investment in low-income areas, focused on the delivery of bulk infrastructure, as well as community-led upgrading of informal settlements to ensure retention of economic livelihood, will address the patterns of hyper-segregation in these areas and encourage further investment therein.	Estimating the future housing demand and population growth in the city will inform all the other resource needs and impact the city.
Transportation	Reduction of single-occupancy private vehicles on roads will reduce the congestion which unjustly slows and blocks formal bus systems and informal taxi systems. Investment in industry and commerce in multiple nodes or industrial corridors across the city will reduce the need for distance transportation for employment.	Transport behaviour patterns that reduce the number of cars on the road will improve the energy and carbon footprint of the city.

Source: Adapted from Currie *et al.* (2017)

Cape Town's ecological footprint indicator is high, especially when compared to South Africa as a whole and to Organisation for Economic Co-operation and Development (OECD) countries, ranking third highest after OECD countries and Johannesburg (Figure 3.2) (Currie *et al*., 2017). A large ecological footprint relates to a large impact on resources. It is estimated that Cape Town's ecological footprint is more than 52 times over its administrative area and more than 165 times over its built area, with a footprint of 128 264 km^2 (Currie *et al.*, 2017; Gasson, 2002).

Stellenbosch University https://scholar.sun.ac.za

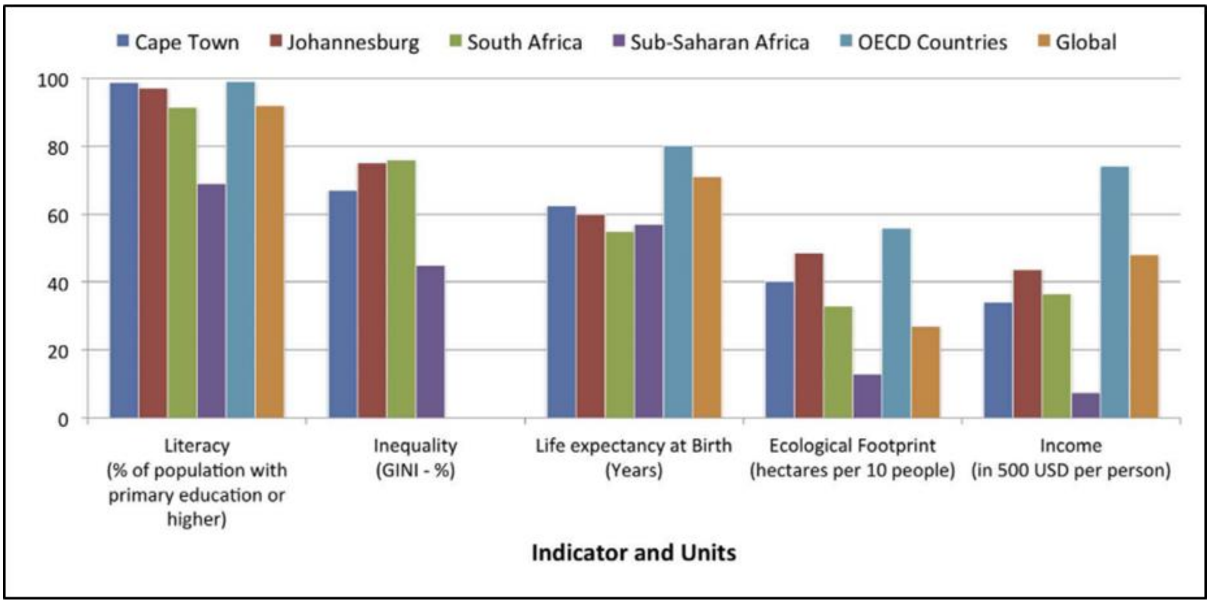

Figure 3.2: Comparison of social-economic and environmental indicators
Source: (Currie *et al.*, 2017)

120 African cities were categorised by Currie & Musango (2016) based on resource consumption intensity in 2010, the categorisation accounted for material consumption per capita and total material consumption of each city (Currie & Musango, 2016). Cape Town was ranked as the fourteenth largest consumption per capita, consuming an estimation of over 13 tonnes per person per year (Currie & Musango, 2016; Currie *et al.*, 2017). However in terms of total material consumption, Cape Town was ranked as the fourth most resource-intense city in Africa, estimated to have consumed just under 50 megatons of material (Currie & Musango, 2016; Currie *et al.*, 2017). As a city in the Global South, Cape Town is unique in the sense that several studies have been conducted on its resource consumption, resource flows, resource access and resource equity sustainability (Currie *et al.*, 2017; Hoekman & Von Blottnitz, 2017). These have been conducted through urban bulk balance, urban material flow analysis, transport dynamics and environmental pressure of material consumption (Beyers & Swilling, 2016; Currie *et al.*, 2017; Ferrão & Fernandez, 2013; Gasson, 2002; Hoekman & Von Blottnitz, 2017). Hoekman and Von Blottnitz (2017) were among the first to conduct an urban metabolism study that used an economy-wide material flow analysis methodology on Cape Town. From this analysis, it was determined that in 2013 the City of Cape Town processed just over 28 megatons of material, of which only just over 13 megatons were actually consumed within the city's limits itself (Currie *et al.*, 2017; Hoekman & Von Blottnitz, 2017).

Stellenbosch University https://scholar.sun.ac.za

3.3.1 Cape Town's energy metabolism

The boundaries of the Cape Town municipality include thirty mines, power plants, including a nuclear power plant, and natural and agricultural land (Hoekman & Von Blottnitz, 2017). Figure 3.3 shows the energy use by sector in Cape Town and indicates that transport is the main consumer of energy in Cape Town, consuming 64% of the city's total energy, while the residential sector accounts for only 12% of the city's total energy use (Currie *et al.*, 2017). However, this was based on sector energy use for the year 2012. In contrast, the Department of Energy (2019a) reported that for 2016, Cape Town's residential sector accounted for 8% of the city's total energy consumption, of which 72% was supplied in the form of electricity (Currie *et al.*, 2017; Department of Energy, 2019a).

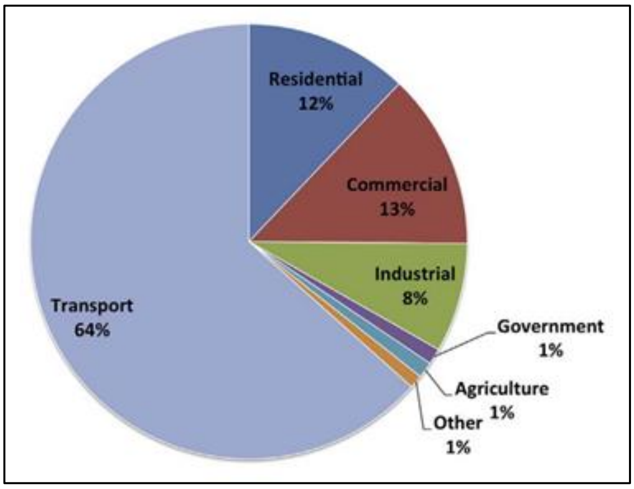

Figure 3.3: Cape Town energy use by sector for 2012
Source: Currie *et al.* (2017)

Based on energy use statistics for 2016, Table 3.2 indicates the percentage use of energy carriers for different sectors in Cape Town. These sectors include industry, commerce and public services, agriculture, transport and residential. Overall, crude oil and petroleum products accounted for more than 50% of all energy for Cape Town, electricity accounted for just under 30%, while coal and renewables accounted for just over 8% each and natural gas accounted for the least at 2% (Department of Energy, 2019a). As Table 3.2 shows, crude oil and petroleum products were the main energy carriers across all sectors aside from the residential sector, where the energy carrier only accounted for 5% of the residential sector's energy consumption (Department of Energy, 2019a). The dominant energy carrier for the residential sector was electricity which was used for 72% of the sector's energy use (Department of Energy, 2019a).

Table 3.2: Energy carriers for different sectors in Cape Town

Sector	Crude oil and petroleum products	Natural gas	Electricity	Coal	Renewables
Industrial sector	5%	10%	25%	35%	25%
Commerce and public services sector	67%		31%	2%	
Agricultural sector	87%		13%	0,5%	
Transport sector	98%		2%	0,1%	
Residential sector	5%		72%	4%	19%
Total %	52.5	2	28.6	8,2	8,8

Source: Adapted from Department of Energy (2019a)

South Africa is dominated by one energy provider – Eskom. This state-owned entity is responsible for supplying 40% of electricity in Africa and 90% of electricity in the country (Department of Energy, 2018). Electricity not provided by Eskom is supplied by municipalities and private generators (Department of Energy, 2018). However, the Cape Town municipality produces very little electricity on its own. A small percentage of renewable energy is produced at the Darling Wind Farm, which is purchased by the city and transported over the Eskom grid to the city (Spencer, 2010; Ward & Walsh, 2010).

Electricity generation from Eskom depends mostly on the burning of low-grade coal, and the use of coal for the production of electricity in South Africa is among the cheapest internationally (Department of Energy, 2019b). According to the Department of Energy (2019b), 62% of South Africa's coal production (after exporting) is used to generate electricity, whereas electricity generated from nuclear power and hydroelectric stations only accounts for 6% and 2,3% of generated electricity respectively (Department of Energy, 2019b; Ward & Walsh, 2010). In terms of electricity consumption for different sectors, Figure 3.4 visually represents Cape Town's electricity flows in the form of a sankey diagram. However, this provides information only about the inflows of energy in the form of electricity into the residential sector, among other things, and not about the flows in households themselves.

Stellenbosch University https://scholar.sun.ac.za

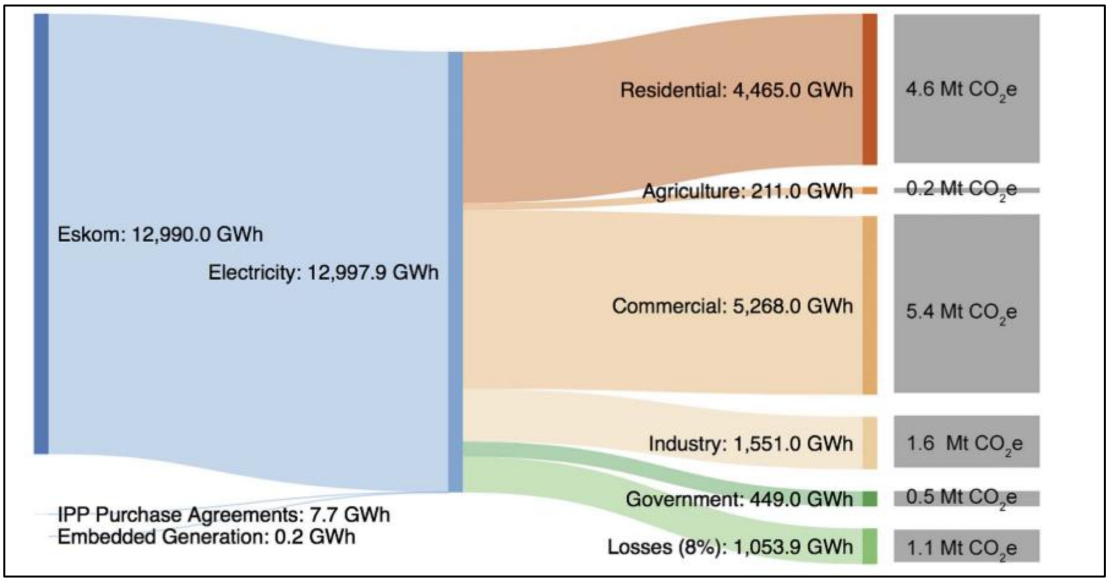

Figure 3.4: Cape Town's electricity flows
Source: Currie *et al.* (2017)

Studies conducted on household energy consumption have a large focus specifically on electricity and outflows in the form of greenhouse gas emissions (Strydom *et al.*, 2019). Most studies conducted for household energy metabolism consider the throughflows, outflows and activities associated with energy consumption but do not, however, consider any other energy forms.

Compared to national figures, the Western Cape has the highest percentage of households with access to electricity, with Cape Town having 98% of households having access to electricity (StatsSA, 2016a). Of these households, 94,8% reported using electricity to heat water, indicating that it was the main energy source used in the majority of households for water heating (StatsSA, 2016a).

To identify sustainability intervention points, Strydom (2019) conducted an urban metabolism assessment on Cape Town households' energy metabolism that focused on direct energy flows. This was considered in the form of energy carriers and services as throughflows (Strydom *et al.*, 2019). The study conceptualised the city's energy system as having four phases, where the first phase is exploitation, which is identified as the energy source for different flows (Strydom, 2019). The second phase is where energy is transformed into carriers via physical infrastructure such as power plants (Strydom, 2019). Energy demand is the third phase and can be separated into two different flows, namely energy sectors and energy services (Carreón & Worrell, 2018; Strydom, 2019). The last phase takes energy recovery into account in the form of heat loss, emissions and energy recovery (Strydom, 2019). The study identified Cape Town energy services and carriers in households by considering all carriers present and not only electricity, and conceptualised these flows with drivers (Figure 3.5).

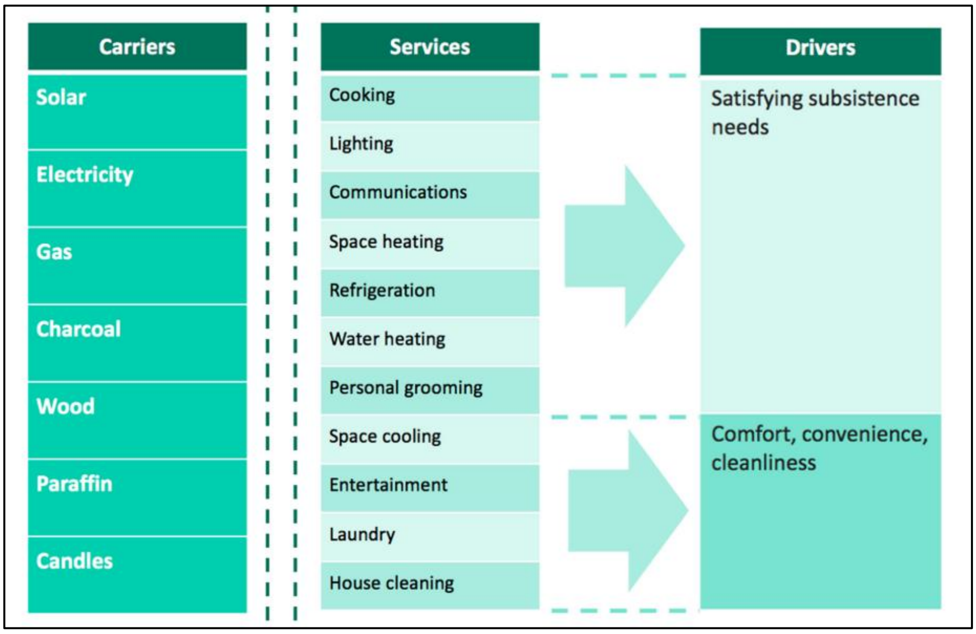

Figure 3.5: Cape Town energy carriers, services and drivers of households
Source: Strydom *et al.* (2019)

The study measured energy services and carriers over four income groups, namely low-income, low-middle-income, high-middle-income and high-income (Figure 3.6 and Figure 3.7). From Figure 3.6, it can be noted that the dominant energy carrier is electricity. However, lower-income households rely on energy carriers that are not electricity more so than higher-income households. This is important, as it emphasises the inequality of energy access as carriers such as paraffin, charcoal and wood are considerably more affordable (Strydom *et al*., 2020).

Stellenbosch University https://scholar.sun.ac.za

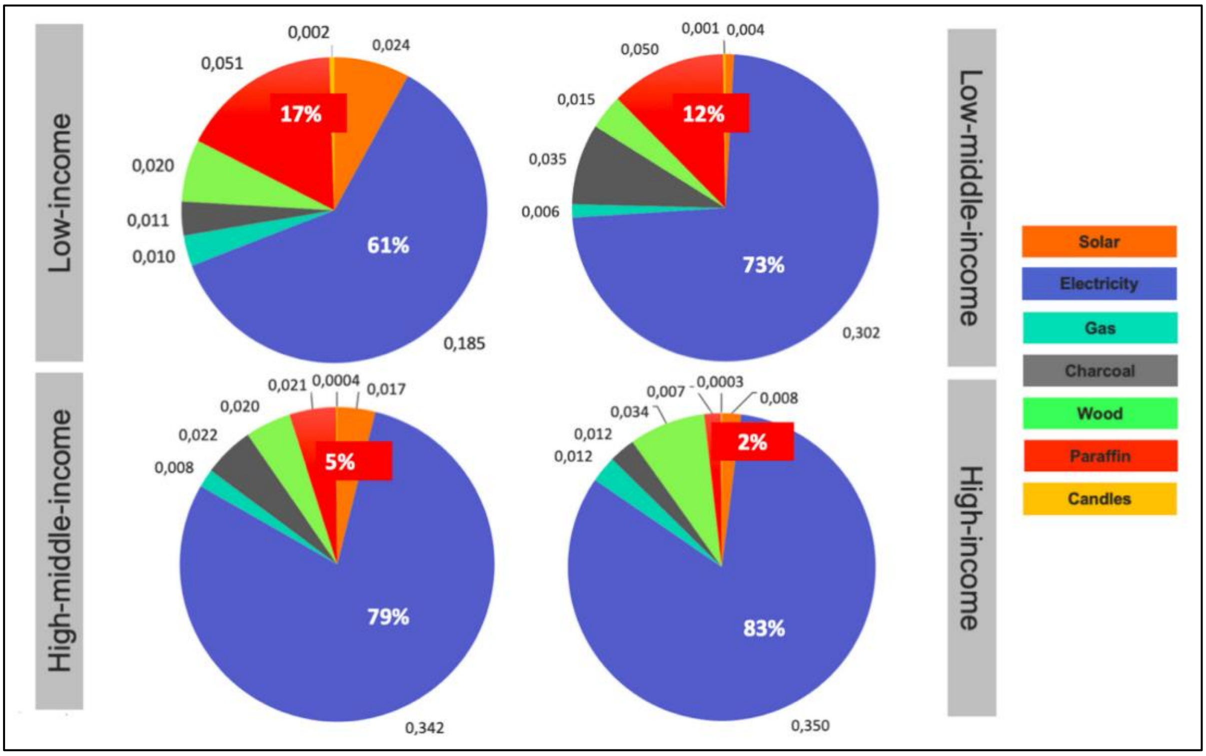

Figure 3.6: Cape Town household energy carriers for different income groups
Source: Strydom *et al*. (2020)

Figure 3.7 shows the proportions of energy services accessed by Cape Town households. It is clear from the image that the main energy service is water heating. This is comparable to household energy assessments conducted in the global north (Ward & Walsh, 2010). These assessments suggest that water heating is highly dependent on energy, indicating the need for an energy-water nexus in households. Furthermore, the second-highest energy service proportion across all income levels is cooking, a service that also requires water consumption, further emphasising the interrelationship between the two resources.

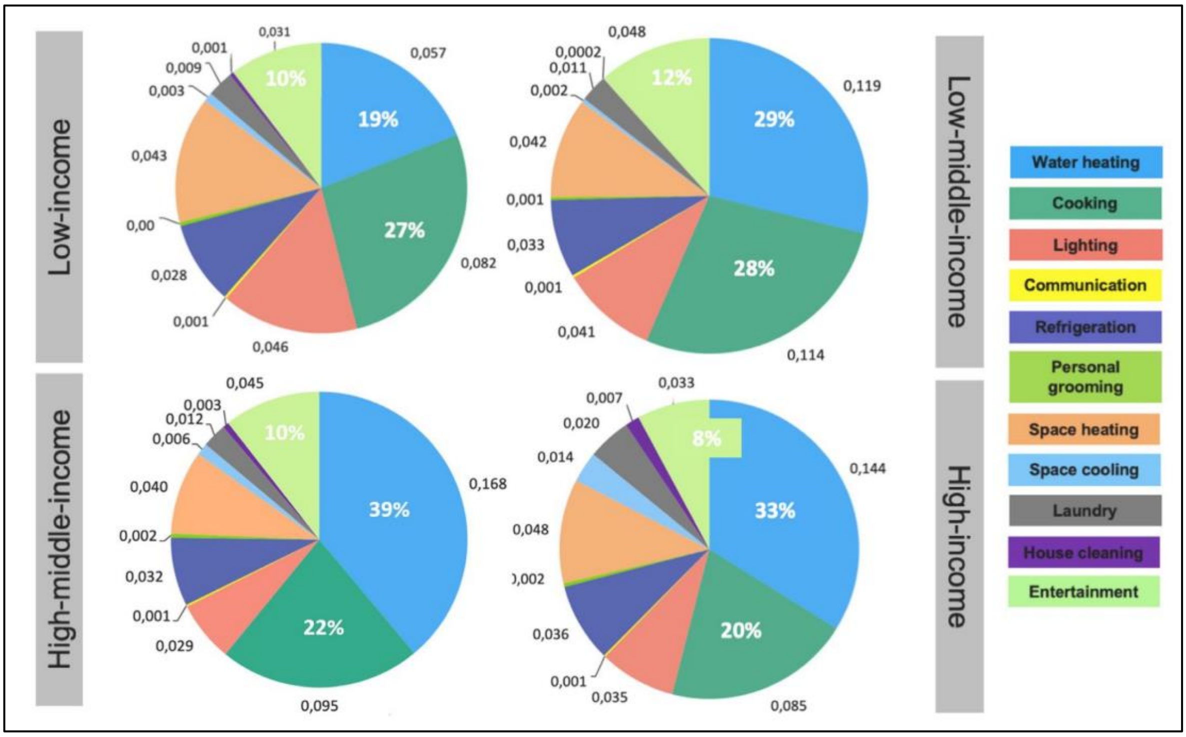

Figure 3.7: Cape Town household energy services for different income groups
Source: Strydom *et al*. (2020)

3.3.2 Cape Town's water metabolism

Cape Town is serviced by and allocated just over 398 kilolitres of water from the Western Cape Water Supply System. This amounts to about 95% of all its water. Of this, 27% originates from Cape Town-owned sources, and the remaining bulk is provided from sources that belong to the National Department of Water Services (City of Cape Town, 2019; Currie *et al.*, 2017). The water goes into water treatment, after which it is pumped and transported for consumption for either domestic, industrial, commercial, unbilled authorised or other use. Water is then transported to wastewater treatment facilities before being let out into the ocean, or it is accounted for through evapotranspiration (Currie *et al.*, 2017).

Due to climate change, Cape Town was prone to erratic rainfall that often resulted in shocks of flooding and drought. Because of these shocks, successful demand management of water was implemented, and the city avoided exceeding its allocated water allowance. That was until June 2016, when dam levels were recorded to be at their lowest. Cape Town's annual allocated water, the Western Cape Water Supply System-contained dam water, Theewaterskloof rainfall, as well as Cape Town's estimated water demand is depicted in Figure 3.8 from 2013, when rainfall started declining (Currie *et al.*, 2017).

Stellenbosch University https://scholar.sun.ac.za

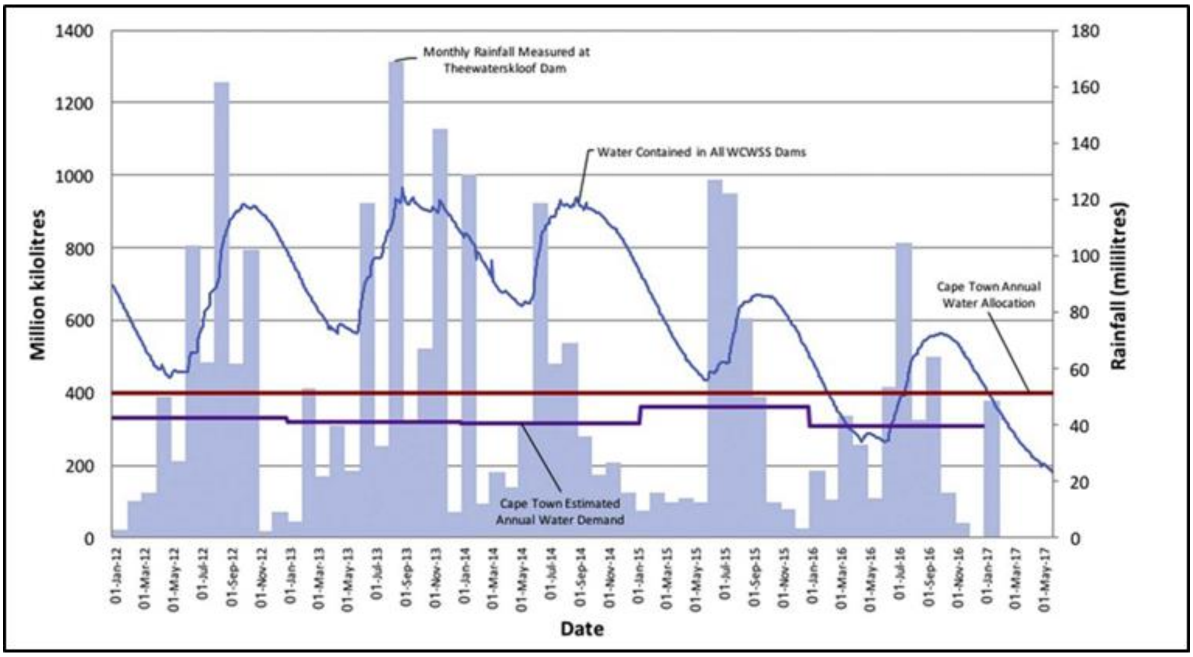

Figure 3.8: Water demand, water allocation, rainfall and dam water level trends
Source: Currie *et al.* (2017)

Figure 3.8 is not a completely accurate portrayal of what had occurred, as it compares stocks and flows simultaneously. Data on the daily water consumption would significantly improve the understanding of the interactions between consumption, rainfall and dam storage, which would be able to identify when the risk of water stress is higher (Currie *et al.*, 2017). Access to water for consumption generally occurs in the form of piped water, and it is more often than not the case that areas that have informal settlements and those on the outskirts tend to have less access to this safe and convenient resource (Currie *et al.*, 2017).

Water makes up a large component of urban flows. This makes the Cape Town water crisis an interesting case in terms of understanding the flows of water resources in Cape Town. Cape Town has been evaluated to have an almost 100% provisioning access to drinking water, which is surprising considering the prevalence of inequality and informal settlements (Currie *et al.*, 2017). Of the households in Cape Town, 93,7% have access to safe drinking water. This is the highest proportion in the country, as it is well above the national average of 84,5% (StatsSA, 2016a).

Figure 3.9 shows that Cape Town's industrial sector accounts for 4,2% of water consumption, commercial use accounts for 13,5%, whereas residential water use accounts for most of the city's water consumption, consuming 68,9% (City of Cape Town, 2018).

Stellenbosch University https://scholar.sun.ac.za

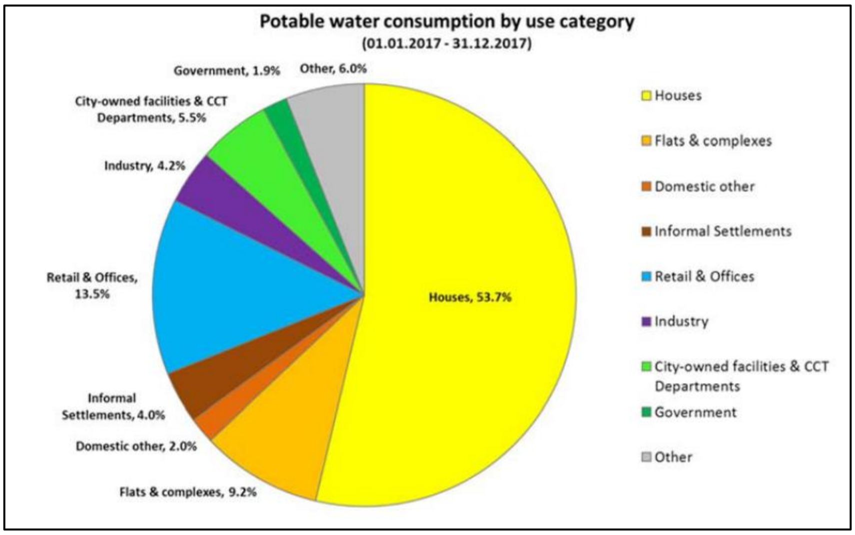

Figure 3.9: City of Cape Town water consumption
Source: City of Cape Town (2018)

Water usage behaviour and drought are topics that are well covered in both international and national literature. Understanding the behaviour of water consumers at the time of shortages is vital to manage water supply and demand effectively and efficiently (Booysen *et al.*, 2019). There have been multiple studies conducted on the responses to the Cape Town drought with regard to water saving. Brick, DeMartino and Visser (2018) studied the behavioural changes of different income-level Cape Town households in response to the drought and found price changes affect demand: a 10% water price increase resulted in a 1,8% reduction in the demand for household water.

Brick and Visser (2018) conducted a study in which households were sent a letter of warning from their local municipality reprimanding the household for its water use in excess of 50 kilolitres and threatening them with monitoring devices if their consumption levels did not reduce. From this it was noted that there was a 3% reduction in water use (Brick & Visser, 2018). However, these studies merely looked at overall water consumptions in households, and not what water was being used for. The primary outcome was to assess overall reduction in water use in response to the drought and did not consider the effects of individual activities. The majority of recent studies looked at overall reduction in water use to mitigate drought effects. There appears to be a lack of studies looking at the metabolic water flows in households in terms of appliance water usage and specific water consumption activities.

Stellenbosch University https://scholar.sun.ac.za

While this was not from a metabolic perspective, Booysen *et al.* (2019) conducted a study that looked at Cape Town households' behavioural response to drought using smart hot- and cold-water meters, which were monitored over the course of the drought restrictions. The study concluded that although municipal water-saving campaigns such as 'Day Zero' elicited fear, they were risky. It was probably the intervention that had the most success in terms of affecting consumers' behaviour (Booysen *et al.*, 2019). It was found that hot and cold water use was reduced overall when water restrictions were implemented, with overall hot-water consumption being reduced more than cold-water consumption (Booysen *et al.*, 2019). This could, however, be attributed to seasons, as it was summer when the strictest restrictions were enforced.

Figure 3.10 indicates the decreasing hot-water consumption trend of Cape Town households over the drought period, and although this study did not examine the services for which the water was consumed, it does indicate that water and energy are directly linked in household consumption (Booysen *et al.*, 2019). In the same way that water consumption, and as a result energy consumption for water heating, was noted to decrease during drought periods, both water and energy demand is expected to increase due to an overall increase in population, indicating the energy-water nexus.

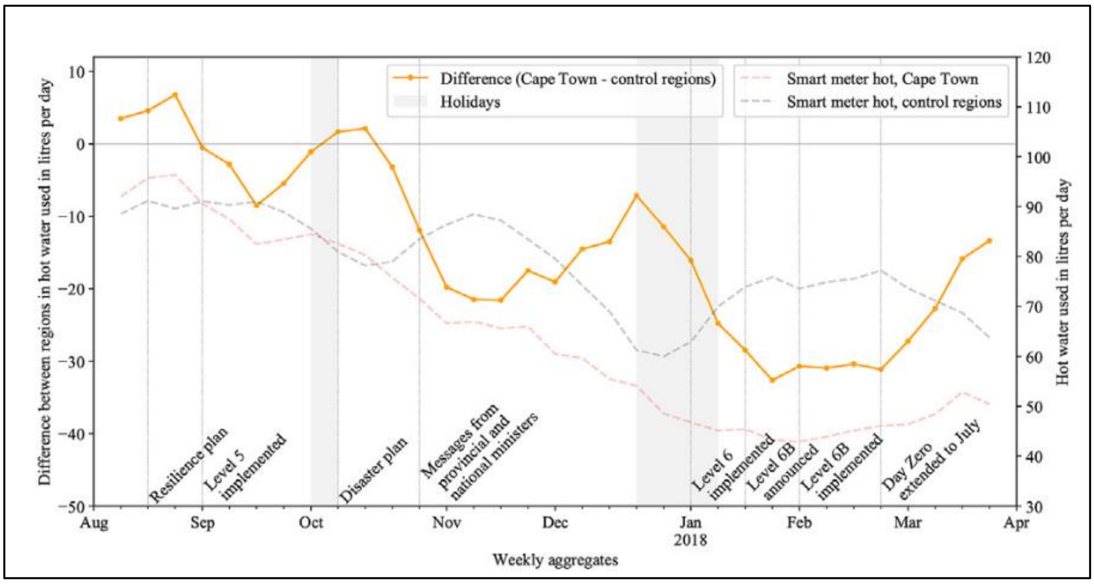

Figure 3.10: Cape Town households hot-water consumption
Source: Booysen *et al*. (2019)

There still appears to be a lack of understanding of household water metabolism, and even though there are empirical studies that quantify total water consumption, the services associated with water consumption are not identified. Limited data available for urban metabolic

Stellenbosch University https://scholar.sun.ac.za

assessments indicate that there is a gap in research and data collection, even when considering the highly studied water supply system of Cape Town, and that more resource flows need to be quantified in order to set up realistic consumption limits and targets. Furthermore, multiple urban metabolism analyses of Cape Town have been carried out in terms of material flow analysis, material consumption and environmental pressure, and detailed studies were conducted on specific flows, such as water and energy. These studies were all conducted on a macro-city-level scale. This explores only a small proportion of the potential application of urban metabolism (Currie *et al.*, 2017; Kenway, 2012).

3.4 Summary

This chapter provided the energy and water metabolism context of the City of Cape Town, which is situated at the south-western point of Africa in South Africa. Generally, South Africa has been subjected to an ongoing energy crisis where the supply of electrical energy cannot meet the demand, and the country has sporadically been subjected to nation-wide load shedding. While experiencing this nation-wide crisis, Cape Town has also been experiencing sporadic droughts, with the most recent drought (2016–2018) almost resulting in there being no municipal running water. These crises highlight the need for sustainable resource management and practices in order to sustain the demand for a growing population. Multiple urban metabolic assessments have been conducted on Cape Town flows, however, these mainly occur at a macro level. With regards to water, studies conducted at a household level mainly examined the overall consumption and reduction of entire households and failed to consider behaviours or individual water use activities for specific services. One urban metabolic energy assessment was conducted at Cape Town household level, but it did not consider its nexus with water.

Stellenbosch University https://scholar.sun.ac.za

Chapter 4 : Research methodology

4.1 Introduction

The primary objective of this study was to explore the household energy-water urban nexus metabolism of Cape Town in order to identify intervention points for energy and water savings. This was achieved through the following research sub-objectives:

1. To undertake a critical review of the energy-water urban nexus metabolism at a household level.
2. To develop a system dynamics model of the energy-water urban nexus metabolism of Cape Town households.

This study was part of a larger research project that focused not only on household energy and water consumption but on food and waste production as well, and different studies were performed by other researchers. However, this chapter focuses on the methods used specifically for this study on household energy-water urban nexus metabolism.

4.2 Research design

The research design for this study is shown in Figure 4.1. It shows how the process of addressing the main objective of the study was done by achieving the two sub-objectives. It illustrates how the first sub-objective forms part of the qualitative part of the system dynamics process by identifying and conceptualising the problem that, in combination with context-specific literature of the case study of Cape Town, informed the model formulation. The curved arrows between the literature review, the conceptualisation of Cape Town and the system dynamics process are to emphasise the iterative nature of this research process. Only through that iterative process could the quantitative part of the system dynamics modelling process in combination with uMAMA data be achieved for the second sub-objective of the study.

Stellenbosch University https://scholar.sun.ac.za

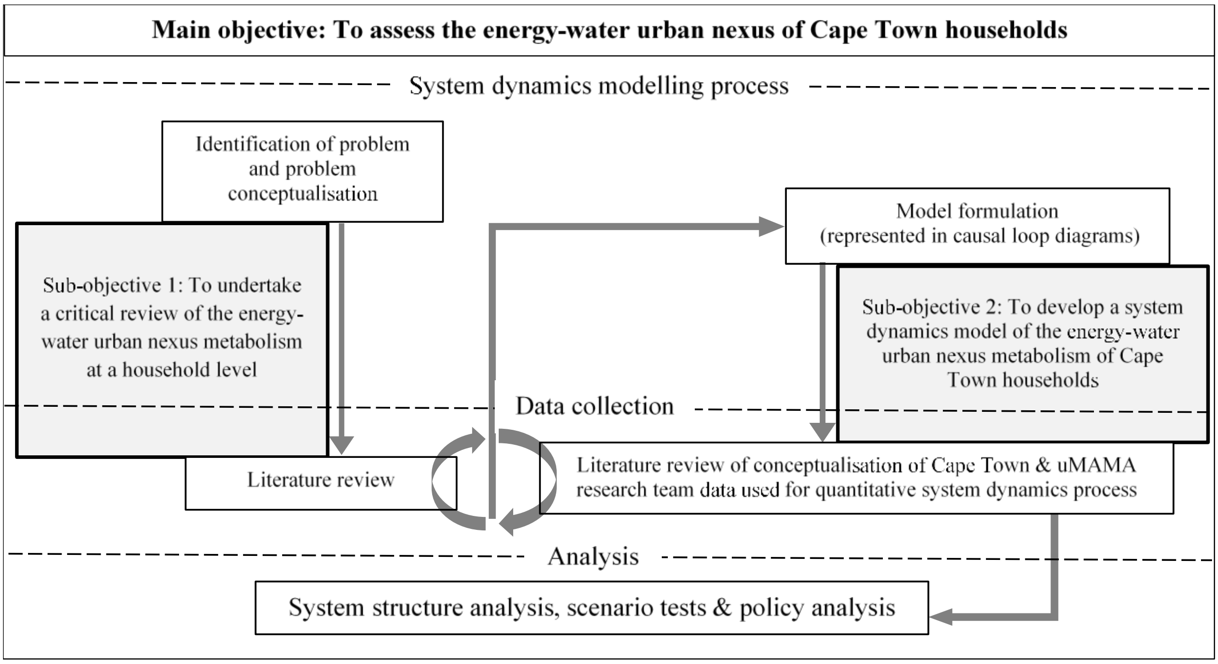

Figure 4.1: Research design
Source: Author

4.3 Research paradigm

The research took on a critical realism ontology. Critical realism allows for the exploration of how reality is understood. It attempts to figure out and understand underlying structures that produce a particular set of events (Pruyt, 2006). 'Realism' accounts for the fact that the reality of a known thing is acknowledged as something other than familiar to the knower, and 'critical' refers to the fact that it is acknowledged that this reality can only be accessed through conversation or interaction between the thing and the knower (Porter & Pitts, 2015). This realisation results in reflection on what 'reality' is in terms of our own. Critical realism is not theory-determined but rather theory-laden. Therefore, conceptual frameworks will not be determined but rather developed from accepted theories (Fletcher, 2017). Critical realism possesses the ability to engage in causal analysis and explanation, therefore making it useful when analysing social situations that call for suggestions for social change, as in the case for identifying high-leverage points in households in Cape Town (Fletcher, 2017).

A critical pluralism paradigm was adopted to address the system dynamics model research objective. This specific paradigm is subjective in terms of epistemology and ontologically critical realism. Critical pluralism focuses on the importance of causality, with a fundamental idea being to understand and learn about the underlying causal structure and behaviour of systems (Pruyt, 2006). A model is appropriate for this paradigm as it will lead to real-world

Stellenbosch University https://scholar.sun.ac.za

insights, which have the potential to transform underlying structures and mental models that govern particular systems (Pruyt, 2006). Critical pluralism is considered an intermediary paradigm between constructivism and positivism (Table 4.1). It assumes that an external reality exists and that it may only be known to a certain extent due to basic assumptions that are made (Pruyt, 2006).

Table 4.1: System dynamics paradigms

	Positivist	Post-positivist	Critical pluralism	Pragmatism	Transformative emancipatory critical	Constructivism
Ontology	(Naïve) realism	(Transcendental) realism	(Critical) realism	(Pragmatism) realism	Relativism	Relativism
Epistemology	Objective	(Probably) objective	Subjective	Objective and subjective	Subjective (and objective)	Subjective
Axiology	Value-free	Controllable value-ladenness	Concerned by value-ladenness	Unconcerned by value-ladenness	Non-neutral value-ladenness	Value-bound
Method [ologie]s	Purely quantitative	Primarily quantitative	Quantitative and qualitative	Quantitative and qualitative	Qualitative, qualitative, mixed	Qualitative
Causality	Knowable real causes	Reasonably stable causal relationships (not necessarily used)	Causality is key to understanding of real world	Maybe causal relationships but not exactly knowable		Indistinguishable causes and effects
Logic	Deductive	Primarily deductive	Deductive and inductive	Deductive and inductive	Deductive and inductive	Inductive
Appropriateness of model	Refutable but not refuted	Validated models, results closest to the real world	Do models lead to real insight and understanding?	Closest to goal or own value system?	Advancing justice, democracy and oppressed?	Confidence in constructed model
Appropriateness of strategies	Optimal strategy	Probably optimal strategy or most appropriate strategy	Potential to structural transformation?	Close to goal or own value system?	Advancing justice, democracy and oppressed?	Any strategy (if agreed to)

Source: Adapted from Pruyt (2006)

4.4 Research methodology

Being situated within the critical realism epistemology, this study utilised a mixed methodology (both quantitative and qualitative). The methodology included both a case study specific to Cape Town urban households, and a simulation using system dynamics. Critical pluralist simulations consist of methodologies that are both quantitative and qualitative (Table 4.1). The simulation results are quantitative and need to be interpreted qualitatively, as this increases the understanding of the underlying structures.

4.5 Research methods

A mixed-methods approach was utilised to understand different households' energy and water flows in terms of services and drivers of consumption behaviours. Every sub-objective utilised different methods to achieve the overall objective.

Stellenbosch University https://scholar.sun.ac.za

4.5.1 Objective 1: Literature review

Within the first sub-objective, the literature review had two main aims. The first was to critically review the energy-water urban nexus metabolism at a household level. This was achieved by reviewing existing literature on urban metabolism, urban nexus, energy-water nexus and household energy-water nexus. This was achieved through a critical literature review that collected data from a variety of sources using search engines such as Google Scholar, Web of Science, Science direct and Scopus. A set of specific keywords was used when searching for sources on the aforementioned search engines, namely: 'urban metabolism', 'household metabolism', 'energy metabolism', 'water metabolism', 'resource nexus', 'energy-water nexus', 'water-energy nexus' and 'system dynamics'. Both the keywords 'energy-water nexus' and 'water-energy nexus' were used, as they were found to be used interchangeably in most literature (Berman *et al.*, 2019; Endo, Yamada, Miyashita, Sugimoto, Ishii, Nishijima, Fujii, Kato, Hamamoto, Kimura, Kumazawa & Qi, 2019).

The second aim was to conceptualise flows of energy and water through a household. Based on the combined literature by Hussien, Memon and Savic (2017) and Kenway *et al.* (2013), the conceptualisation of energy and water flows in a household could be developed, as is shown in Figure 4.2. The conceptualisation divides energy and water flows in a household into three subsystems: a supply subsystem, a service subsystem and a waste subsystem. The supply subsystem contains all the energy and water carriers that flow into the service subsystem, which contains all the energy and water-related services in a household that flow into the waste subsystem. From this conceptualisation, the services that utilise both energy and water are able to be visually identified in Figure 4.2, with green emphasising the services where the nexus of energy and water occurs in households.

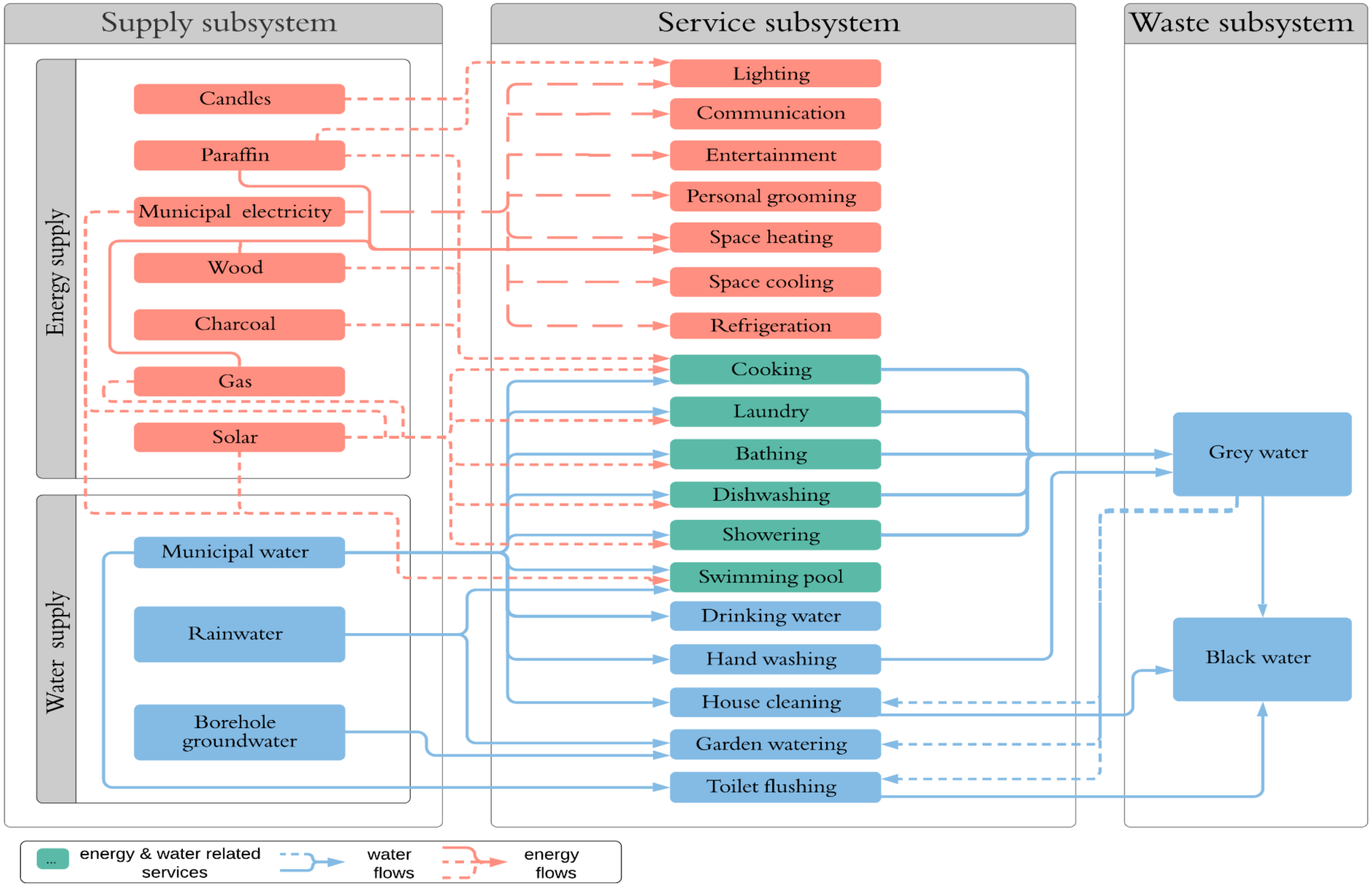

Figure 4.2: Conceptualisation of energy and water flows in households
Source: Author

Stellenbosch University https://scholar.sun.ac.za

4.5.2Objective 2: Case study simulation

In order to achieve this sub-objective, two methods were used: a case study of the City of Cape Town, of which a literature review was conducted, and a simulation using a system dynamics model.

4.5.2.1 Case study

Cape Town was chosen as the case study for this research on the basis of available data on the city's metabolism from the urban Modelling and Metabolism Assessment (uMAMA) research team (www.umama-africa.com). A critical literature review of Cape Town was conducted using data on the city's metabolism and energy and water flows collected from a variety of sources by means of search engines such as Google Scholar, Web of Science, Science direct and Scopus. Keywords and search queries used included a combination of the following: 'City of Cape Town', 'residential sector', 'water consumption', 'energy consumption', 'households', 'Cape Town water sector' and 'Cape Town energy sector'.

Subsequently it was found that most studies conducted on Cape Town household energy and water were limited to overall consumption. When urban metabolic studies of these resource flows were conducted, they occurred mainly at a macro level, and those that did undertake urban metabolic assessments at a household level focused on end use consumption. However, a metabolic energy assessment based on Cape Town households in a study was conducted by Strydom (2019) as a part of uMAMA research, which conceptualised Cape Town's household energy flows.

Based on this literature, combined with the literature from the first objective and the conceptualisation of energy and water flows in a household (Figure 4.2), a framework for Cape Town household energy-water urban nexus metabolism could be developed (Figure 4.3). This framework identified the services where the nexus of energy and water can occur in households in Cape Town. Hot-water supply forms a part of the supply subsystem, and although it may be considered a service, services within the nexus such as cooking, showering, bathing, laundry and dishwashing do not necessarily heat water when the service is carried out, and all require hot water as a supply. While not all the services apply to every household in Cape Town – (for example, not every household will have a swimming pool, let alone a heated swimming pool), – these flows form part of the framework since they do occur in some Cape Town households.

Stellenbosch University https://scholar.sun.ac.za

Similarly, some energy carriers may not apply to some households, or some may not make use of a grey water system, but the flows are indicated for those that do.

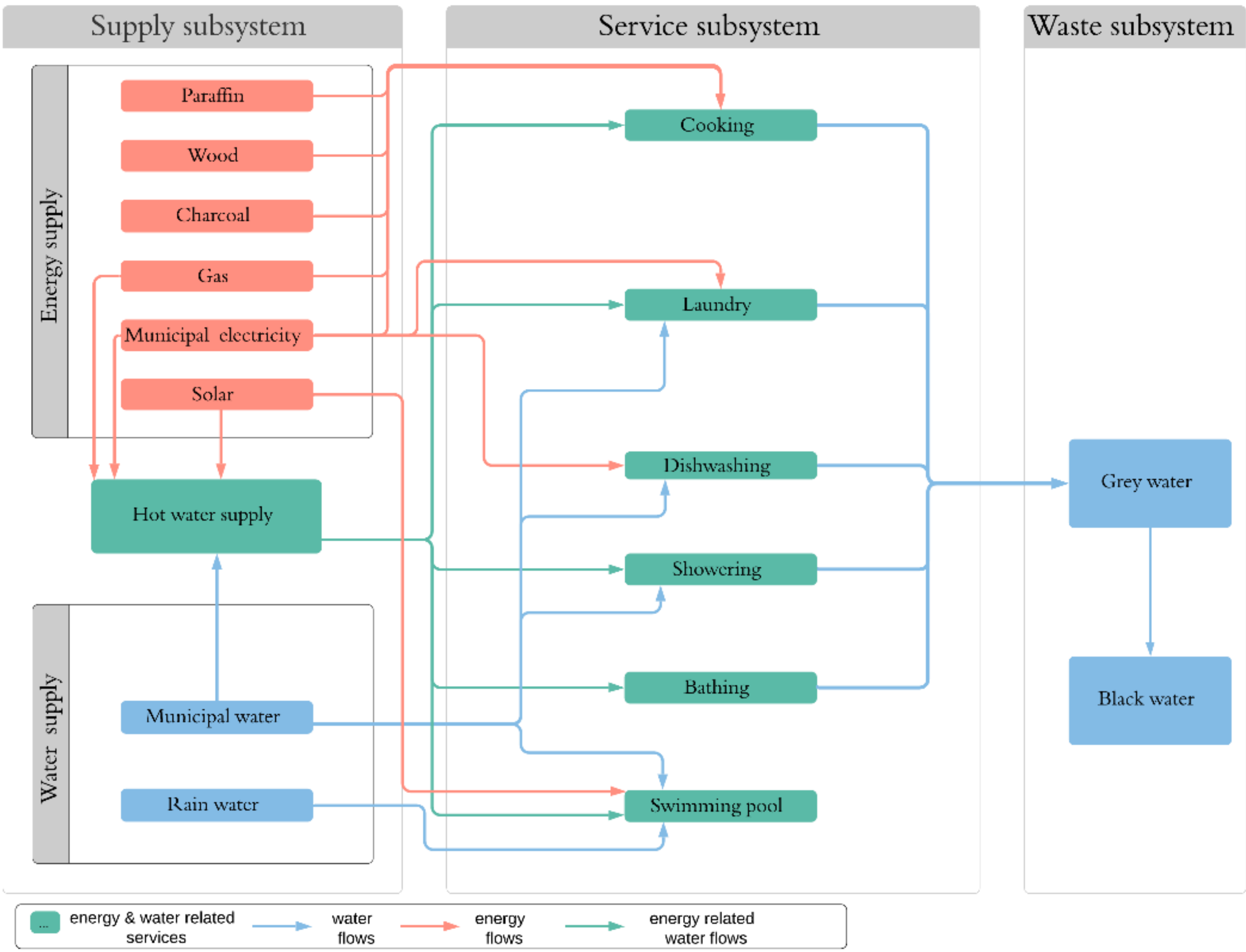

Figure 4.3: Cape Town household energy-water urban nexus metabolism framework
Source: Author

Stellenbosch University https://scholar.sun.ac.za

4.5.2.2 System dynamics simulation

The system dynamics model was developed using Vensim DSS Version 8.0.7, developed by Ventana Systems. Vensim is a visual modelling tool that allows the conceptualisation, simulation, analysis and optimisation of dynamic models (Ventana Systems Inc, 2007). The software provides a flexible way of building the model simulations of both causal loops and stock and flow diagrams. Causal relationships are recorded by entering the connection of words with arrows, with the relationships between the system variables being stated.

Based on the literature, the swimming service was excluded from the model, as the reality of Cape Town is that less than 35% of households have swimming pools and the majority are not heated (Fisher-Jeffes, Gertse & Armitage, 2015). Furthermore, municipal electricity was the only energy carrier considered in the model since, according to the 2016 census and the study conducted by Strydom (2019), on average the majority of Cape Town households rely on electricity for water-heating purposes (StatsSA, 2016a). Therefore, in the energy-water urban nexus metabolism model developed, energy was understood to be specifically municipal energy.

With this understanding, and based on the framework of Figure 4.3, a systems architecture map (Figure 4.4) was developed for the system dynamics model that took the specific activities done to carry out and satisfy the identified services into account. The cooking service includes heated water used for eating and drinking, and therefore the service activities identified were 'stovetop cooking' and 'kettle'. 'Stovetop cooking' does not necessarily refer to water heated on a stovetop, but rather to water heated and used while cooking for eating purposes, where 'kettle' refers to water heated for drinking purposes. The electricity and energy requirements for stovetop cooking water and kettle cooking water will differ.

The laundry service can be carried out either by hand-washing laundry, by making use of a front-loaded washing machine or of a top-loaded washing machine. The electricity and water requirements for each way that laundry is done differ, which is why the service was separated into different laundry service activities. Similarly, with the dishwashing service, activities were divided into hand-washed dishes and machine-washed dishes. However, with the bathing and showering services, the service was not divided into activities, since bathing and showering are not conducted in various ways. While it could be argued that bathing can be done by filling a

Stellenbosch University https://scholar.sun.ac.za

tub with heated water from a kettle, assumptions were made where this was not considered. All assumptions are detailed in Chapter 5, which discusses the Cape Town Energy-Water Urban Nexus Metabolism (EWNEX) model.

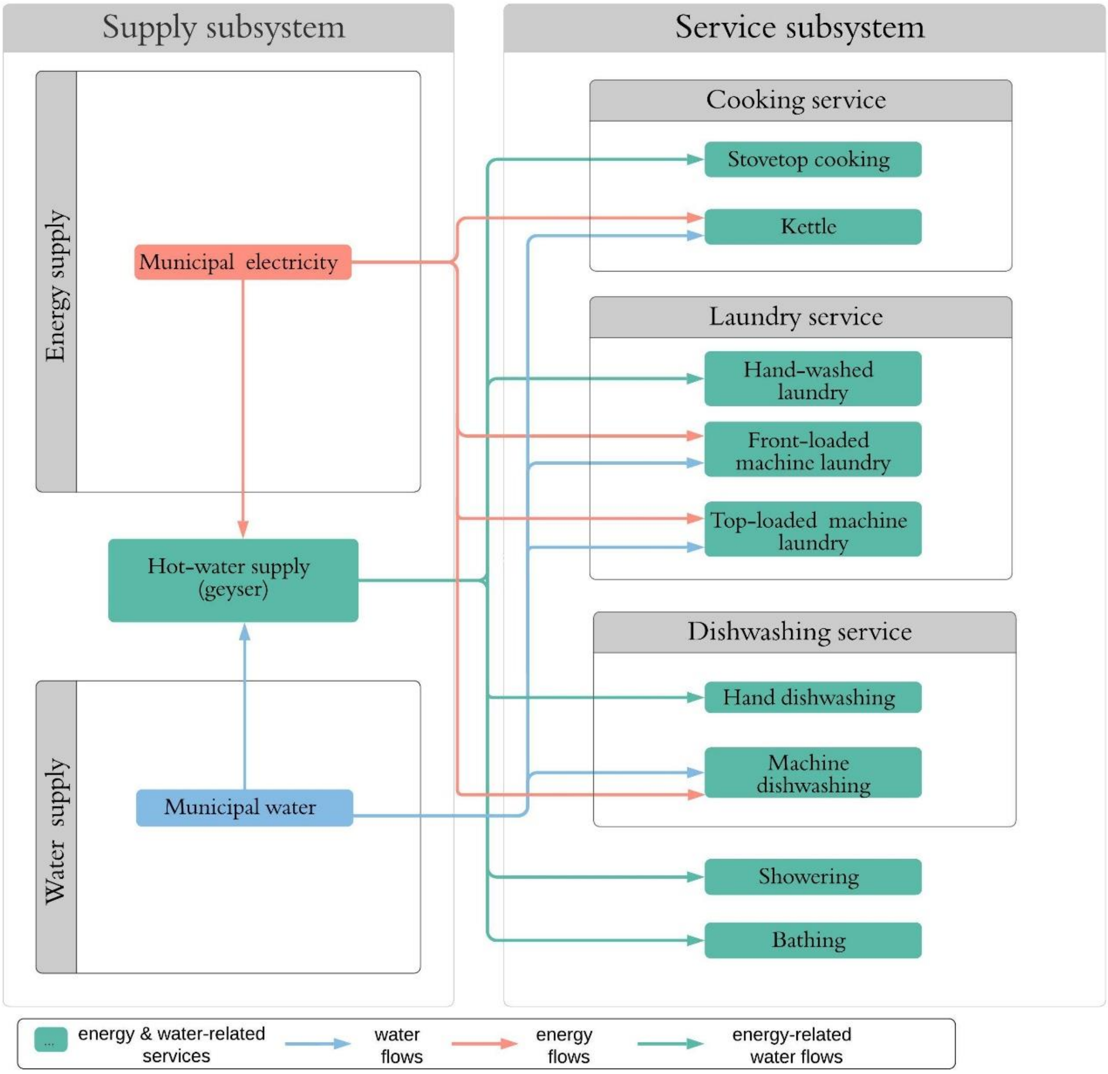

Figure 4.4: Systems architecture map
Source: Author

Furthermore, in order to interpret the results of the simulated model, households were categorised and simulated by income group, and an average of all the income groups was considered too. The income-level categorisation of households followed previous uMAMA research, which was based on the StatsSA categorisation as shown in Table 4.2 (Strydom, 2019). This was done since the amount that households budget for electricity and water services forms part of the dynamics of the conceptualised system dynamics model, and the income group of a household determines the expenditure and allocated budget for services. While the dynamics of households in different income groups are the same, the exact behaviours such as which service activities the household utilises vary for the different income groups.

Table 4.2: Classification of household groups

Income group	***Monthly household income***
Low-income	R0 – R6 400
Low-middle-income	R6 401 – R12 800
High-middle-income	R12 801 – R51 200
High-income	R51 201 +

Source: Adapted from Strydom (2019)

Data

The study utilised data that was collected by urban Modelling and Metabolism Assessment Research Team (uMAMA) studies by Paul Currie and Adel Strydom for their PhD and master's-degree studies, respectively. However, it should be noted that the data collection for these studies occurred during a drought in 2018, when water restrictions were in place. Therefore, the data may not be a true reflection of households' consumption in a non-drought context, as citizens were already encouraged to reduce daily water consumption. Household energy metabolism data from Strydom (2019) was used to provide averages for the income groups to inform the system dynamics model. Similarly, household water metabolism data was used to inform the system dynamics model regarding the water flows of Cape Town households. Where data gaps were identified, additional data from the City of Cape Town and Cape Town's census data from STATS SA were used. Additional data on Cape Town's metabolism from literature such as Currie *et al.* (2017) were considered as well.

4.6 Summary

This chapter provided insight into how the main objective of the research was achieved through the explanations of the research paradigm, methods and design for every sub-objective. This research aimed to provide a methodological contribution by using a system dynamics to model for the energy-water nexus at a household level in Cape Town. A subjective epistemology and realistic ontology were adopted, with the premise that in order to understand the world fully, causality is vital.

Stellenbosch University https://scholar.sun.ac.za

A research paradigm that suitably encompassed the ontology and epistemology of the research was chosen, with a mixed-methods approach adopted due to the nature of system dynamics modelling. This research adopted a mixed-methods approach using both a simulation in the form of system dynamics modelling and a case study of Cape Town to provide context to the simulation. Based on the literature a conceptual framework of household energy-water urban nexus metabolism was developed which informed the development of the system architecture map used for the system dynamics model. The model, ideally, will be able to provide real-life insight into the dynamics of the energy-water nexus at a household level. The following chapter presents the built simulated model.

Stellenbosch University https://scholar.sun.ac.za

Chapter 5 : Cape Town Energy-Water Urban Nexus Metabolism (EWNEX) model

5.1 Introduction

The purpose of the system dynamics model was to understand the dynamics of household energy and water flows from an urban metabolism perspective, and to determine the leverage points where both energy and water could be saved within the context of Cape Town households. Cape Town household energy and water flows were previously investigated, and these studies informed the model. This study involves understanding the links between energy and water in Cape Town households, where energy and water are explicitly understood to be municipal electricity and municipal water. This chapter followed the first three phases of Sterman's (2000) system dynamic modelling steps (presented in Section 2.5.1), to describe the energy-water urban nexus metabolism (EWNEX) model of the problem.

5.2 Problem articulation

The Cape Town municipality faces periodic droughts and electricity load shedding and therefore faces a significant problem with the sustainable provisioning of water and electricity to households of all income groups. Periodic droughts remain a constant threat to Cape Town households and the sustainable and constant water supply to the entire city is therefore at risk. Without this supply, all services relating to water consumption will be under threat – with most being necessary for human survival. Similarly, unsustainable energy supplies affect all energy-related services, which at a household level include basic services such as heating, cooling and cooking, all of which are again basic services for daily activities.

The dilemma is the question of how energy and water consumption can be minimised in their nexus without compromising the service provisioning of the resources where they are linked. Therefore, in order to ensure that Cape Town households have a continuous and sustainable municipal energy and water supply, energy and water savings need to be maximised where they are linked in the household.

The scope of the study included only Cape Town households' energy, specifically electricity and water consumption, and no other sectors. The model was based on the broad Cape Town

Stellenbosch University https://scholar.sun.ac.za

household energy-water urban nexus metabolism framework (Figure 4.3) and the further identified conceptualisation of the relevant service activities (Figure 4.4).

Figure 5.1 shows the goal tree for the articulated problem. The goal tree's purpose is to visually display the indicators that are relevant for the articulated problem and are divided into branches until the smallest measurable unit is reached.

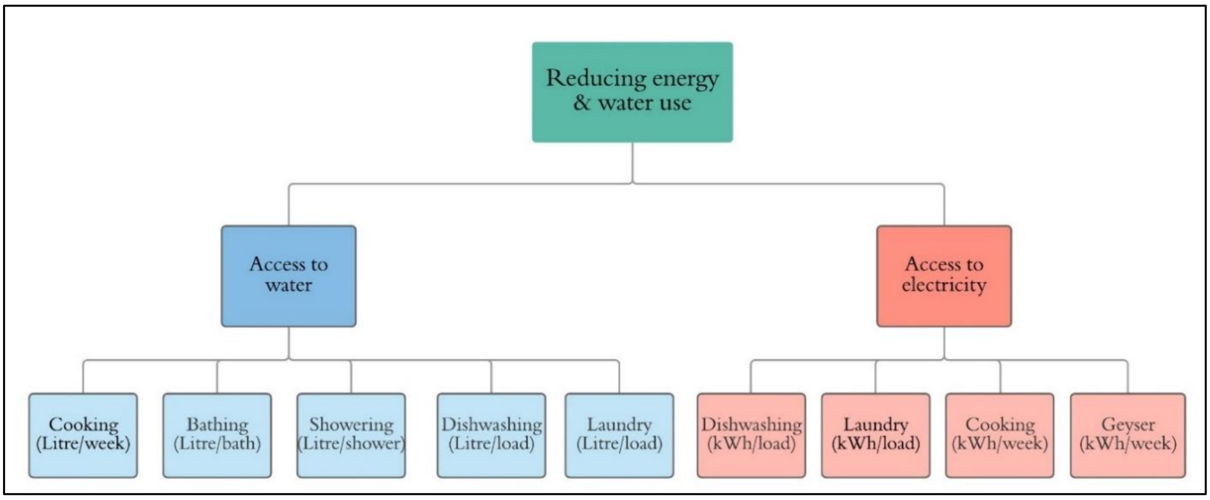

Figure 5.1: Goal tree for articulated problem
Source: Author

5.3Dynamic hypothesis

Causal relationships and feedbacks for minimising energy and water in Cape Town households include five causal loops in total. Two reinforcing loops, the hot-water usage loop (R1) and the electricity usage loop (R2), and three balancing loops: the water savings loop (B1), the electricity savings loop (B2) and the energy-water nexus loop (B3). The relationships and feedback of the five causal loops and how they relate to each other are described in the sections that follow.

5.3.1 Hot-water usage loop (R1)

The hot-water usage loop (R1) shown in Figure 5.2 illustrates the reinforcing causality of a household's water requirements and the household's water usage. Household (HH) hot-water requirement is understood to be the amount of hot water that the household requires every month, and the HH hot-water usage is determined by the use of services dependent on hot water. If more hot water is needed every month, it will encourage the users to use more, since resources will be consumed to satisfy services. Therefore, the more the HH hot-water requirement, the more the HH hot-water usage. Subsequently, the more the HH hot-water usage, the more the HH hot-water requirement, and if more is used, it will increase the required amount every month. This feedback loop is considered reinforcing, since the causal relationship dictates that if it occurs in isolation, hot water will continue to be required and used in a household.

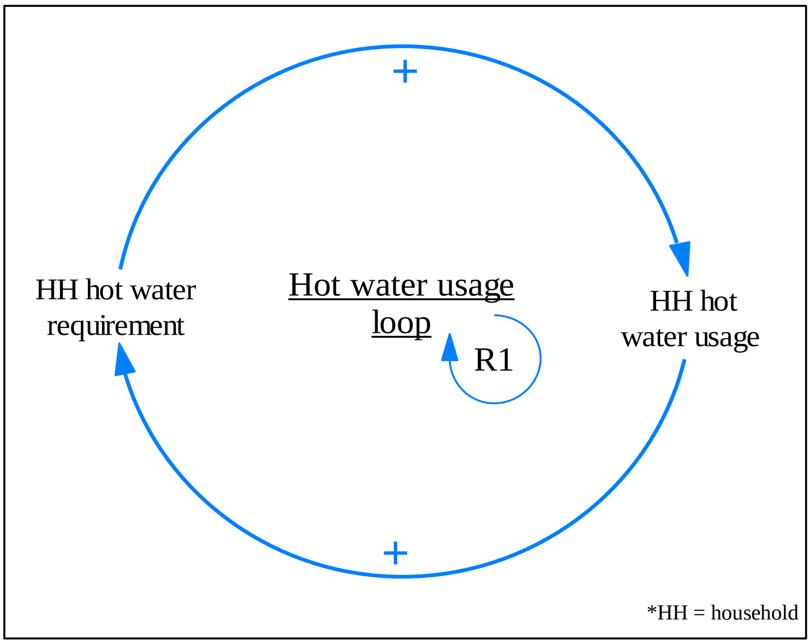

Figure 5.2: Hot-water usage loop (R1)
Source: Author

5.3.2 Water savings loop (B1)

The balancing loop in Figure 5.3, the water savings loop (B1), has a different effect on HH hot-water requirements. This balancing loop illustrates the causality between HH hot-water requirements and HH water savings. More HH hot-water requirement means more HH water savings, and the more the HH water savings, the less the HH hot-water requirement. The understanding behind this is that the more water a household requires in a month, the more it has the ability to save water. Subsequently, with more water being saved every month, the water requirement for the month decreases.

Stellenbosch University https://scholar.sun.ac.za

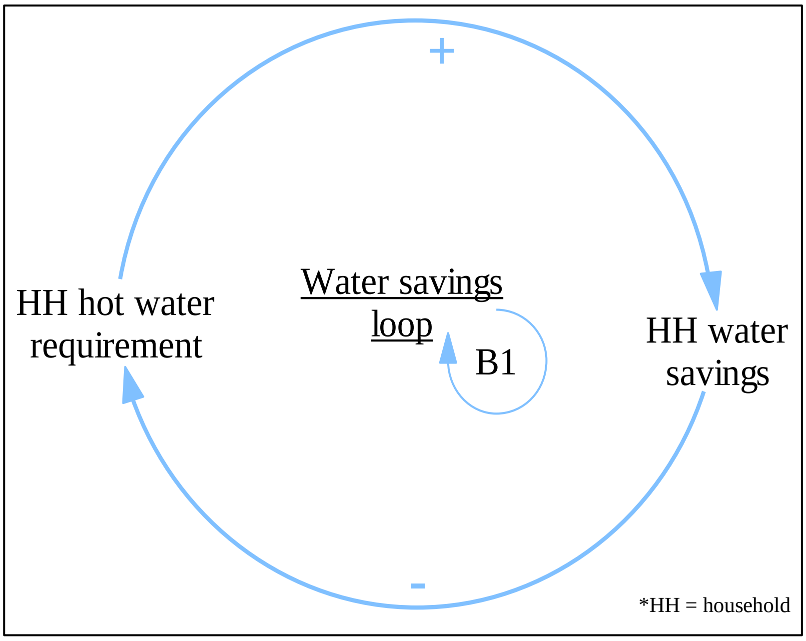

Figure 5.3: Water savings loop (B1)
Source: Author

5.3.3 Electricity usage loop (R2)

In Figure 5.4 the electricity usage loop (R2) is also one relating to usage. However, instead of water usage, it shows the reinforcing causality of household electricity usage and household electricity requirement: the more the HH electricity usage, the more the HH electricity requirement will be. The more the HH electricity requirement, the more the HH electricity usage will be.

Stellenbosch University https://scholar.sun.ac.za

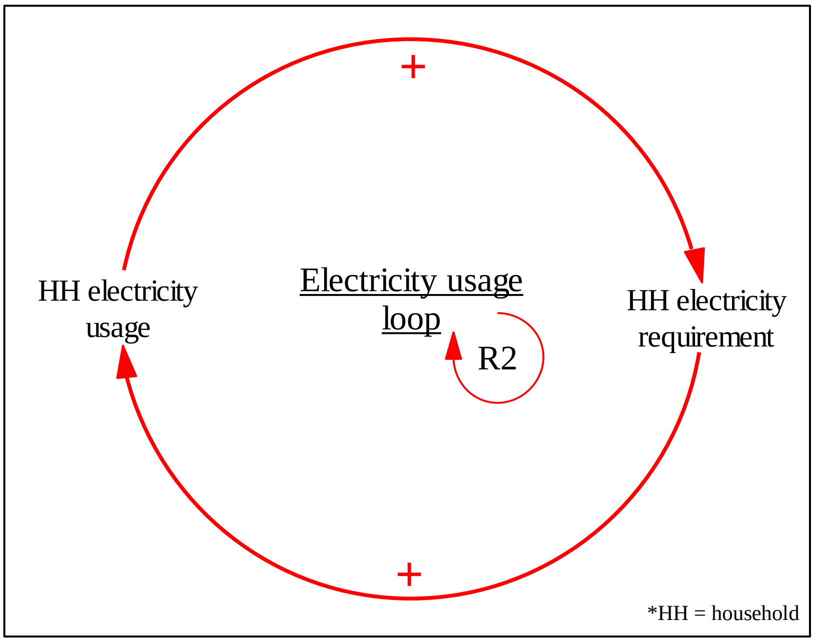

Figure 5.4: Electricity usage loop (R2)
Source: Author

5.3.4 Electricity savings loop (B2)

Figure 5.5 shows the balancing dynamics of the households' electricity savings loop (B2). The dynamics explained in R2 (Figure 5.4) indicated that the more the HH electricity requirement was, the more the electricity usage would be. However, for this balancing loop, the more the HH electricity usage, the more the HH electricity savings will be. The reason is that, since there is an increase in usage and electricity required, it will provide an incentive to save electricity. However, with an increase in HH electricity savings, the HH electricity requirement decreases, since electricity saved is electricity the household does not require for a given month.

Stellenbosch University https://scholar.sun.ac.za

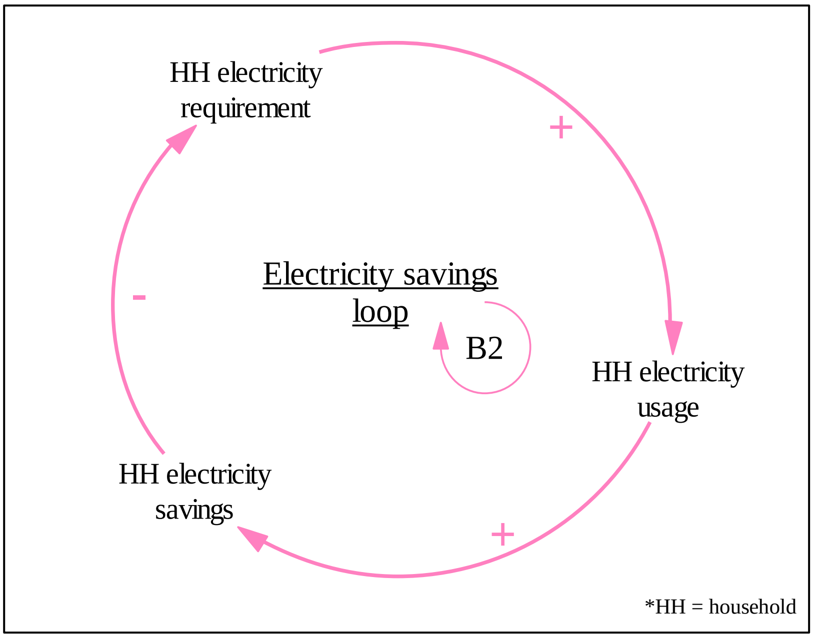

Figure 5.5: Electricity savings loop (B2)
Source: Author

5.3.5 Energy-water nexus loop (B3)

Based on literature and the conceptualised framework for the household energy-water urban nexus metabolism (Figure 4.3) it was determined that the two resources are predominantly linked for water heating purposes. Therefore, the balancing loop in Figure 5.6, the energy-water nexus loop, shows the causal dynamics between water and electricity for heating water. The more the HH hot-water requirement, the more the HH electricity usage will be, since in order to heat the water, electricity usage is necessary. An increase in HH electricity usage will increase a households' incentive to save electricity, subsequently, increasing HH electricity savings. An increase in HH electricity savings decreases the HH electricity requirements. This decrease in HH electricity requirements increases HH water savings, since there is no electricity used to heat water, thus saving on water usage with regard to heated water. Ultimately, an increase in HH water savings decreases the HH hot-water requirement, since that water is being saved.

Stellenbosch University https://scholar.sun.ac.za

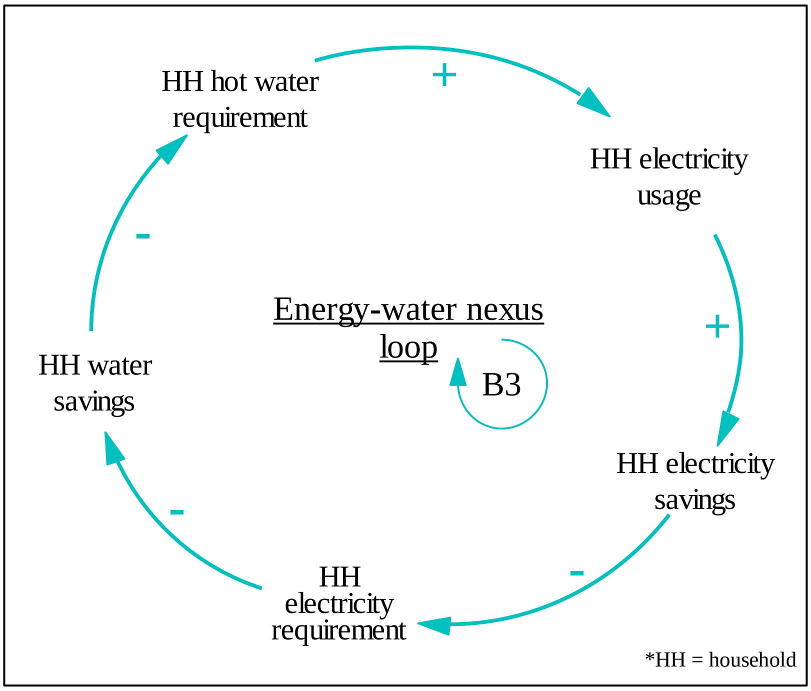

Figure 5.6: Energy-water nexus loop (B3)
Source: Author

5.3.6 Overall loop

Figure 5.7 shows how each of the previously explained causal loops connects and interacts with the others. This depiction shows how the dynamics of loops B1 (electricity usage loop), B2 (electricity savings loop) and R2 (water savings loop) are all found within the larger energy-water nexus loop B3. From this illustration, it can be seen that the two main interactions at play are between the reinforcing hot-water usage loop (R1) and the energy-water nexus loop (B3),

Stellenbosch University https://scholar.sun.ac.za

where the HH hot-water requirement is the common variable. This reinforces the concept of energy for water (heating purposes) and not water for energy at the household level.

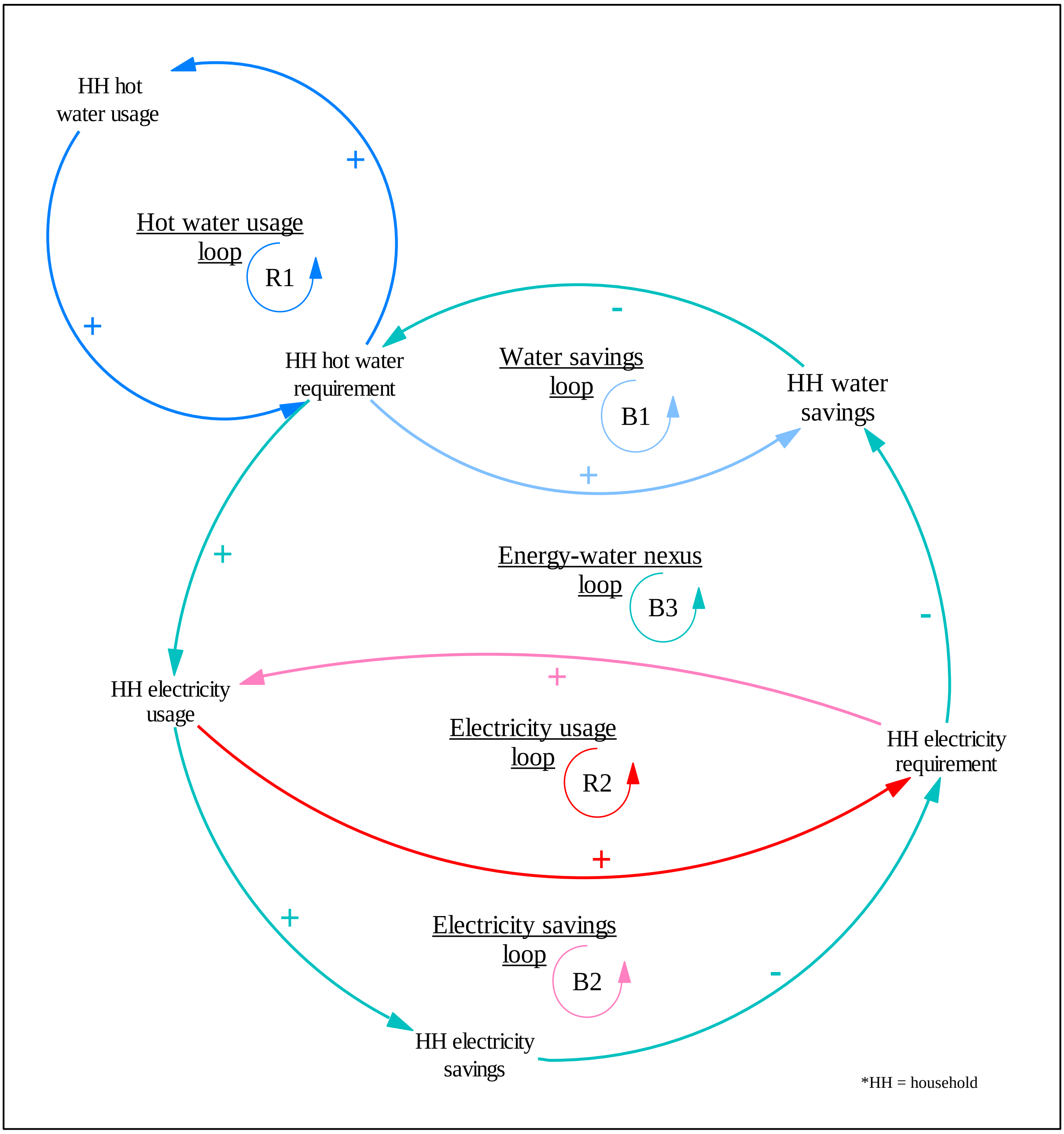

Figure 5.7: Overall CLD
Source: Author

5.4 Model formulation

For the quantitative phases of the system dynamics process, the scope and boundary of the model were limited to Cape Town households and a simulation model in the form of stocks, flows and auxiliaries was constructed consistently for an average of 12 months (i.e. not accounting for a seasonal change). While the model consisted of only two stocks and four flows, it made use of subscripts in order to model the different energy-related water services that occur in a household. In Vensim, subscripts allow one equation or variable the ability to represent various concepts – in this case, the different energy-water nexus household services and service activities (Ventana Systems Inc, 2007). This made it possible to have the same equations applied to every different service or service activity value for a particular variable.

The model consisted of the five services identified in the scope and considered how every service is carried out (service activity), as outlined in the system architecture map (Figure 4.4). Therefore, the model consisted of nine service activity subscripts (Figure 5.8): cooking stovetop and cooking kettle (accounting for the cooking service), dishwashing hand and dishwashing machine (accounting for the dishwashing service), bathing, showering, laundry hand, laundry front-loaded and laundry top-loaded (accounting for the laundry service).

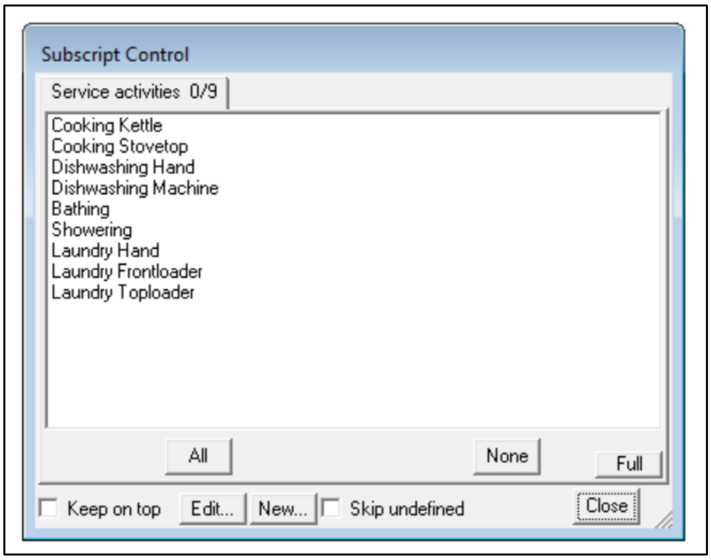

Figure 5.8: Subscripted service activity range
Source: Author

In order to build the model to run and simulate results, parameters, initial variables and assumptions needed to be set. The model makes use of subscripts, since the equations applied to the service activities are the same. However, the parameters, initial variables and assumptions for every service differ, and they will be discussed individually in the following sections as five different sub-models for each of the services. All the sub-models feed into the larger main subscripted stock and flow sub-model.

5.4.1 Nexus electricity and water requirements sub-model

This sub-model, shown in Figure 5.9, is considered the main subscripted model and consists of four flows and two stocks. The stock HH hot-water requirement has an inflow of hot-water

Stellenbosch University https://scholar.sun.ac.za

usage and an outflow of water savings, given the dynamics that usage adds to a households' water requirement and that savings decrease a household's water requirement. The second stock of HH electricity requirement has the inflow electricity usage and outflow of electricity savings, giving similar dynamics as the HH water requirement stock. It should be noted that in general electricity is not usually considered a stock unless referring to installed capacity for example, however for the purposes of this model HH electricity requirement is considered a stock since it is almost considered as the amount of electricity within a household at a given time.

As was mentioned, five sub-models, the cooking sub-model, laundry sub-model, dishwashing sub-model, bathing sub-model and showering sub-model, all have subscripts allocated to the respective service activities. Therefore, the equations in the nexus model are applied to each of the subscripts individually. The water used for every service activity governs the 'services water usage' variable, which informs the 'hot-water usage' inflow the 'water usage' flows into, adding to the 'HH hot-water requirement' stock. However, 'water savings' does decrease the stock. The HH hot-water requirement for every service activity is added together to get the total water requirement for the household. If this total water requirement is less than the amount of water budgeted for hot-water use for the month, the total water requirement informs the electricity usage, since that is the amount of water that needs to be heated. However, if the total water requirement exceeds the amount budgeted, then the budgeted amount of water will inform electricity usage. The required hot water (either the total or budgeted amount) is then used to inform the electricity usage. Electricity usage is calculated per kilowatt-hour it takes to heat a litre of water for each service activity.

The electricity usage informs the household electricity requirement, from which the total sum of the electricity requirement for all the service activities is calculated in order to compare it to the monthly electricity budget. The ratio of the total electricity requirement and the budgeted amount informs the effect of electricity use on water requirement, and this effect will govern the water and electricity savings of the household that decrease the amount of 'HH hot-water requirement' and 'HH electricity requirement' respectively. The dynamics of the nexus sub-model in Figure 5.9 are colour coded to match the dynamic hypothesis causal loop diagram of Figure 5.7 in order to make the causal links and effects clearer.

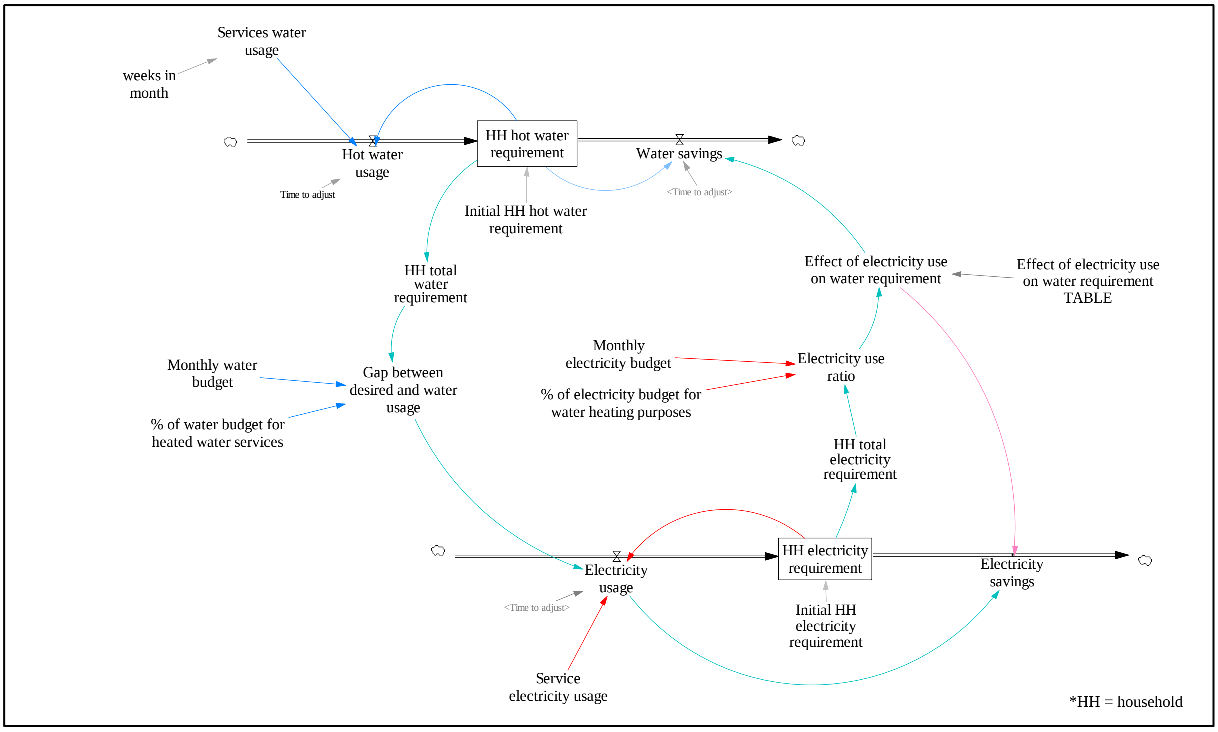

Figure 5.9: Nexus sub-model
Source: Author

Assumptions for this sub-model were as follows:

a. There is sufficient and continuous water supply to meet the demand, i.e. there are no water shortages affecting water availability for water heating purposes.

b. There is enough energy supply to meet the demand. Supply is only that of municipal energy supply in the form of electricity.

c. All households, of all household income groups, have and make use of an electric geyser.

d. All persons in the households are adults.

e. A household cannot exceed its budgeted amount for hot water. If water requirements exceed this amount, only the maximum amount of the budget would be heated.

f. Effect of electricity-use lookup table:

It was assumed that the total of a households' electricity requirement cannot exceed the amount of the households' total electricity budget for water heating purposes. Therefore, once the ratio between the total required electricity and the budgeted amount gets to 80%, it will start influencing both water and electricity savings. The assumption is that the effect of the ratio has a positive exponential

Stellenbosch University https://scholar.sun.ac.za

effect on the savings, i.e. the more a household goes over budget, the more they would have to save.

An average of the initial values and parameters of all the income groups used for the nexus sub-model is summarised in Table 5.1. The initial values and parameters used for each specific income group can be found in Appendix A: Initial values and parameters of household income groups for the EWNEX system dynamics model.

Table 5.1: Nexus sub-model parameters and initial values

Parameter	***Initial value***	***Unit***
Monthly electricity budget	516,60	kWh
% of electricity budget used for water heating purposes	28%	Dmnl
Monthly water budget	16 321	Litre
% of water budget for heated water services	20,8%	Dmnl

Source: Author

5.4.2 Cooking service electricity and water requirements sub-model

The cooking sub-model accounts for the service's contribution to the energy-water urban nexus metabolism of a household. It was determined that hot water used for the cooking service comes from two primary sources: a kettle for hot drinking water and preheated water from a geyser for stovetop cooking. This sub-model consists of the stovetop cooking service activity and kettle service activity, which considers all heated water used for both cooking and drinking. The cooking sub-model is based on the following assumptions:

a. Heated water used for cooking is used preheated and not heated during cooking, i.e. hot water is supplied from a heated geyser.
b. Cold water used to clean, prepare and make food was not considered for this model.
c. Based on World Health Organization (2013) reports, approximately three litres of water are required for cooking per day. The assumption was made that a third of that total is heated water, considering that the other two-thirds are used for food preparation and cold water use.

d. The equation to calculate stovetop electricity usage per litre was based on those provided by experts consulted (Strydom, 2019). This calculation considers the electricity required to heat a litre of water.
e. Hot drinking water can only be provided by using a kettle, and a kettle only provides hot drinking water and no other service (e.g. heated water from a kettle is not used for bathing).
f. The fullness of a kettle is directly proportional to the electricity required to heat the kettle.
g. Households of all income groups need to satisfy the cooking service, therefore they will all carry out cooking service activities.
h. The frequency of cooking is not affected by seasonal changes.

The cooking service model has two sections; Figure 5.10(a) accounts for the heated water used for stovetop and kettle cooking service activities. This required variables that considered the water consumption of every cooking service activity, as well as the frequency at which the activity took place. This frequency of cooking and water usage for the respective cooking activities creates the water usage demand for the cooking service as a whole. This informs the 'services water usage' variable, which consisted of the subscripted values of all the services to inform the previously discussed nexus sub-model stock and flow section. Figure 5.10(b) accounts for the electricity used to heat water used for stovetop and kettle activities per litre.

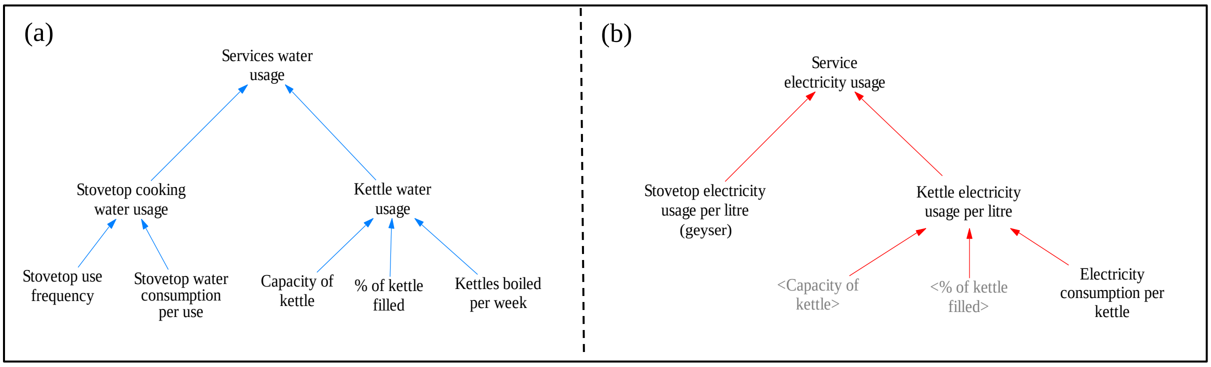

Figure 5.10: Cooking service sub-model
Source: Author

Averaged initial values and parameters for the income groups used for the cooking service sub-model are summarised in Table 5.2. The initial values used for each specific income group can

Stellenbosch University https://scholar.sun.ac.za

be found in Appendix A: Initial values and parameters of household income groups for the EWNEX system dynamics model.

Table 5.2: Cooking service sub-model average parameters and initial values

Service	***Service activity***	***Parameter***	***Initial value***	***Unit***
Cooking	Kettle	Kettles boiled per week	26	Kettle/week
		Capacity of kettle	1,7	Litre/kettle
		% of kettle filled	0.5	Dmnl
		Electricity consumption per kettle	0,04	kWh/kettle
	Stovetop	Stovetop use frequency	4	Hour/week
		Stovetop water consumption per use	1	Litre/hour
		Stovetop electricity usage per litre	$4 \times 23 \div 34\ 124$	kWh/litre

Source: Author.

5.4.3 Laundry service electricity and water requirements sub-model

The laundry service sub-model consists of two parts, with Figure 5.11(a) accounting for the water usage for hand, front-loaded and top-loaded laundry service activities, and Figure 5.11(b) accounting for the electricity usage for the laundry activities. For each laundry service activity, the frequency that the activity occurs, and the amount of water used per activity load affects the demand for heated water for the laundry service, which in turn informs the 'services water usage' variable that informs the main subscripted model. Similarly, the electricity usage per litre of heated water for each laundry service activity informs the 'service electricity usage' variable that feeds into nexus sub-model.

The assumptions made for the laundry service sub-model were as follows:

a. All laundry, hand-washing and machine-washing, uses heated water only. No cold water is used for laundry washing.
b. Heated water for hand-washing laundry is provided from an electric geyser.

c. The equation to calculate hand-laundry electricity usage was based on that provided by experts consulted (Strydom, 2019). This calculation considers the electricity required to heat a litre of water.
d. Washing machines, both front-loaded and top-loaded, heat water as a load of laundry runs and are not dependent on preheated water from a geyser.
e. All household income groups have access to the three laundry activities.
f. Households of all income groups need to satisfy the laundry service, therefore they will carry out at least one laundry service activity.
g. A household can make use of multiple or all laundry service activities in order to satisfy the service.
i. Laundry service activities are not affected by seasonal changes.

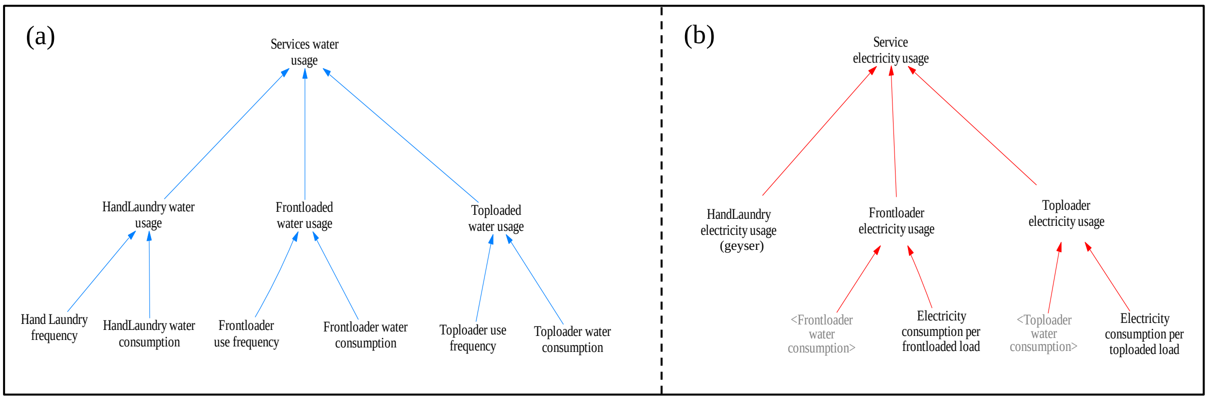

Figure 5.11: Laundry service sub-model
Source: Author

The average initial values and parameters of all the income groups used for the laundry service sub-model are summarised in Table 5.3. The initial values used for every specific income group for this sub-model can be found in Appendix A: Initial values and parameters of household income groups for the EWNEX system dynamics model.

Table 5.3: Laundry service sub-model parameters and initial values

Service	*Service activity*	*Parameter*	*Initial value*	*Unit*
Laundry	Hand-wash	Hand-laundry frequency	3	Load/week
		Hand-laundry water consumption	25	Litre/load
		Hand-laundry electricity usage	$4 \times 23 \div 34\,124$	kWh/litre
	Front-loaded	Front-loaded use frequency	1	Load/week

Stellenbosch University https://scholar.sun.ac.za

		Front-loaded water consumption	100	Litre/load
		Electricity consumption per front-loaded load	0,94	kWh/load
	Top-loaded	Top-loaded use frequency	2	Load/week
		Top loaded water consumption	100	Litre/load
		Electricity consumption per top-loaded load	0,94	kWh/load

Source: Author

5.4.4 Dishwashing service electricity and water requirement sub-model

Similarly to the cooking and laundry sub-models, the dishwashing service sub-model consists of two parts: water usage relating to the dishwashing service activities (Figure 5.12(a)) and electricity usage relating to the activities (Figure 5.12(b)). From Figure 5.12(a) it can be seen that the frequency at which the respective activities are done and water consumption for the activity informs the water usage for the dishwashing activity. This, in turn, feeds into the 'services water usage' variable, which informs the main stock and flow nexus sub-model as subscripts. The same logic is used in Figure 5.12(b), but for the electricity usage for each activity instead of water usage. The following assumptions for the dishwashing service sub-model were made:

a. All dishwashing, hand and machine washing, uses heated water only. No cold water is used for dishwashing service activities.
b. Heated water for hand dishwashing is provided from an electric geyser.
c. Machine dishwashing heats water as a load runs and is not dependent on pre-heated water from a geyser.
d. The equation to calculate hand dishwashing electricity usage was based on that provided by experts consulted (Strydom, 2019). This calculation considers the electricity required to heat a litre of water.
e. All household income groups have access to the two dishwashing activities.
f. Households of all income groups need to satisfy the dishwashing service, therefore they will carry out at least one dishwashing service activity.
g. A household can make use of all dishwashing service activities in order to satisfy the service.
h. Dishwashing service activities are not affected by seasonal changes.

Stellenbosch University https://scholar.sun.ac.za

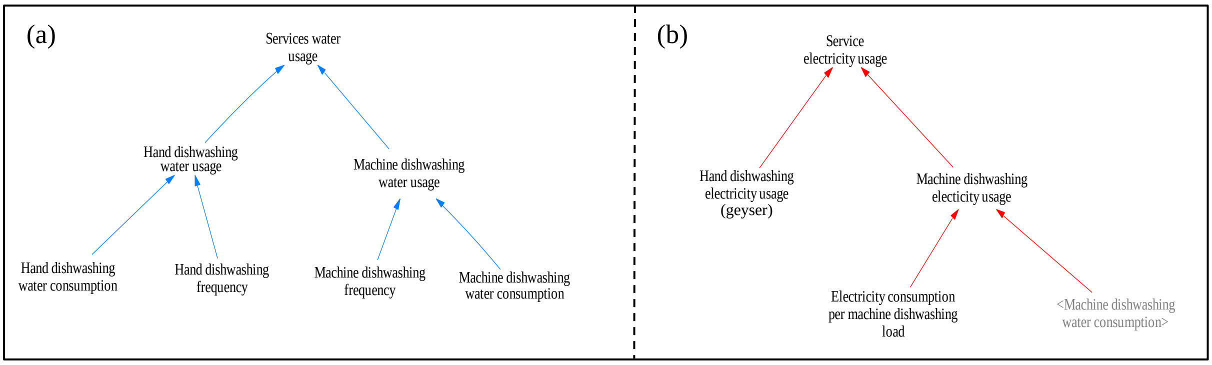

Figure 5.12: Dishwashing service sub-model
Source: Author

The averages of the parameters and initial values of the income groups used for the dishwashing service sub-model are summarised in Table 5.4. The parameters and initial values used for each specific income group for this sub-model can be found in Appendix A: Initial values and parameters of household income groups for the EWNEX system dynamics model.

Table 5.4: Dishwashing service sub-model parameters and initial values

Service	*Service activity*	*Parameter*	*Initial value*	*Unit*
Dishwashing	Hand dishwashing	Hand dishwashing frequency	14	Load/week
		Hand dishwashing water consumption	22	Litre/load
		Hand dishwashing electricity usage	4 × 23 ÷ 34 124	kWh/litre
	Machine dishwashing	Machine dishwashing frequency	1	Load/week
		Machine dishwashing water consumption	22,5	Litre/load
		Electricity consumption per machine dishwashing load	0,94	kWh/load

Source: Author

5.4.5 Bathing service electricity and water requirement sub-model

The bathing service sub-model, Figure 5.13, is structured similarly to the previous sub-model, but encompasses only a single service activity in the sense that the service itself is also the service activity. The following assumption was made for the bathing sub-model:

a. All baths use heated water from an electric water geyser. No cold water is used for bathing.
b. Heated water for baths comes only from an electric geyser. For example, heated water for baths does not come from the kettle.
c. The equation to calculate bathing electricity usage per litre was based on those provided by experts consulted (Strydom, 2019). This calculation considers the electricity required to heat a litre of water.
d. All members of a household bath at the same frequency and use the same amount of water per bath.
e. Households of all income groups need to satisfy the bathing or showering service. Therefore, it makes use of either both the bathing and showering services or of at least one of the services.
f. Bathing services are not affected by seasonal changes, i.e. the same amount of heated water is required in summer as in winter. More heated water is not required in winter compared to summer.

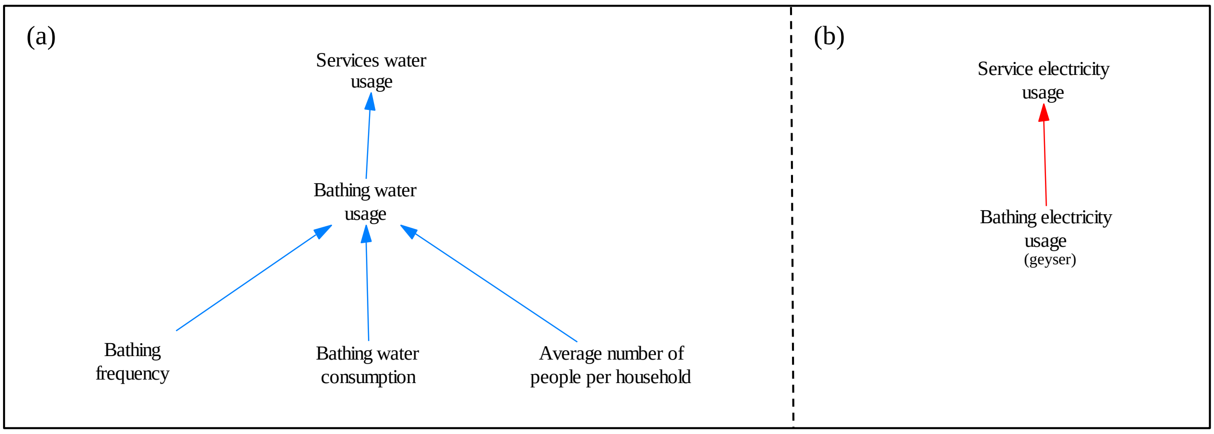

Figure 5.13: Bathing service sub-model
Source: Author

Figure 5.13(a) shows how bathing water usage is influenced by the number of people in the household, how often they bath, and the amount of water used per bath. The information is used to inform the ‘services water usage’, which accounts for all the other service activities as well. Similarly, Figure 5.13(b) uses the electricity used per litre for bathing, which informs the ‘services electricity usage’ that accounts for all the other service activities electricity usage as well.

Stellenbosch University https://scholar.sun.ac.za

The average initial values and parameters of the income groups used for the bathing service sub-model are summarised in Table 5.5. The initial values and parameters used for every specific income group for the bathing sub-model can be found in Appendix A: Initial values and parameters of household income groups for the EWNEX system dynamics model.

Table 5.5: Bathing service sub-model parameters and initial values

Service	*Parameter*	*Initial value*	*Unit*
Bathing	Bathing frequency	13	Bath/person/week
	Bathing water consumption	26	Litre/bath
	Average number of people per household	3	Person
	Bathing electricity usage	$4 \times 23 \div 34\,124$	kWh/litre

Source: Author

5.4.6 Showering service electricity and water requirement sub-model

The showering service sub-model, like the bathing sub-model, has two parts: Figure 5.14(a), accounting for the water usage associated with the service, and Figure 5.14(b), accounting for the electricity usage for the service. As with the bathing sub-model, the showering sub-model's service and service activity are the same, since there is no other showering type considered. The following assumptions were made for the showering sub-model:

a. All heated water for showers is comes from an electric geyser. No cold water for showering is considered in the model.
b. The equation to calculate showering electricity usage per litre was based on those provided by experts consulted (Strydom, 2019). This calculation considers the electricity required to heat a litre of water.
c. All members of a household shower at the same frequency and use the same amount of water per shower.
d. Households of all income groups need to satisfy the bathing or showering service, therefore it makes use of either both the bathing and showering services or of at least one of the services.
e. Showering services are unaffected by seasonal changes, in other words, the same amount of heated water for showering is required in summer as in winter.

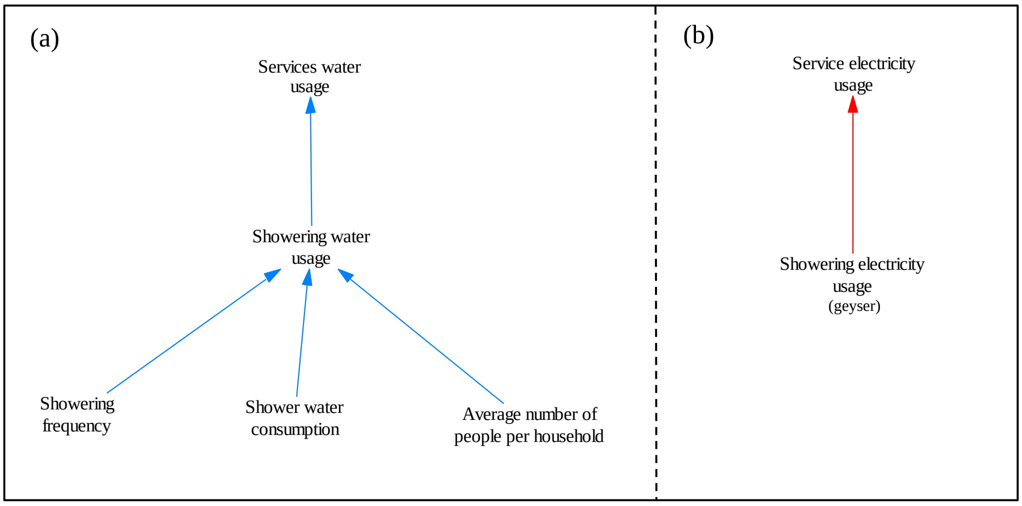

Figure 5.14: Showering service sub-model
Source: Author

The average initial values and parameters for the income groups used for the showering service sub-model are summarised in Table 5.6. The initial values and parameters used for each specific income group can be found in Appendix A: Initial values and parameters of household income groups for the EWNEX system dynamics model.

Table 5.6: Showering service sub-model parameters and initial values

Service	*Parameter*	*Initial value*	*Unit*
Showering	Showering frequency	11	Shower/person/week
	Showering water consumption	28	Litre/shower
	Average number of people per household	3	Person
	Showering electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre

Source: Author

5.4.7 Model testing and validation

When regarding the validation of mathematical models, Panjabi (1979) noted a basic dilemma in the process (Panjabi, 1979). The dilemma being that a model can only be validated in a number of known situations but the main intent of models are to predict unknown situation behaviours, therefore ‘no perfect validation is possible’ (Panjabi, 1979, p. 238). There has been criticism on system dynamics modelling validation processes due to its reliance on qualitative, informal and subjective validation procedures as there had not been established model validity and validation definitions (Barlas, 1996). But over the past 20 years more formal model validation processes have emerged, however Barlas (1996) still highlights the importance of the informal, non-technical and qualitative validity processes (Barlas, 1996).

Stellenbosch University https://scholar.sun.ac.za

When considering validation, Barlas (1996) classified two distict types of models; black-box and white-box models. Black-box models are data-driven and purely correlational, where there is no causality in the model structure where the model is considered valid if outputs are in line with 'real' outputs within a specified acuracy range (Barlas, 1996). White-box models on the other hand are therory like and causal descriptive which are articulations of how real systems actually operate (Barlas, 1996). Therefore simply generating outputs in a specified range of accurany is not sufficient and validity of the internal model structure is crucial (Barlas, 1996). Since white-box models represents the theory of real systems, it must therefore not only predict behaviour but also explain how the behaviour is generated as well (Barlas, 1996).

In order to develop confidence in this model, model testing and validation occurred continuously throughout the building phase. Functions built into Vensim software such as unit checks and model checks were used continually to validate that both the model and units were correct at all stages. A sensitivity analysis was also conducted to help build confidence in the model. To test and validate the model, its behaviour was compared to the knowledge of real systems and it was checked that its behaviour modelled that which is observed in the real world. For example, in the nexus sub-model, if the initial water requirement is set to 0 litre, water usage is set as 10 litre/month and water savings were set to 5 litre/month. The expected behaviour is that the usage and savings remain at the respective rates, but there will be an increase in the amount of required water, since the usage is greater than the savings. In this sense, a model can be categorised as a white-box or causal-descriptive model according to Barlas (1996). These types of reality behaviour checks were applied to every part of the model building process as validation occurs at every step of the modelling methodology (Barlas, 1996).

5.5 Summary

This chapter consisted of the first four steps of the system dynamics process. First, the problem of minimising linked electricity and water consumption needs was identified and articulated. Then the dynamic hypothesis of the articulated problem in the form of the causal loop was described. Five causal loops were described, two reinforcing loops – the hot-water usage loop (R1) and the water savings loop (R2), and three balancing loops – the electricity usage loop (B1), the electricity savings loop (B2) and the energy-water nexus loop (B3). From these causal loops that capture the dynamics of the articulated problem, the quantitative model was formulated. The model consisted of six sub-models:

- The cooking service electricity and water requirements sub-model
- The laundry service electricity and water requirements sub-model
- The dishwashing service electricity and water requirement sub-model
- The bathing service electricity and water requirement sub-model
- The showering service electricity and water requirement sub-model
- The nexus electricity and water requirement sub-model (which was informed by all of the previously mentioned sub-models)

The sub-models made use of subscripts in order to capture all service activities. In total, nine service activities were subscripted into the model. Model testing and validation was an iterative process throughout the model building process to gain confidence in the model. The next chapter presents the results from the simulated model and forms part of the last phase of the system dynamics process, which is policy analysis and evaluation.

Stellenbosch University https://scholar.sun.ac.za

Chapter 6 : Results and discussion

6.1 Introduction

The results from the simulated EWNEX system dynamics model are presented in this chapter. The results are based on the total energy and water requirements for a household, as well as the energy and water requirements for specific service-related activities. The developed model energy and water are limited to and expressly understood to be municipal electricity and municipal water respectively.

Results were simulated for the four identified household income groups: low-income, low-middle-income, high-middle-income and high-income (Table 4.2). A result that took the average variables of the four income groups identified for all the sub-models in Chapter 5 into account was simulated as well. The results were simulated over a period of 12 months. This did not necessarily depict a full calendar year from January to December in Cape Town, but an average overview over 12 months. It did not differentiate seasonal requirements of energy and water over that period but rather provided an average. Further results are presented for different possible scenarios that could affect the other income groups' household energy and water requirements.

The results presented for the baseline and scenarios of all the income groups were used to inform the last phase of the system dynamics process, policy and analysis by providing an indication of intervention points for energy and water savings in households. Based on the results and identified intervention points, policies relating to the maximisation of energy and water savings where they are linked in a household were recommended.

6.2 Baseline results of the energy-water urban nexus metabolism of Cape Town households

The articulated problem of minimising energy and water in a household where they are linked requires the investigation of how the household water requirement (HH hot-water requirement) can be reduced while reducing the households' energy requirement (HH electricity requirement). Figure 6.1 shows the general trend lines for the total energy and water requirements for an average household. From this, it can be seen that both energy and water use increased rapidly until such time as the electricity requirement remained constant and the water requirement decreased and remained constant as well.

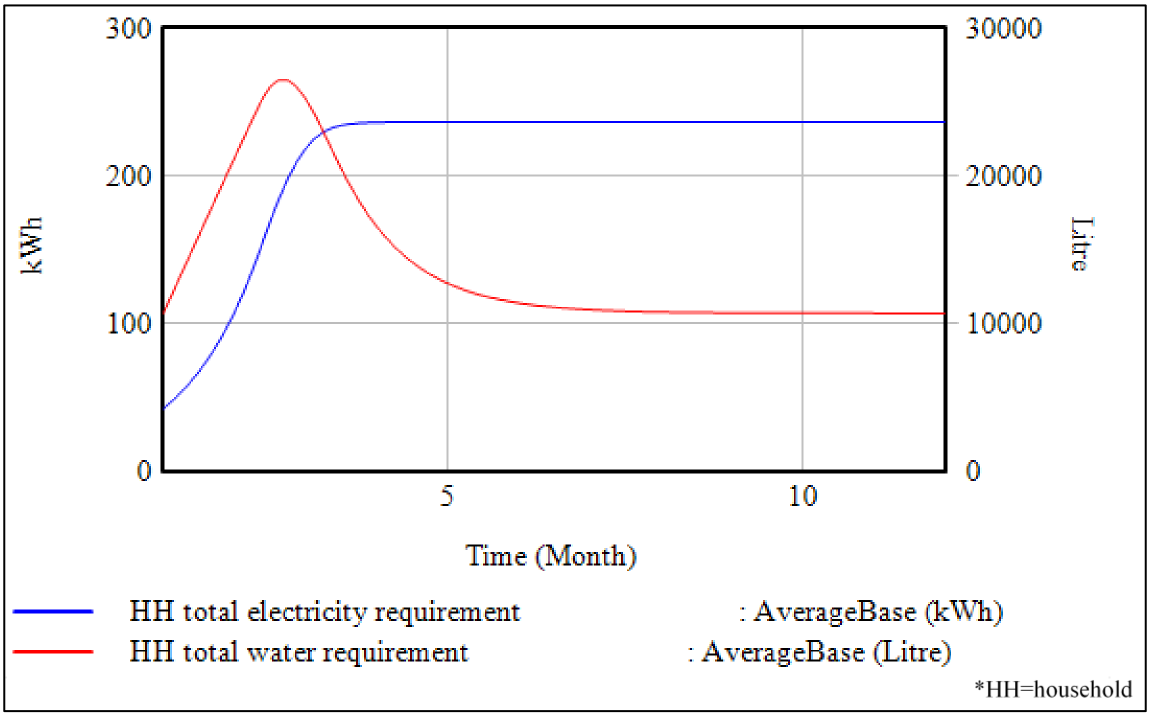

Figure 6.1: Total energy and total water requirements average base results
Source: Author

Both electricity and water requirements increased rapidly, since more electricity and water would have been used if more of the resource was required (as was illustrated in CLD's R2 and R1 Figure 5.4 and Figure 5.2 respectively). However, the electricity and water budgets also came into effect, which was why the electricity requirement became constant, and the water requirement decreased before becoming constant. More water would have been used as more was required, which was accounted for by the initial increase of water. As the water requirement increased, the electricity usage increased in order to heat that required water. This accounted for the initial increase of the electricity requirement as well. However, change occured once the electricity and water budget limit for water heating purposes was approached, since more electricity could not be used than that which had been budgeted for. As the gap between the required electricity and the electricity budgeted for water heating purposes increased, an exponential effect on the water savings came into effect, thus decreasing the water requirement (as was illustrated and described in CLD B1 in Figure 5.3). The water requirement then became constant, having reached the maximum water that can be heated by the required electricity.

Stellenbosch University https://scholar.sun.ac.za

These general energy and water requirement trends were seen in all the simulated household results, irrespective of income level, because the dynamics that govern the model were the same. The quantities varied for each income level, however, as those were reliant on the specific service activities that the household undertook. While these trends in Figure 6.1 were helpful in understanding the quantities of energy and water that a household required every month, they only accounted for the overall total requirements. To gain a better understanding of the flows in a household, the requirements of each service activity provided a better understanding of the exact requirements met. Due to the use of subscripts in the model, both the energy and water requirements for each service activity could be analysed.

Figure 6.2 shows the average household's water requirement for each service activity. From this, it can be seen that bathing and showering services accounted for the majority of the total water requirement respectively, which means that these services would prove to be high intervention points for water savings. Generally, the difference between bathing and showering is no more than 150 litres. However, there was a considerable difference between the water requirements for these two services and the next most intensive water-requiring activity, hand dishwashing, which on average required three times less water than showering per month. Following hand dishwashing, the laundry service activities accounted for less of the total water requirement, with top-loaded laundry accounting for the most water required per month, followed by front-loaded and subsequently hand-washed laundry.

The laundry service activities' water requirement results were interesting, since hand-washing was conducted at a higher frequency compared to the machine-dependant counterparts, but it required less water. The water requirement for the cooking service activities was less than for the laundry services. However, it should be noted that the water requirement for kettle over stovetop was higher. This shows that, based on the assumptions made for the model, for the cooking service, heated water is required more for drinking than for eating. The results could also show that other energy carriers such as gas, coal or wood, may be used to heat water for cooking.

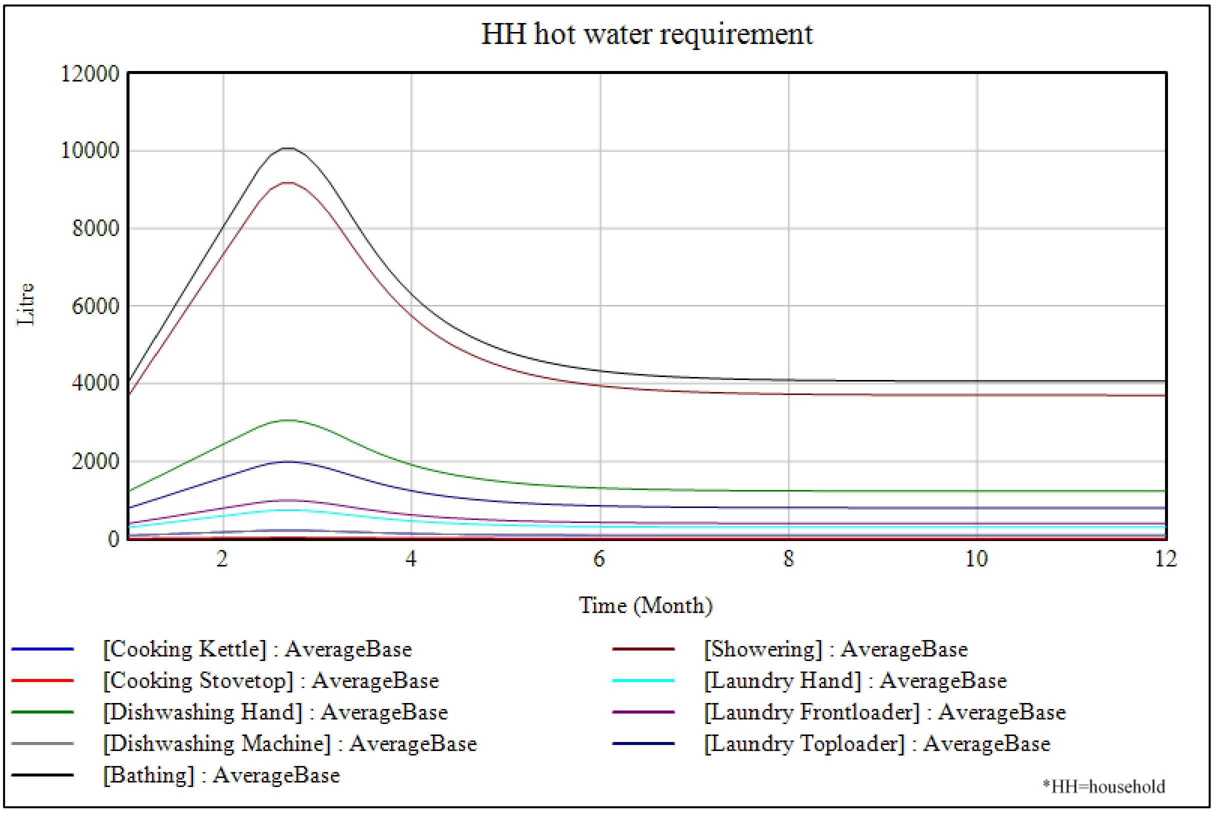

Figure 6.2: Service activities water requirements average base results
Source: Author

Figure 6.3, on the other hand, accounts for the average energy requirements of household service activities. As with the water requirements, the energy requirement results indicated that the bathing and showering service accounted for the principal amount of the total energy requirements. These energy requirement results indicated that these services would be high intervention points for energy savings. After that, the service activities that require the most energy after the showering service were top-loaded and front-loaded laundry respectively, followed by hand dishwashing. These results contradict the results of water requirements, where hand dishwashing required more water than the laundry activities. This indicates that there was not necessarily a direct correlation between energy and water requirements, and the way in which water was heated was important to understand when looking at the nexus of the resources. The means that water heating was more energy-intensive for machine laundry activities compared to hand dishwashing, which was dependent on a geyser. Similarly, kettle activities required more electricity compared to hand-washed laundry activities, even though hand-washed laundry had a water requirement that was more than three times that of the kettles in any given month. Therefore, the machine laundry activities and kettle cooking activity proved to be a high intervention point for energy savings.

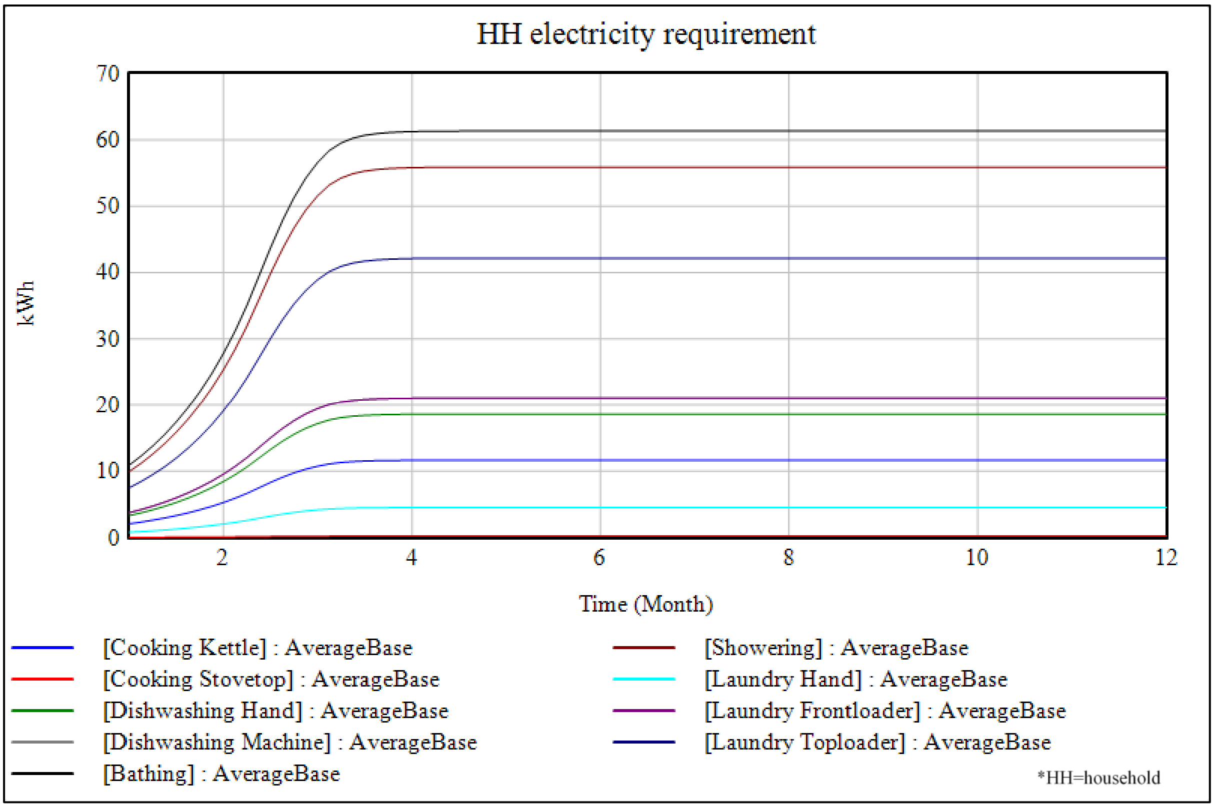

Figure 6.3: Service activities energy requirements average base results
Source: Author

From the results presented in Figure 6.2 and Figure 6.3, it is determined that the bathing and showering services respectively showed the most nexus in the energy-water urban nexus metabolism for an average household. These results indicate that these services proved to be the high intervention points towards minimising energy and water requirements and maximising energy and water savings in the average household.

The base results for the total household energy and water requirements for the different income groups and the averaged values are presented in Figure 6.4. From this, it can be noted that the high-middle-income households had the highest energy requirement. However, low-middle-income households had the largest water requirement. While high-middle-income households required the second-highest amount of water, low-middle-income households required the second-lowest energy requirement of the four income groups. This revelation is interesting as it suggests that total energy requirements and total water requirements for energy-water urban nexus metabolism services are not necessarily directly proportional. Therefore, further investigation is needed to understand how these services are carried out in their service activities and the energy and water they require. After the high-middle-income group, the high-income group had the second-largest energy requirement. However, the high-income group only had the third-largest water requirement after the high-middle-income group. The low-income group had the lowest total energy and water requirements out of all four income groups.

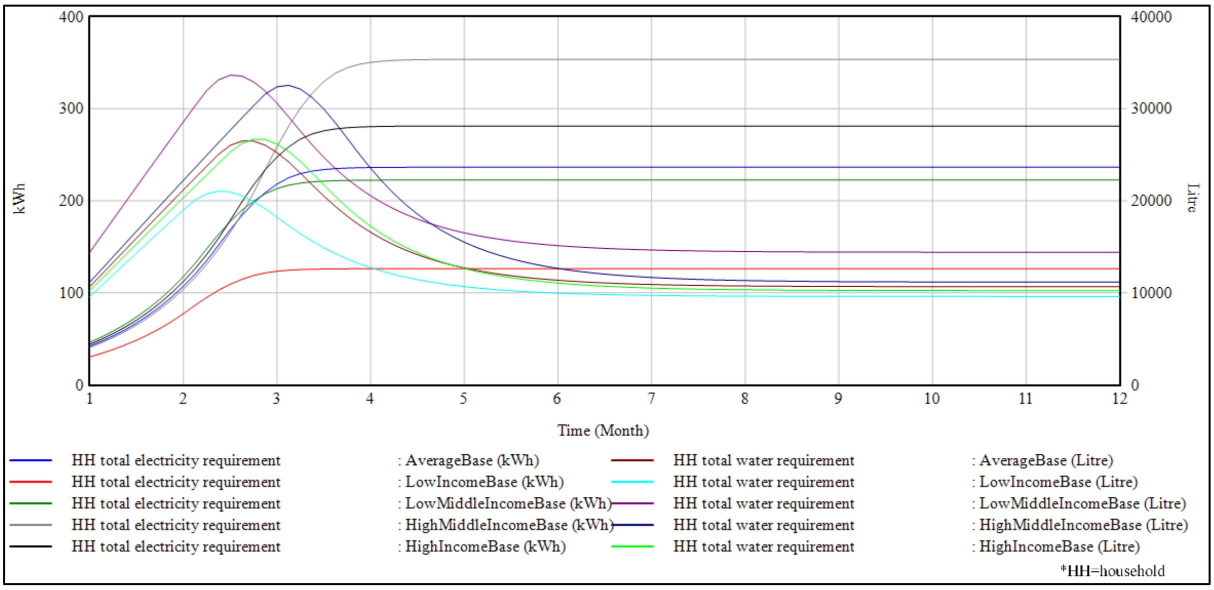

Figure 6.4: Total energy and water requirements for different household income groups
Source: Author

The total requirements in Figure 6.4 provide an understanding of the energy and water quantities required every month over a year for the different income levels. Looking at the energy and water requirements of each service activity conducted in a household may provide a better understanding as to what governs the total requirements for each income group. These are presented and examined individually for each income group in the sections below.

6.2.1 Low-income household energy-water urban nexus metabolism base results

The water requirement for the different service activities utilised by low-income households is shown in Figure 6.5. This figure indicates that the bathing service had the predominant water requirement for low-income households, using more than half the total water requirements. Therefore, the bathing services were a high-leverage intervention point for maximising water saving. Hand dishwashing accounted for the second-largest water requirement for low-income households, followed by showering. These service activities would also prove to be beneficial intervention points when it came to water savings. When compared to other income groups, hand dishwashing's water requirements appeared significantly larger. In contrast, the proportion of water required for hand dishwashing for low-income households was larger. The actual quantity of water required for the service activity was only slightly greater than the other income groups. This reveals that for low-income households, interventions for hand dishwashing would have more impact compared to the other income groups. On average, low-income households did not make use of machine dishwashing to complete the dishwashing service. The literature suggests that dishwashing machines are generally considered to be luxury comfort items.

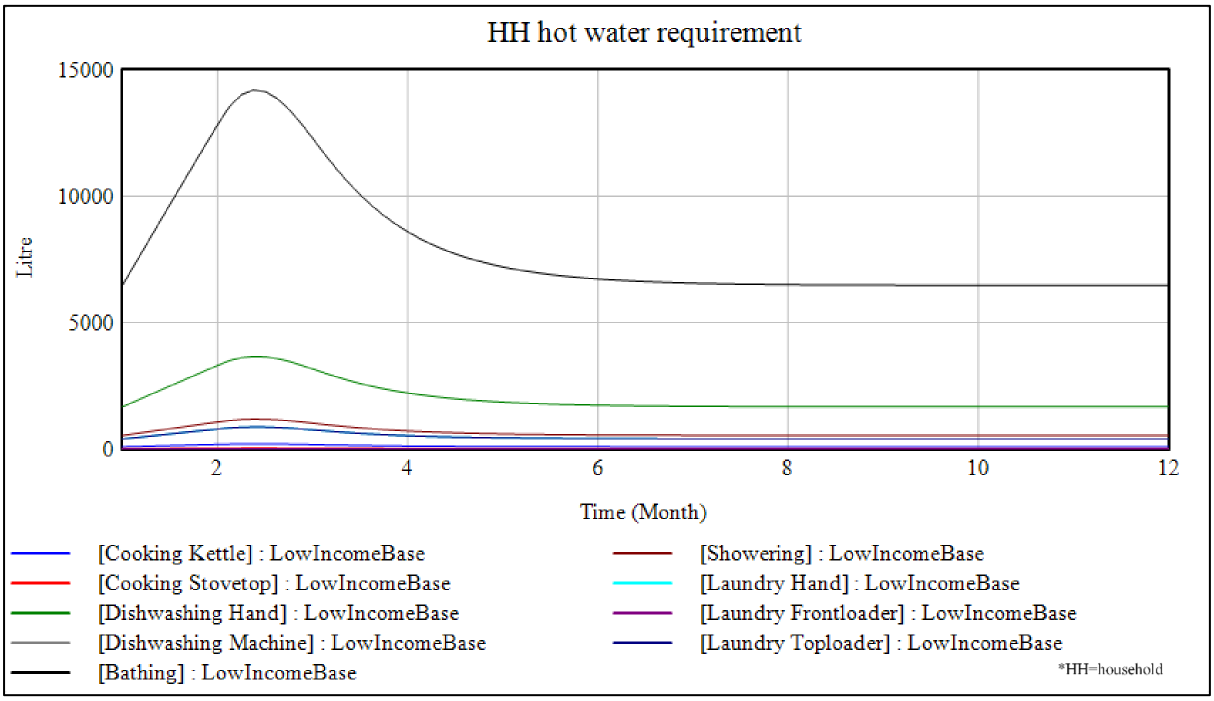

Figure 6.5: Low-income household activities hot-water requirements
Source: Author

With regard to the laundry service, low-income households on average did not utilise a front-loaded washing machine, but interestingly preferred to hand-wash laundry. Top-loaded laundry had the same water requirements for low-income households, even though the frequency at which the activities happened varied. Hand-washed laundry was done on average four times a week, and a top-loaded washing machine was utilised only once a week. This goes against the perception that hand-washing laundry uses less water, as it proves that it is dependent on the frequency that the activity happens.

The cooking service accounted for the lowest water requirement for low-income households. However, the use of a kettle required just less than five times the amount of water needed for stovetop cooking. The reason for this may be because the heated water requirement was underrepresented, since only preheated water used for cooking was considered and not water heated during the cooking process itself.

Stellenbosch University https://scholar.sun.ac.za

Figure 6.6 depicts the energy requirements for the service activities utilised by low-income households.

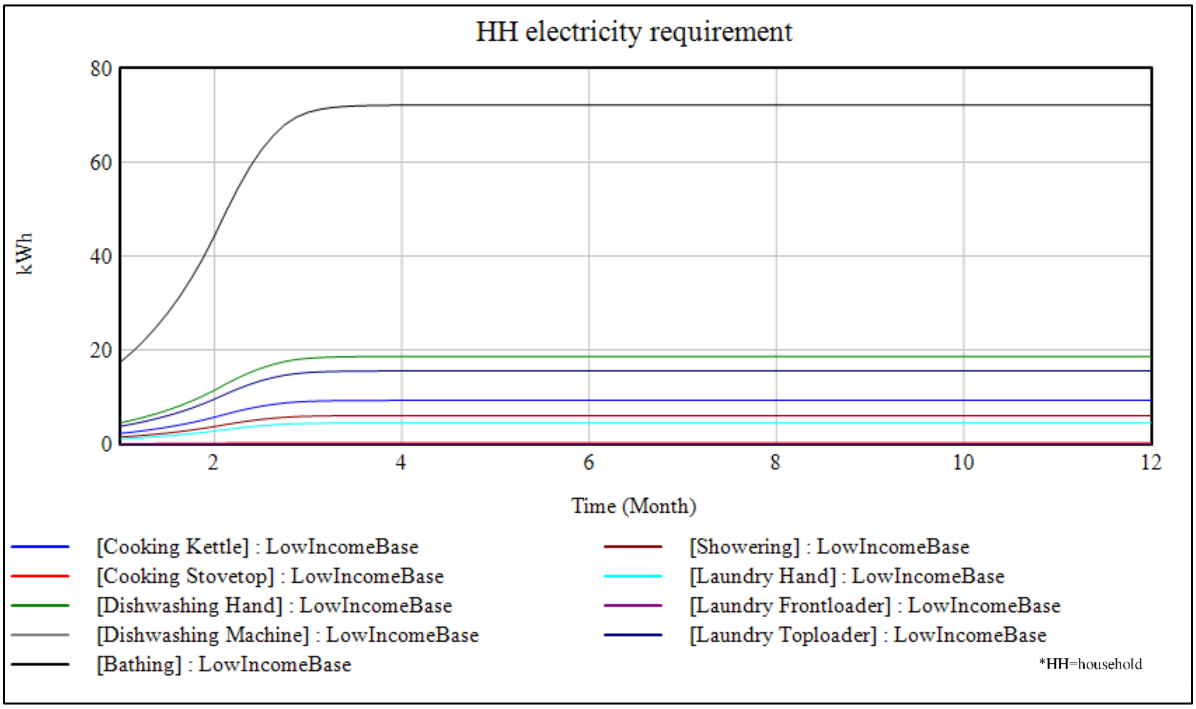

Figure 6.6: Low-income household activities' energy requirements
Source: Author

The bathing services required the highest amount of energy for low-income households, accounting for just under half the household's total energy requirements. This high requirement to satisfy the bathing service was consistent with the service's high water requirement. Following the trend of water requirements, hand dishwashing accounted for the second-highest energy requirement. However, apart from that, there proved to be no correlation between water requirement and energy requirement, since the service activity that required the next highest energy was top-loaded laundry, followed by using a kettle and then only the showering service, which accounted for the third-highest water requirement. Interestingly, although top-loaded laundry and hand-washed laundry had the same water requirements, the hand-washed laundry energy requirements were just over three times less than those for the top-loaded laundry. This indicates that an intervention point for energy (energy savings) can be found in the laundry service, depending on the activity utilised to satisfy the service.

In order to achieve a more sustainable energy and water system in their nexus, the intervention points for the low-income household group proved to be the highest for the bathing service. When both energy and water requirements were considered, it became apparent that the most feasible intervention point for the low-income household group would be bathing. The bathing service accounted for both the highest energy and water requirements for the household. Therefore, interventions would be maximised in their nexus for this service. Interventions regarding bathing frequency would reduce overall household energy and water requirements considerably. Interventions regarding water consumption per bath would also prove beneficial.

6.2.2 Low-middle-income household energy-water urban nexus metabolism base results

The water requirement for the different service activities utilised by low-middle-income households is shown in Figure 6.7. As with the low-income water requirements, the low-middle-income households' highest water requirement was accounted for by the bathing service. However, low-middle-income households on average required 1,5 times more water to satisfy their bathing service, compared to low-income households. The showering service accounted for the second-highest water requirement of low-middle-income houses. These results indicate that a large proportion of heated water was used for personal hygiene purposes for low-middle-income households. Therefore, the bathing and showering services that satisfied this need can be considered high-leverage intervention points for water saving in low-middle-income households.

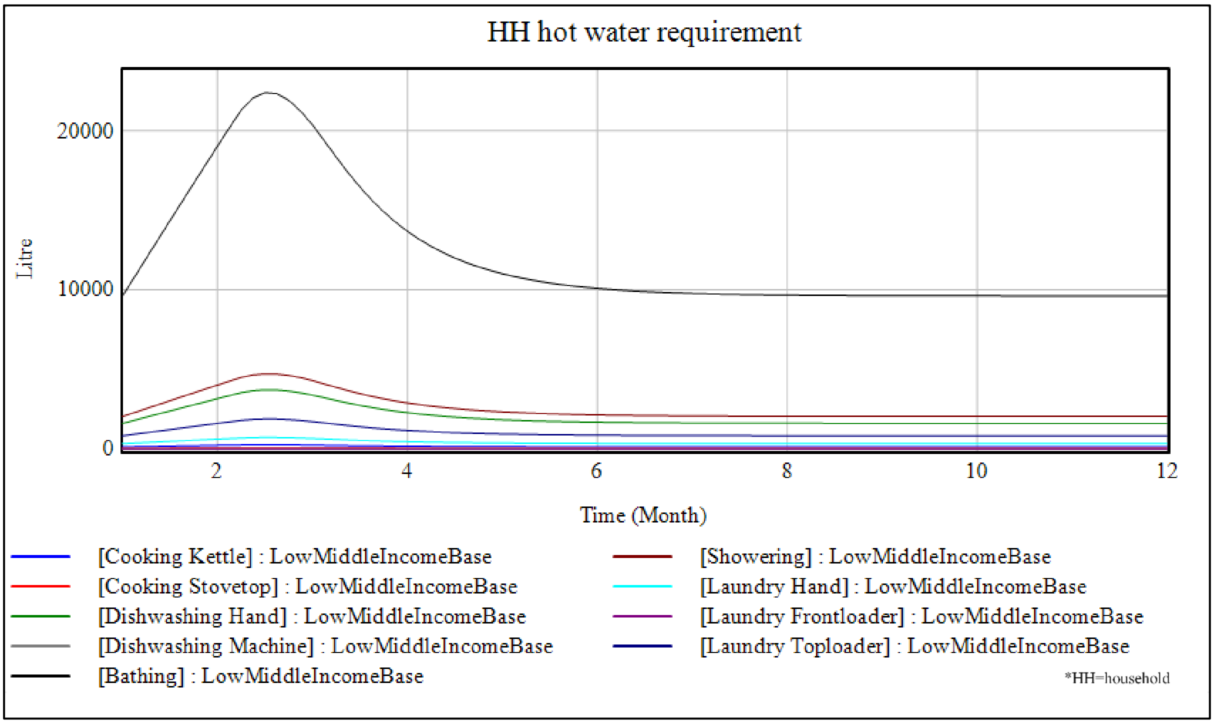

Figure 6.7: Low-middle income household activities hot-water requirements
Source: Author

Stellenbosch University https://scholar.sun.ac.za

Hand dishwashing accounted for the third-highest water requirement for low-middle-income households, followed by top-loaded laundry. Similar to the low-income households, low-middle-income households did not make use of dishwashing machines and front-loaded laundry. This could be due the former being considered a luxury item and that other forms of laundry activities satisfied the service.

To fulfil the laundry service, low-middle-income households utilised top-loaded washing machines and hand-washed their laundry. Households may carry out both or either of these laundry service activities. However, the average for low-middle-income households used for the model simulation indicates that of the two, the top loader had a much higher water requirement in order to satisfy the need compared to the water required for hand-washing laundry. Even though the household on average hand-washed laundry three times a week, the water requirement was still less compared to the water requirement from utilising a top-loaded washing machine twice a week. Lastly, the cooking service accounted for the lowest water requirement for low-middle-income households. However, the use of a kettle required more than six times the amount of water needed for stovetop cooking.

The results for the energy requirements for the service activities utilised by low-middle-income households are shown in Figure 6.8. From this, the service that required the highest water was bathing. Therefore, as with the low-middle-income households' high-leverage water savings intervention, another high-leverage energy-saving intervention point would be the bathing service. While showering had the second-highest water requirement, it only had the third-highest energy requirement, with top-loaded laundry requiring more energy, even though the activity required less water. Following showering energy requirements, the next highest energy requirement was accounted for by hand dishwashing, then kettle use, and lastly hand-washed laundry. The fact that kettle use had a larger energy requirement than hand-washed laundry is interesting to note, since the latter required almost three times as much water compared to using the kettle. It proves that more energy was required to heat water by using a kettle, compared to water heated by using an electric geyser. However, this could be accounted for by the fact that water heated in a kettle was typically heated to boiling point, whereas water from an electric geyser used in hand-washed laundry was typically only heated to a maximum of 65 ºC.

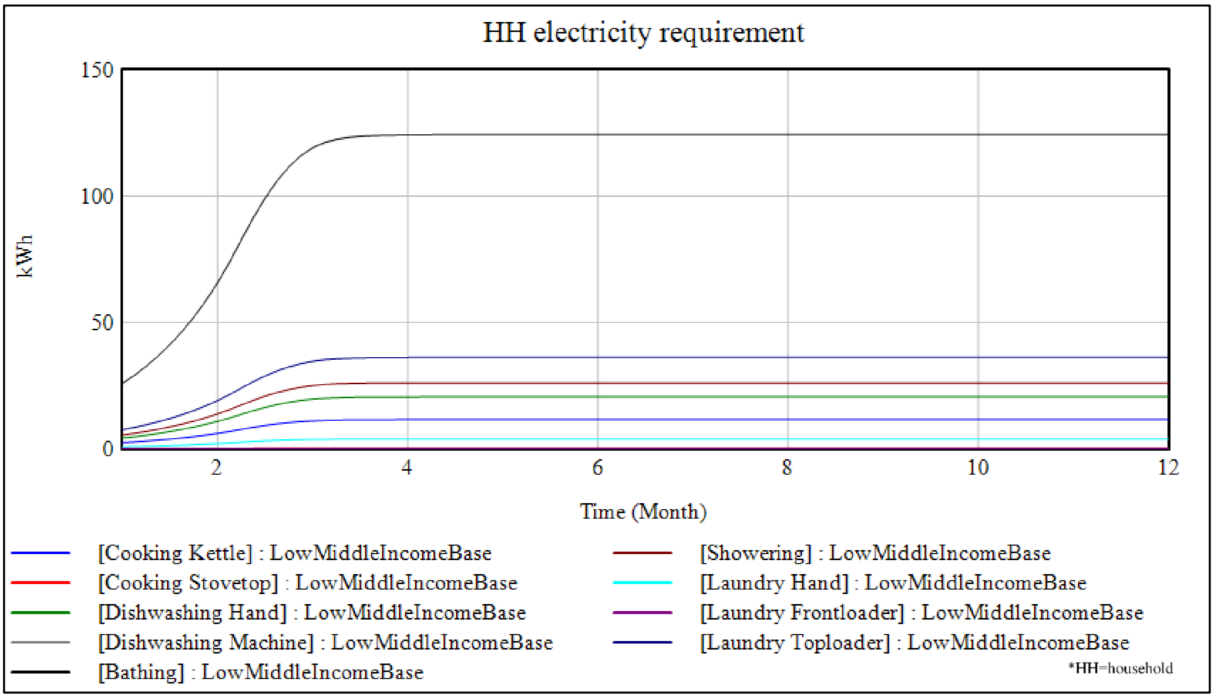

Figure 6.8: Low-middle-income household activities energy requirements
Source: Author

Taking the energy and water requirements of every service activity for low-middle-income households to achieve a more sustainable energy and water system in their nexus into account, the high-leverage intervention point for the low-middle-income households proved to be the highest for the bathing service. This was because the bathing service accounted for both the highest water requirement and energy requirement. Therefore, in order to save energy and water in their nexus, intervention with regard to bathing would prove to be the most feasible. Furthermore, the showering service also proved to be a beneficial intervention point, since the service had the second- and third-highest water and energy requirement respectively. Intervention for the showering service, such as reducing the quantity of water consumed per shower, could prove valuable towards creating more sustainable energy and water systems in their nexus, but interventions with regard to the bathing service may prove to have more impact.

6.2.3 High-middle-income household energy-water urban nexus metabolism base results

As was previously mentioned, the high-middle-income households require the most energy and second most water in total when compared to the other household income groups. Therefore, attention should be paid to interventions that would allow maximum savings for energy and water requirements in high-middle-income households.

The water requirement for the different service activities utilised by high-middle-income households is shown in Figure 6.9. From this, it is clear that unlike the two sets of household water requirements previously discussed, the service that accounts for the highest proportion of the high-middle-income household's total water requirement is the showering service. Therefore, a high-leverage intervention point towards maximising water savings in high-middle-income households revolves around the showering service.

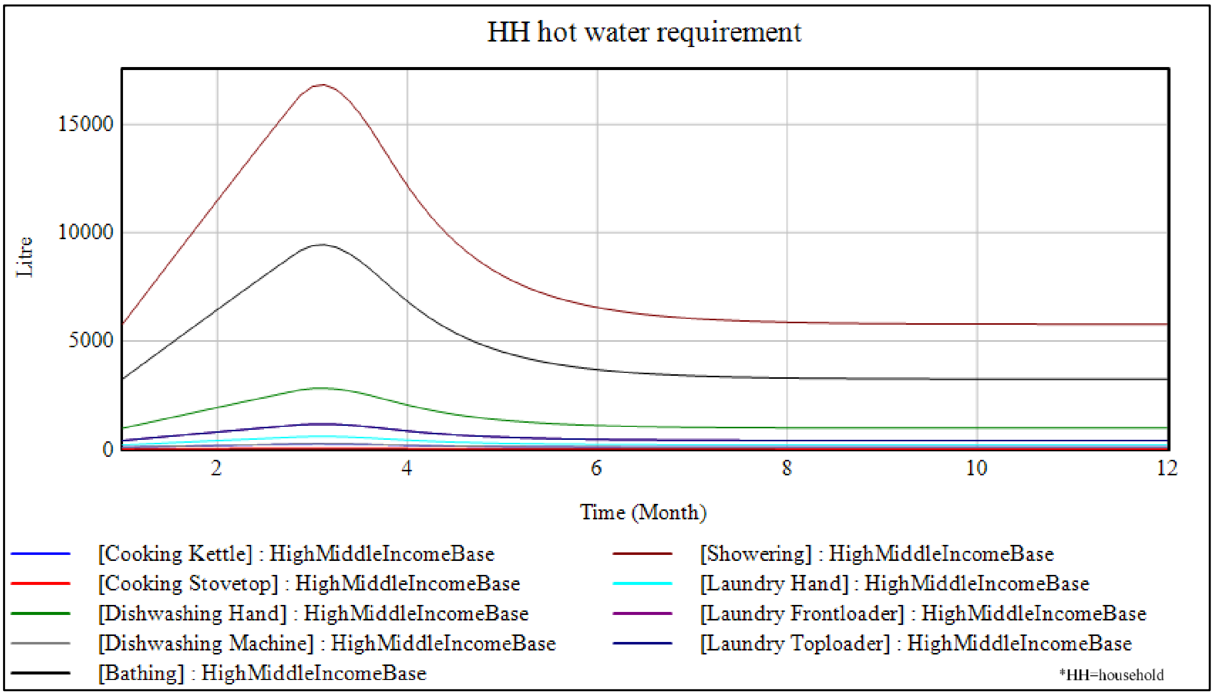

Figure 6.9: High-middle-income household activities hot-water requirements
Source: Author

The service that required the second-highest amount of water in high-middle-income households was the bathing service. Like with the low-middle-income group, this indicates that the services revolving around personal hygiene would be beneficial intervention points for water savings for the high-middle-income households too.

Hand dishwashing accounted for the third-highest water requirement in high-middle-income households, contributing to just over 8% of the household's total water requirements. With regard to the laundry service, high-middle-income households on average utilised all types of activities to satisfy the service. This could be due to higher access to the services, compared to lower-income households. Top-loaded and front-loaded machine laundry both accounted for over 3% of the household's total water requirements, followed by hand-washed laundry, which

Stellenbosch University https://scholar.sun.ac.za

contributed just over 1%. Interventions for any of these laundry service activities would therefore not prove significant for water savings.

Following the water requirement for hand-washed laundry was the water required on average for a dishwashing machine that high-middle-income households used. High-middle-income households utilising a dishwasher, whereas lower-income households did not, reinforce what the literature suggests, namely that dishwashers are considered more to be comfort items, and only those who have access and can afford them will utilise them.

The kettle use water requirement was almost the same as the required water for the machine dishwashing activity for high-middle-income households, with stovetop cooking requiring a minuscule amount of water. This indicates that for high-middle-income households, the cooking service has the least potential for water-saving interventions.

The energy requirements for the service activities for high-middle-income households are shown in Figure 6.10. Showering was the service that accounted for most of the total energy requirements for high-middle-income households, followed by bathing. Since these services accounted for the majority of the total water requirements in this income group, it can be determined that both are intervention points for maximising energy and water savings in their nexus. However, for high-middle-income households, showering accounted for 38% of the household's total energy requirement, whereas bathing accounted for 21%. Therefore, between the two, for high-middle-income households showering showed a greater energy-water nexus compared to low-middle-income households, where bathing showed a greater nexus than showering.

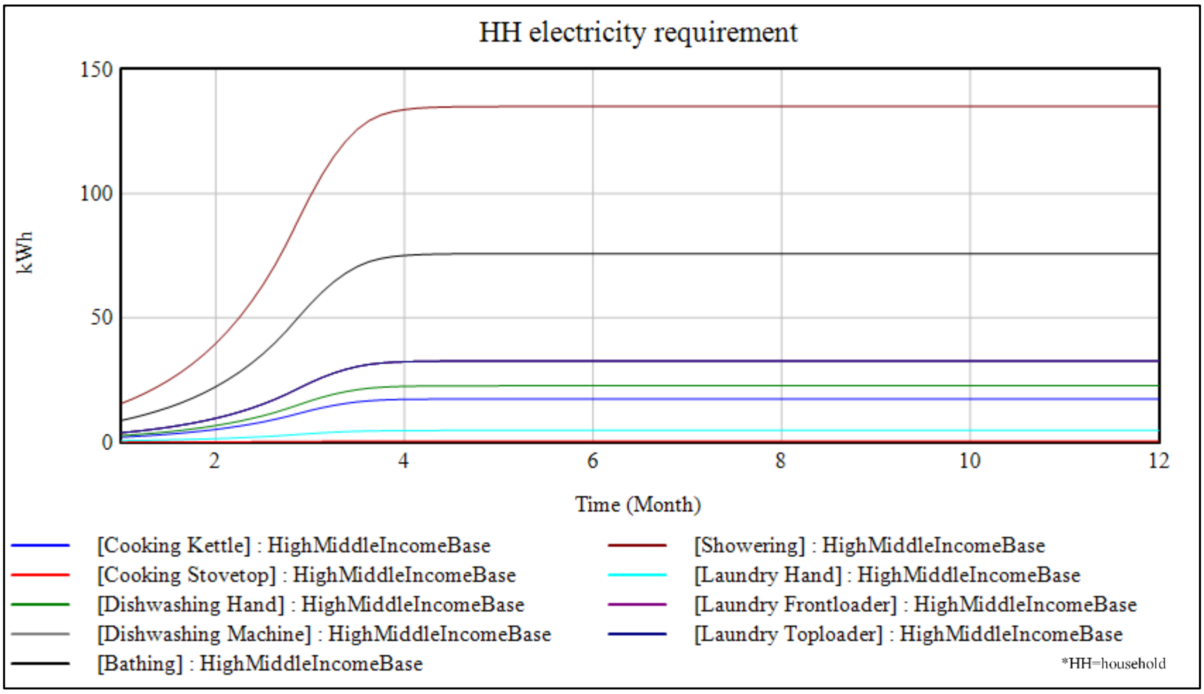

Figure 6.10: High-middle-income household activities energy requirements
Source: Author

The energy requirements for machine dishwashing front-loaded laundry and top-loaded laundry were all the same, accounting for just over 9% of the total energy requirement for the household. Interestingly, although the two laundry service activities had the same water requirements, the machine dishwashing activity had a significantly lower water requirement compared to the laundry activities. While these activities serve different services, it indicates that machine dishwashers require more energy to heat less water when compared to top-loaded and front-loaded washing machines. While it could be due to different temperatures water is heated to for the respective activities, this does provide some indication that interventions surrounding machine dishwashing may be found to be more beneficial for energy savings than for water savings in their nexus. This is demonstrated similarly for the use of a kettle, where the water requirement for the kettle activity was less than the requirement for hand dishwashing. However, the energy requirement to heat the lower required water was greater than the energy required to heat the water utilised for hand dishwashing. The temperature at which the water was utilised in the different service activities differ and may not be the best representative comparison.

6.2.4 High-income household energy-water urban nexus metabolism base results

The water requirement for the different service activities utilised by high-income households is shown in Figure 6.11. Similar to the service activities water requirements of high-middle-income households, the service that accounted for the highest water requirement for high-income households was showering. However, the proportion that showering contributed towards the total water requirement was significantly larger than for high-middle-income households. While the showering service accounted for just over half of the total water requirement in high-middle-income households, in high-income households, over 71% of the total water requirement was accounted for by showering. These results indicate that interventions for the showering service will have a significant impact on water savings.

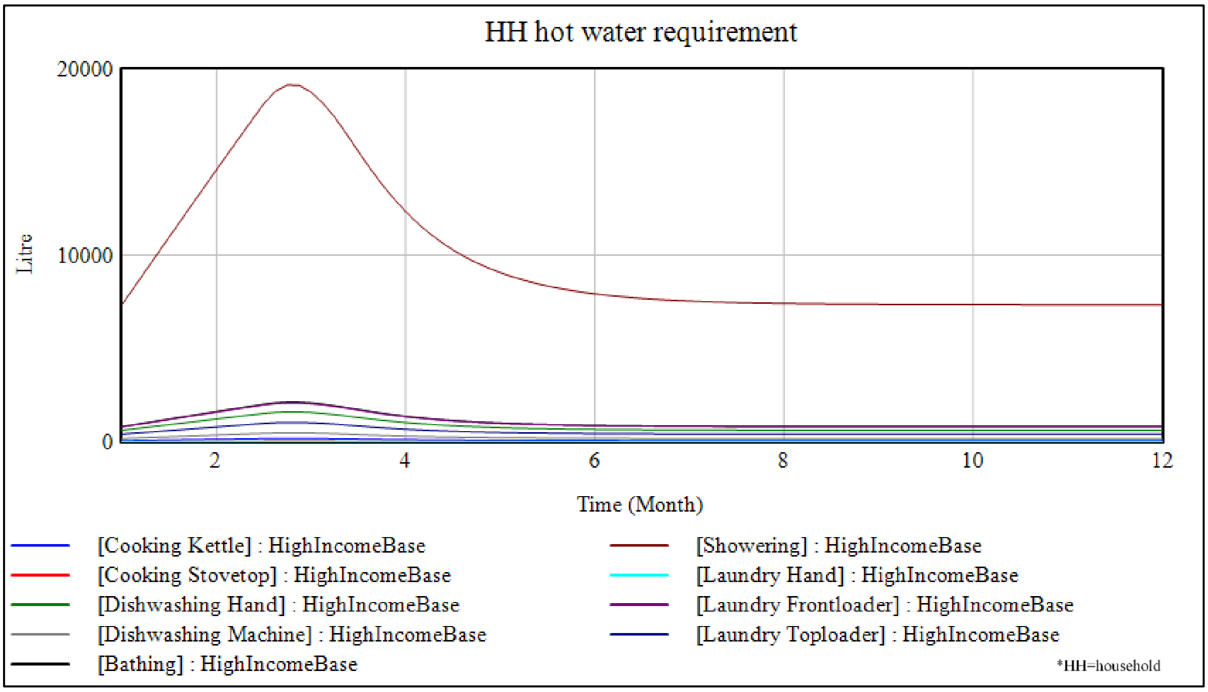

Figure 6.11: High-income household activities hot-water requirements
Source: Author

The rest of the service activities therefore collectively accounted for less than 30% of the total water requirement for high-income households. The bathing service had the next highest water requirement after showering. Even though the bathing service did not contribute as much towards the total water requirement, it is interesting to note that it accounted for the second-highest water requirement. The reason for this was that, aside from low-income households, the other household groups – low-middle-income and high-middle-income households' services that accounted for the two highest water requirements were showering and bathing. This suggests a strong link between the water requirement of linked energy-water nexus heated water and personal hygiene. This does not suggest that this does not stand for low-income households as well, as bathing was the dominant water requirement. However, it does show that for low-income households there was a stronger affinity towards bathing than towards

Stellenbosch University https://scholar.sun.ac.za

showering. In contrast, in high-income households, there was a stronger affinity towards showering.

After showering, in descending water requirement order, followed front-loaded laundry, hand dishwashing, top-loaded laundry, machine dishwashing, kettle use and, lastly, stovetop cooking. For high-income households, hand-washing laundry was on average not utilised.

The energy requirements for the different service activities utilised by high-income households are shown in Figure 6.12. As was expected, the showering service accounted for most of the total energy requirement. Therefore it would also prove beneficial for energy savings if interventions with respect to the service were implemented. Interestingly, while the water requirement of showering accounted for more than 71% of the total need, the energy requirement for showering was just under 45% of the total energy requirement of high-income households. This proves that water and energy requirements do not necessarily have a direct correlation.

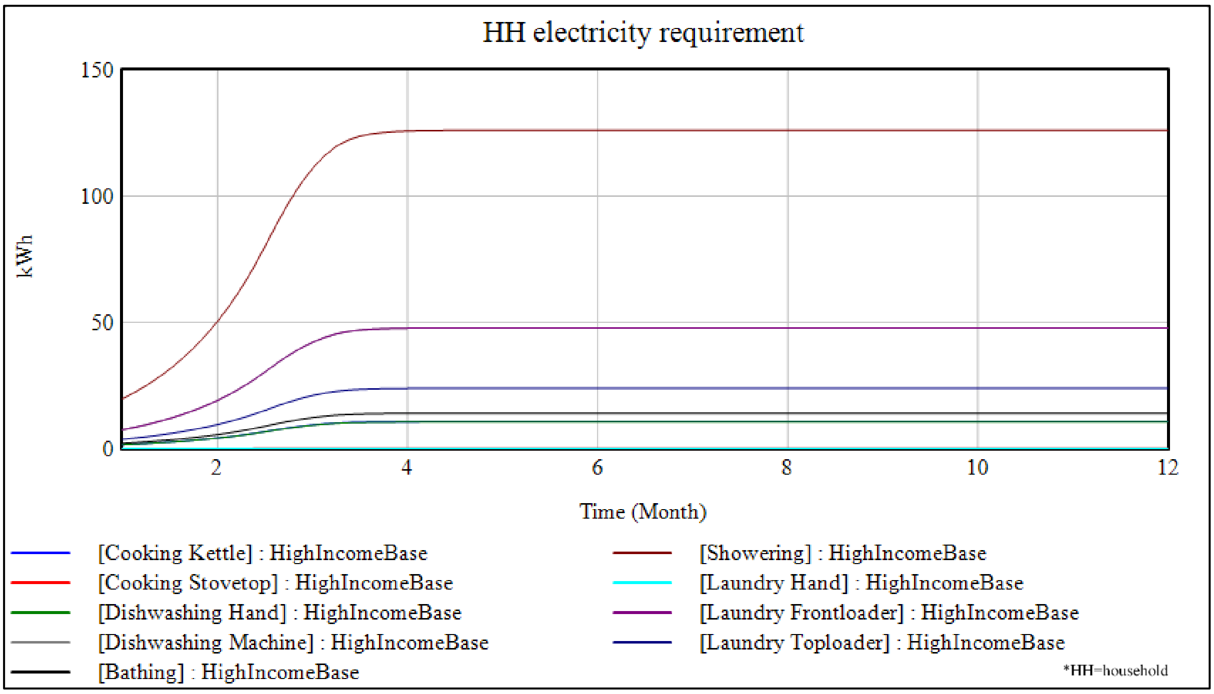

Figure 6.12: High-income household activities energy requirements
Source: Author

The service activities that accounted for the second-highest energy requirement were front-loaded laundry and machine dishwashing. What is interesting is that machine dishwashing

Stellenbosch University https://scholar.sun.ac.za

accounted for the third-lowest water requirement but the second-highest energy requirement. At the same time, hand dishwashing accounted for the third-highest water requirement but contributed the second-least towards the total energy requirement. This indicates that interventions for hand dishwashing will prove more beneficial towards water savings, whereas interventions for machine dishwashing will prove more beneficial towards energy saving. After front-loaded and machine dishwashing, in descending energy requirement order, followed top-loaded laundry, bathing, kettle use, then hand dishwashing, and finally stovetop cooking.

Based on these results, the showering service for high-income households proved to be a high-leverage intervention point towards energy and water-saving in their nexus. The service also proved to be higher in the nexus compared to the other service activities utilised by high-income households.

Lastly, when compared to the other household income groups, high-income households contributed the second-highest energy requirement, but had the second-lowest water requirement. This indicates that high-income households are more energy-intensive than water-intensive.

6.3 Scenario testing

Three scenario tests based on the household energy-water nexus requirements were conducted. The first scenario, 3'sACrowd, tested the influence of household size on household water and energy requirements. The second scenario, WiseOrWaste, tested the effect of a reduced allocated water budget for water heating purposes on energy and water requirements. The final scenario, PowerPlay, tested the effect of reducing the allocated electricity budget for water heating purposes on energy and water requirements.

The changes of variables for each of the outlined scenarios are tabulated in Table 6.1.

Stellenbosch University https://scholar.sun.ac.za

Table 6.1: Scenario variables

Scenario / *Parameter*		*Base*	*3'sACrowd*	*WiseOrWaste*	*PowerPlay*
Household size (person)	Low-income	3	*4*	3	3
	Low-middle-income	3	*4*	3	3
% of water budget for heated water services (%)	Low-income	26	26	*13*	26
	Low-middle-income	16,3	16,3	*8,15*	16,3
	High-middle-income	20,2	20,2	*10,1*	20,2
	High-income	20,8	20,8	*10,4*	20,8
% of electricity budget for water heating purposes (%)	Low-income	19	19	19	*8,5*
	Low-middle-income	27	27	27	*13,5*
	High-middle-income	36	36	36	*18*
	High-income	31	31	31	*15,5*

Source: Author

6.3.1 Realistic household (3'sACrowd scenario)

StatsSA (2019) reported that the average household size in the Western Cape is three people per household. uMAMA data on household size was not complete, so this seemed in line for high-middle and high-income groups (Strydom, 2019). However, households in a Global South context typically have more than this number. The limited uMAMA data on household size indicated that for low-income and low-middle-income groups the average household sizes are four people per household. Figure 6.13 and Figure 6.14 show the effect of this increase on the total energy and water requirements of low-income and low-middle-income groups respectively. In both figures it can be seen for the respective income groups that the total water requirement increased in the 3'sACrowd scenario. However, a significant change for the total energy cannot be noted. This conclusion reinforces the notion that the water requirement is dependent on the energy available. The curve trend of the water requirement for both income groups of the base and scenario test is the same, showing that the energy requirement limits the water requirement in both cases.

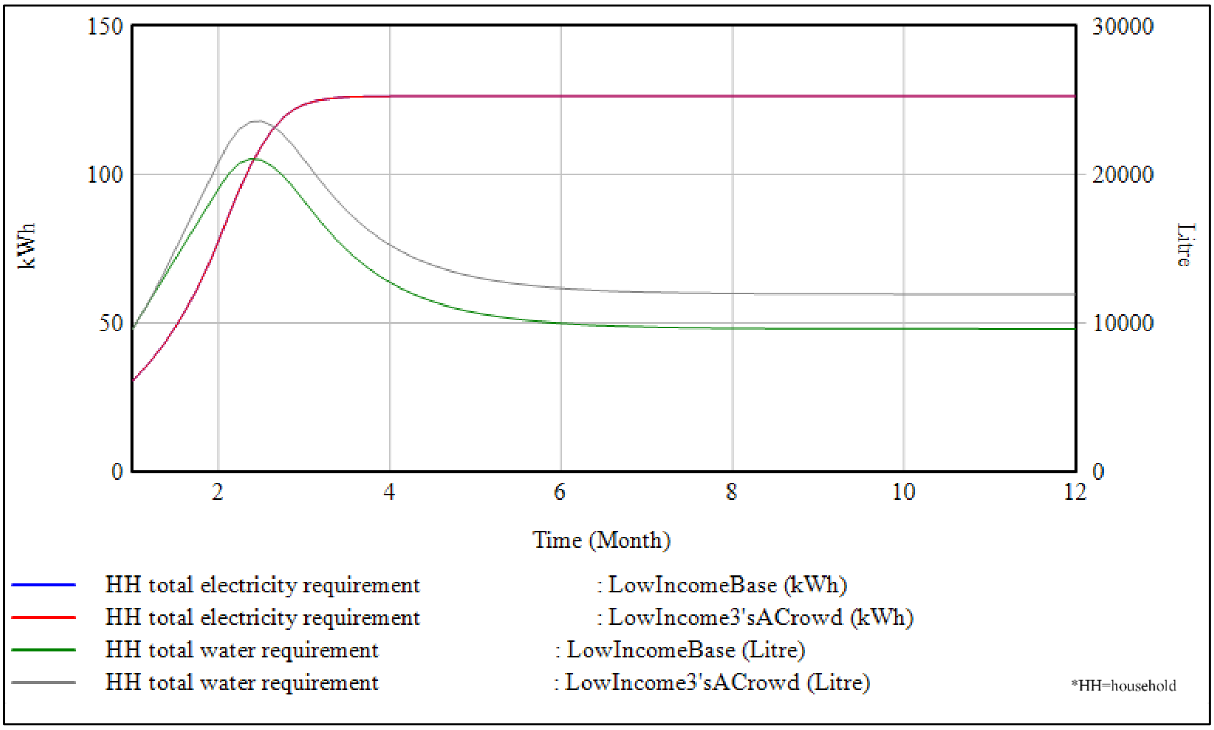

Figure 6.13: Low-income household 3'sACrowd scenario
Source: Author

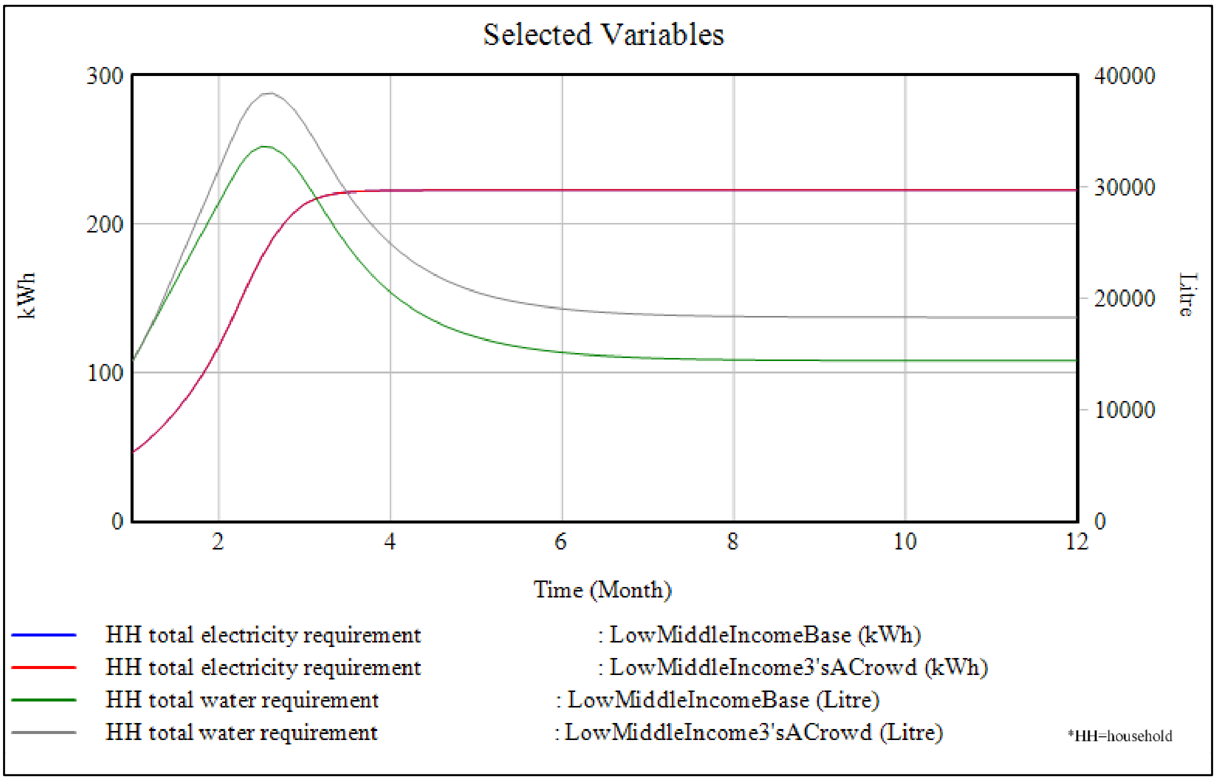

Figure 6.14: Low-middle-income household 3'sACrowd scenario
Source: Author

6.3.2 Decreased water budget allocation (WiseORWaste scenario)

Where water conservation is concerned, the term 'water-wise' is often used in association with beneficial and sustainable water-saving practices. The WiseOrWaste scenario looks into the effect of decreasing a household's water budget on the total energy and water requirements by half. This could happen because of, for example, increased water restrictions. This means that the allocated water budget for the low-income household group decreased from 26% to 13%. The WiseOrWaste results and base result are shown in Figure 6.15. For the low-middle-income household group, the allocated water budget decreased from 16,3% to 8,15%, with the results shown in Figure 6.16. The allocated water budget for the high-middle-income household group decreased from 20,2% to 10,1% – see the results in Figure 6.17. Lastly, the results for the base and the WiseORWaste scenario results for the high-income household group are shown in Figure 6.18. Their allocated water budget decreased from 20,8% to 10,4%.

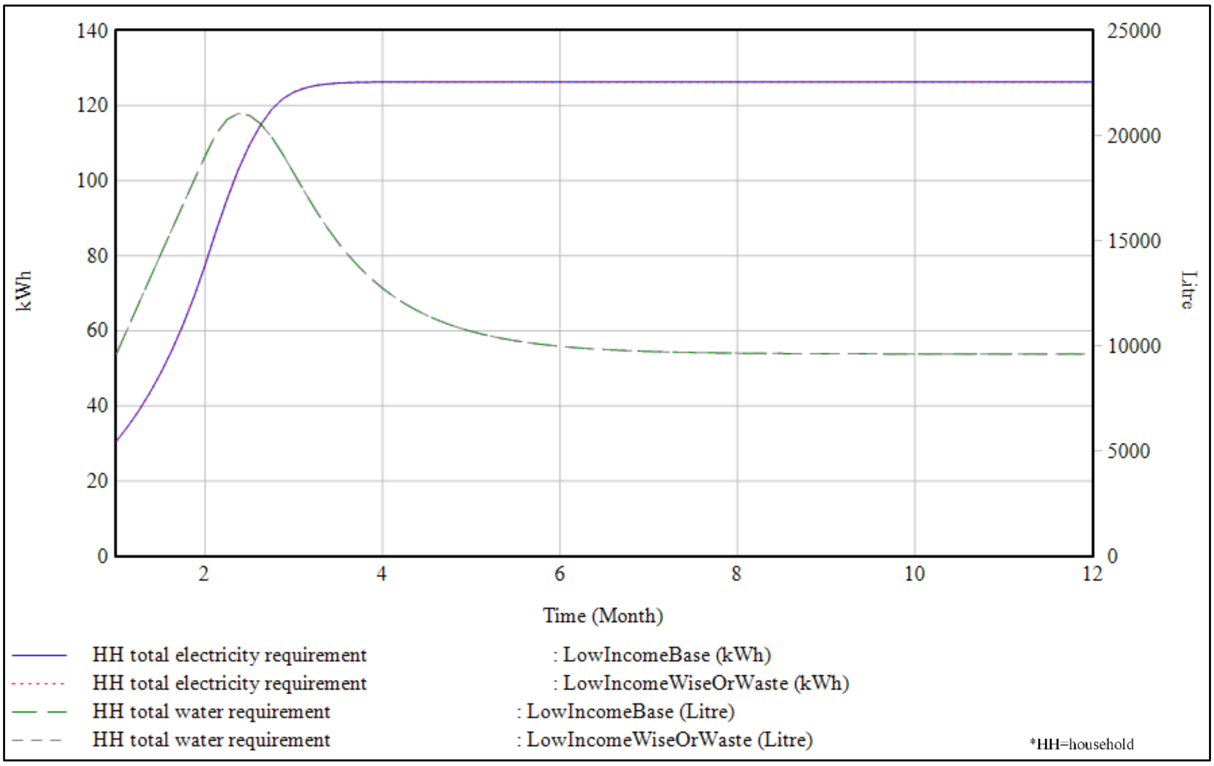

Figure 6.15: Low-income household WiseORWaste scenario
Source: Author

Stellenbosch University https://scholar.sun.ac.za

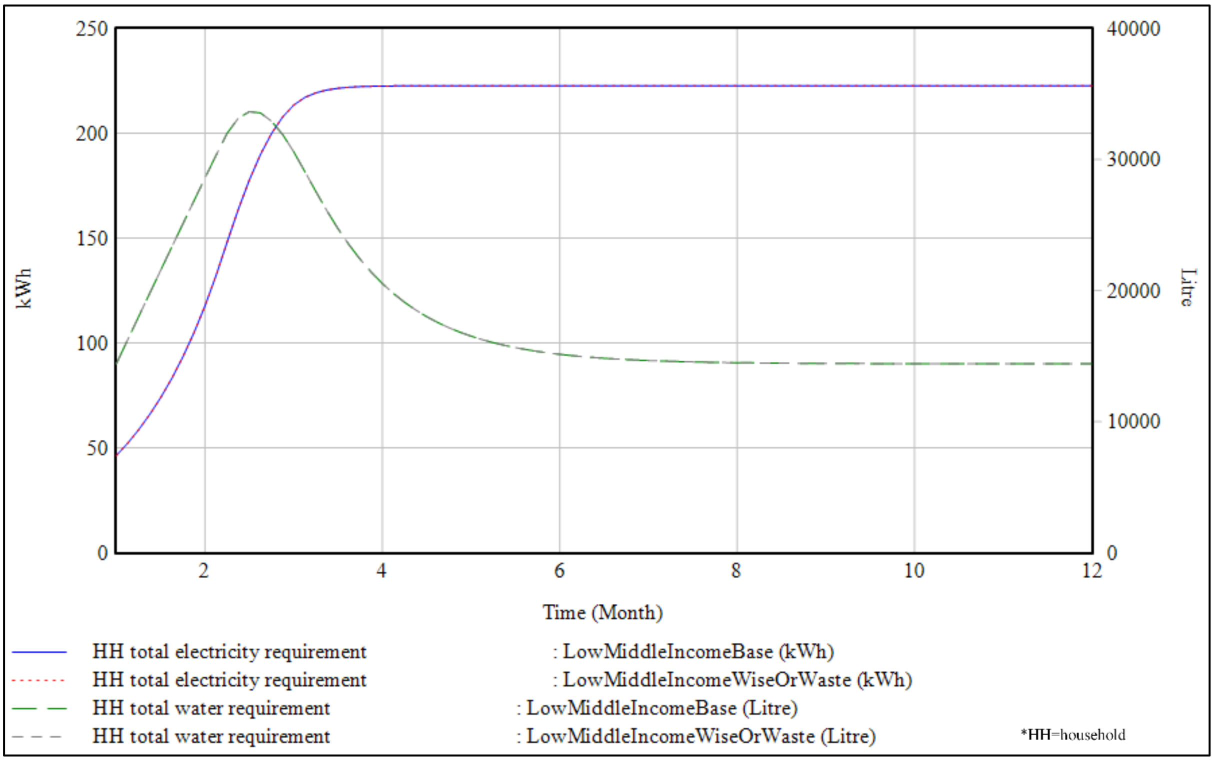

Figure 6.16: Low-middle-income household WiseORWaste scenario
Source: Author

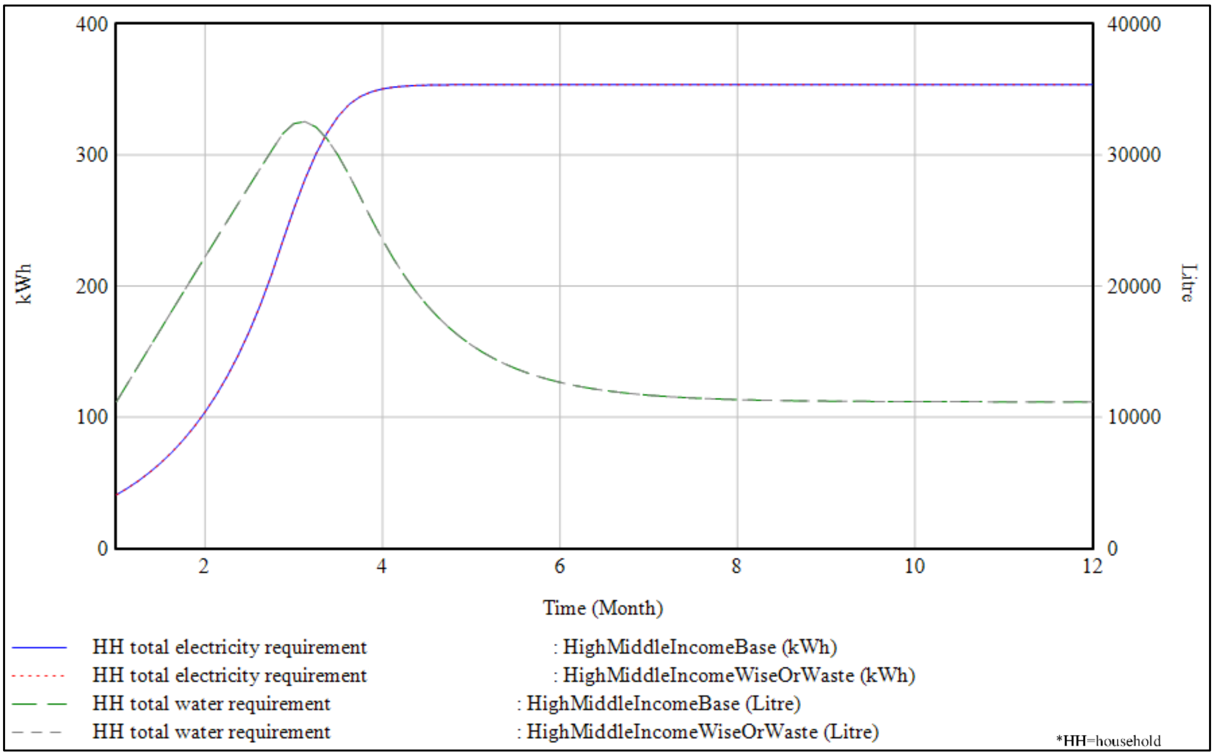

Figure 6.17: High-middle-income household WiseORWaste scenario
Source: Author

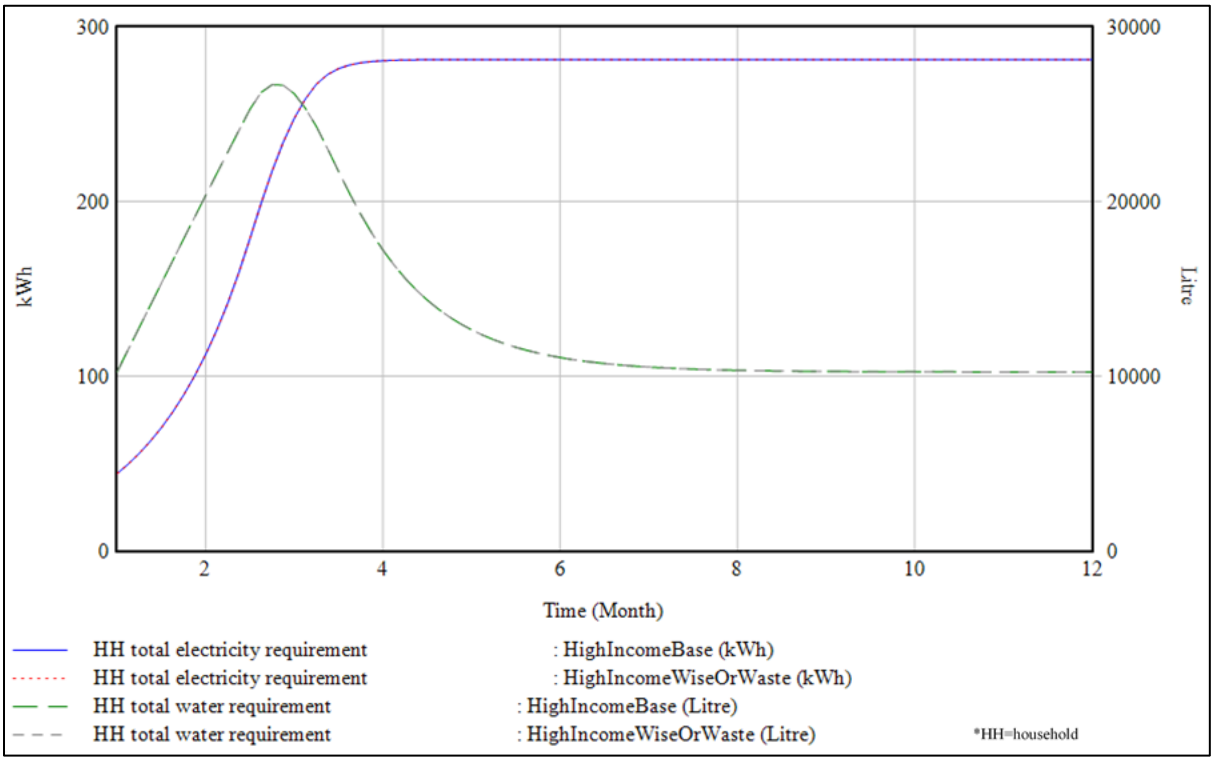

Figure 6.18: High-income household WiseORWaste scenario
Source: Author

The results of all four income household groups show no change between the base result and the WiseORWaste scenario result (Figure 6.15, Figure 6.16, Figure 6.17 and Figure 6.18). This indicates that for all income groups, the water requirements in the base results do not exceed the allocated water budget for water heating purposes. Therefore, a reduction in the water budget will not affect water savings (therefore no impact on water requirements) or the energy requirement. Therefore, in this scenario, for these base dynamics and results, a household's decision to reduce its water budget is more of a waste than it is wise. A reduction in the allocated water budget will only prove more beneficial if the budget was already being met or exceeded.

6.3.3 Decreased energy budget allocation (PowerPlay scenario)

Similar to the WiseORWaste scenario, the PowerPlay scenario is one in which the allocated percentage of each household income group's electricity budget for water heating purposes is halved from the base scenario, in other words playing with the power. Figure 6.19 shows the base and PowerPlay scenario results for the low-income household group, where the allocated electricity budget was reduced from 19% to 8,5%. The results for the base and PowerPlay scenario for the low-middle-income household group are shown in Figure 6.20, where the allocated electricity budget decreased from 27% to 13,5%. Figure 6.21 shows the base and PowerPlay scenario results for the high-middle-income household group, where the allocated electricity budget for water heating purposes decreased from 36% to 18%. Lastly, Figure 6.22 shows the base and PowerPlay scenario results for the high-income household group, where the allocated electricity budget for water heating purposes decreased from 31% to 15,5%.

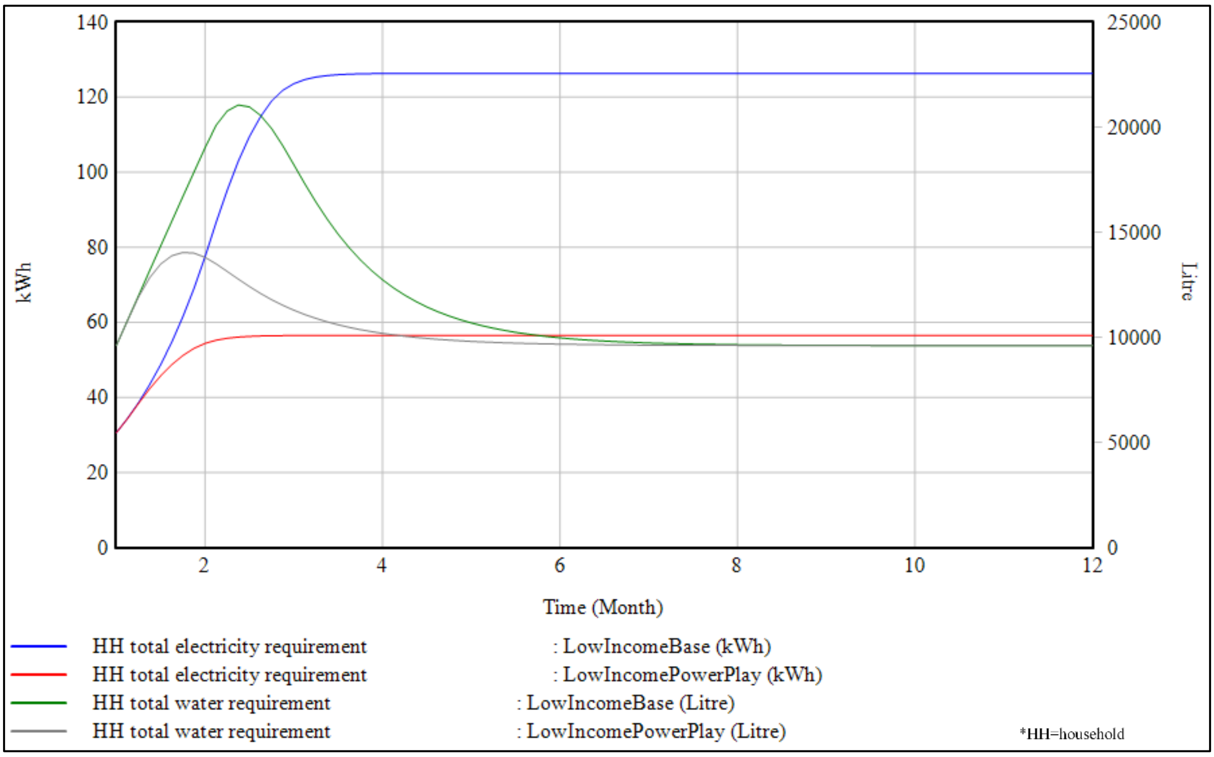

Figure 6.19: Low-income household PowerPlay scenario
Source: Author

Stellenbosch University https://scholar.sun.ac.za

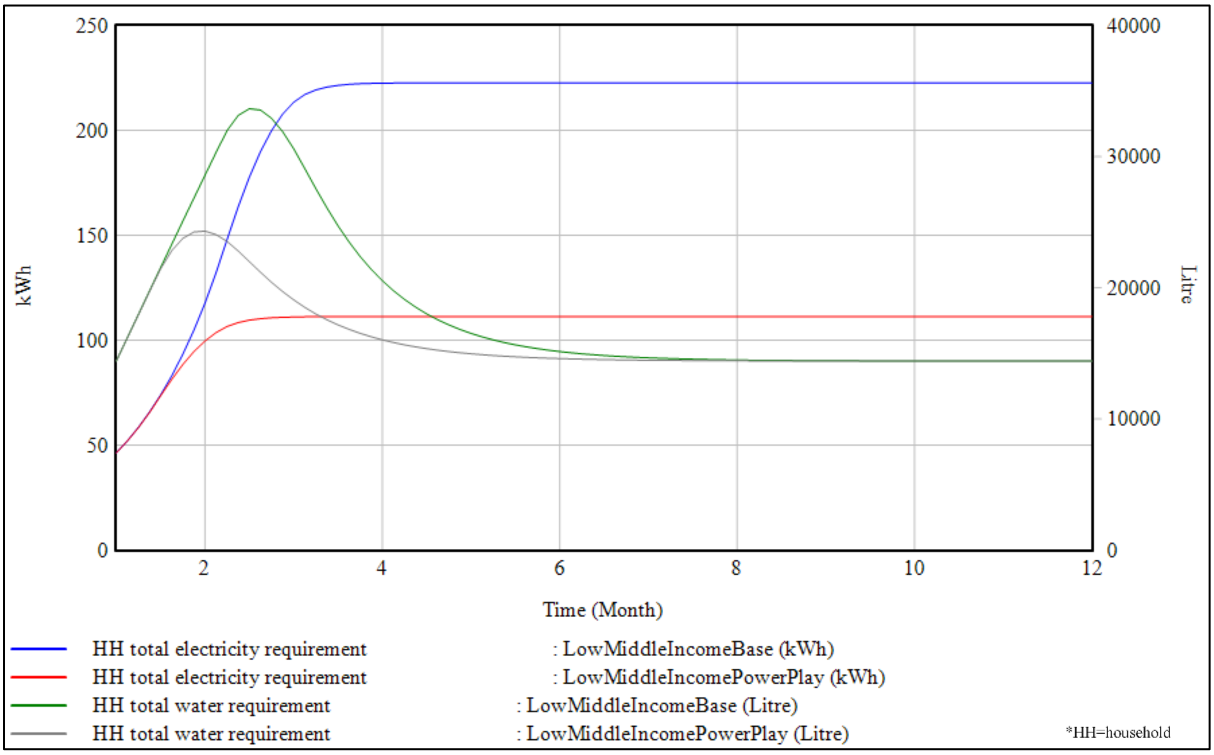

Figure 6.20: Low-middle-income household PowerPlay scenario
Source: Author

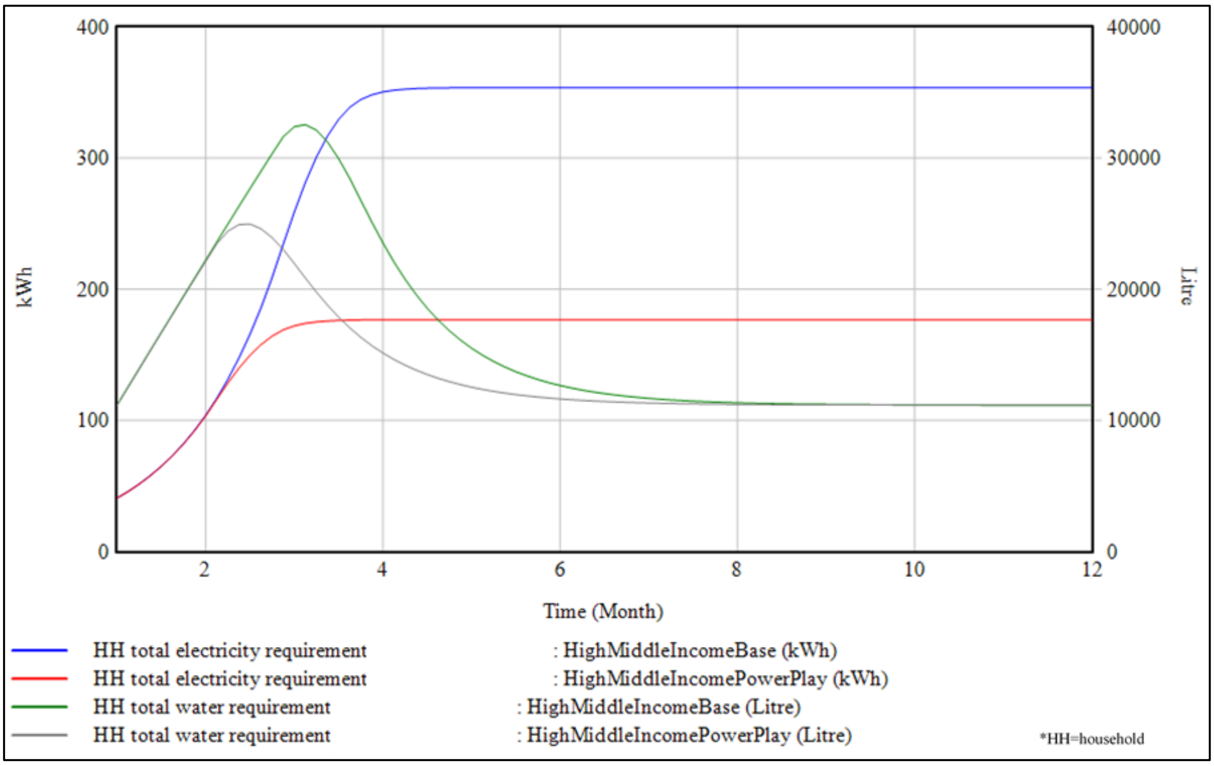

Figure 6.21: High-middle income household PowerPlay scenario
Source: Author

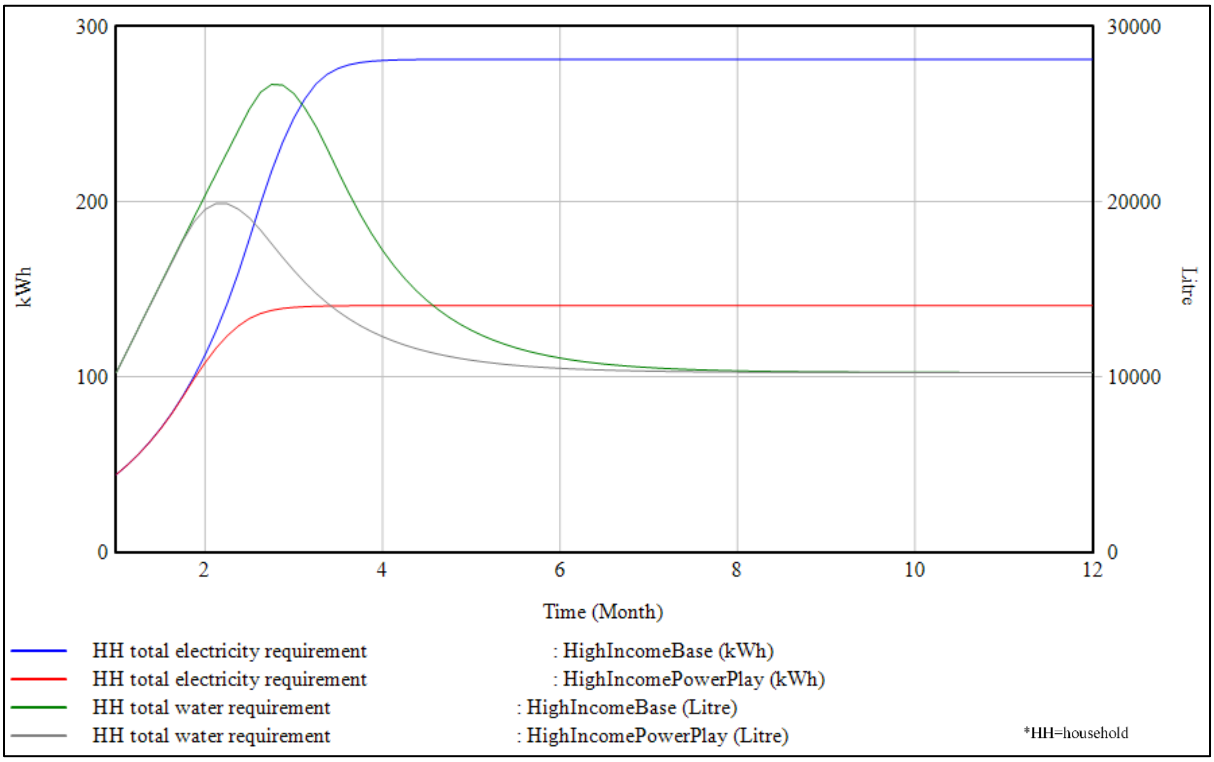

Figure 6.22: High-income household PowerPlay scenario
Source: Author

The results of the PowerPlay scenario compared to the base results of the respective income groups show, for all income groups, a reduction in both total water requirement and total energy requirements when the allocated electricity budget for water heating purposes was reduced. This indicates that changes made in electricity budgets had an impact on both energy and water in their nexus for a household. Therefore, a high-leverage intervention point for the allocated electricity budget for water heating purposes could prove beneficial towards energy and water savings in their nexus. If a household decides to allocate a smaller amount towards water heating, there will be less energy available for water heating purposes. This dynamic proves that for all household income groups, energy availability is a governing factor for water heating purposes, therefore it is a limiting factor for the energy-water nexus to occur in a household. These results are understandable, since the literature suggests that for households in Cape Town, access to potable water is widespread and (relatively) affordable. In contrast, energy access, especially electricity access, is less affordable. This means that households will more often than not stick to a strict electricity budget, as it is all they can afford/require and focus less on the water consumed, since it is more readily available.

Stellenbosch University https://scholar.sun.ac.za

6.4 Policy analysis

From the base and scenario results presented, policy recommendations can be made to try to minimise energy and water requirements and maximise energy and water savings in their nexus in households. The results from the 3'sACrowd scenario show that household size increases the water and energy requirements. Therefore, it can be recommended that household units become smaller, but this is not necessarily feasible for two main reasons. The first is that if it were purely an issue of household size, households with large occupancy could merely split and move to become two or more households with smaller occupancy. However, this merely reduces the energy and water requirements of the households by creating more household units. The requirements of Cape Town households, in general, remain the same. Secondly, it can then be argued that curbing population growth by reducing average family unit sizes (incentivise having less children) is not feasible, especially in a Global South context where family unit sizes are on average much larger compared to average family units found in the Global North.

The WiseOrWaste scenario, where the allocated water budget for water heating purposes was decreased, showed no change in water or energy requirements for any of the income groups. This decrease indicated that interventions for the water budget would not be beneficial in terms of water and energy savings. A decision to simply spend less on water (that is required as heated water) is not enough. Active behaviour changes in water usage need to be made to minimise water and energy requirements in households. For example, high-middle-income households were identified to have the highest water and energy requirement. Therefore, policies geared towards this income group specifically can be implemented. Furthermore these results suggest that increasing water restriction levels may have very little impact on energy and water savings. However this speaks specifically to energy and water savings in their nexus and not water savings in its entirety. As research by Brick *et al.* (2018) indicated an increase in water price resulted in reduced water demand across all household income levels, on average a 10% water price increase resulted in a 1,8% reduction in the demand for household water (Brick *et al.*, 2018). This shows that water restriction levels may prove more beneficial when only considering water consumption and savings in total (inclusive on non-energy related services) compared to water savings in its nexus with energy.

However, when minimising energy and water specifically in their nexus for high-middle-income households is considered, policies recommending interventions regarding showering

Stellenbosch University https://scholar.sun.ac.za

and bathing services may be more beneficial. Overall, showering or bathing was the service that showed the greatest nexus in households. For low-income and low-middle-income households, bathing showed the biggest nexus, and in high-middle-income and high-income households showering showed as having the biggest nexus. Therefore, policies geared towards interventions for the frequency and water consumption of personal hygiene services in general may be beneficial for both energy and water in this nexus.

Of the scenarios presented where the allocated amount of energy for water heating purposes was decreased, only the PowerPlay scenario minimised all household groups' energy and water requirements. Based on these results, it is apparent that it would be important to focus on households' electricity budget and the percentage of that budget allocated for water heating purposes. Policy recommendations for reducing the allocated electricity budget for water heating purposes are therefore recommended.

This can be achieved through investment in smart and low flow faucet technology, as this would decrease the amount of water consumed at a given time. Furthermore investment in the installation of solar water heaters could be beneficial, as this would decrease the proportion of energy required for water heating. This merely reduces the specific electricity energy carrier by increasing the use of the solar energy carrier. So although there is a decrease in the electricity requirement, the total energy requirement of the household does not decrease. Since in South Africa most of the municipal electricity is derived from coal, the change to solar energy for this purpose is not necessarily negative, as renewable energy has a less negative impact on a larger environmental scale.

However, the same water requirement remains to be heated by solar power as had to be heated by electricity, as changing energy carriers has no effect on household water requirements and reducing the water requirement. Therefore, the use of solar geysers would only prove beneficial in combination with water usage behavioural changes. Solar water heaters are common in low-income households due to the Solar Water Heater Programme in the Reconstruction and Development Programme of the government's Department of Energy, which aims to install 5 million solar heaters by 2030 (Rycroft, 2016). Policies geared towards incentivising and making investments in the installation of solar water geysers, which are easier and more affordable for higher-income households, especially high-middle-income households, could prove extremely beneficial with regard to reducing electricity requirements for households.

Stellenbosch University https://scholar.sun.ac.za

6.5 Summary

This chapter detailed the results of the energy-water urban nexus metabolism of households in Cape Town. Results were focused on low-income, low-middle-income, high-middle-income and high-income households in order to gain a better understanding of the energy and water requirements and address the question of minimising the requirements in their nexus.

Energy and water requirement profiles of identified services and activities for the different household income groups allowed a more detailed analysis of the requirements of both energy and water in their nexus. Furthermore, scenario tests were conducted to provide a further understanding of the effect of budgets and household size on the requirements for energy and water for the different households.

All these results provided the ability to understand and identify different intervention points in the different households that would minimise the requirements of energy-water in their nexus. The next chapter concludes the study by providing recommendations for sustainability based on the results presented. It describes the key findings of this research relating to the energy-water urban nexus metabolism of Cape Town households.

Stellenbosch University https://scholar.sun.ac.za

Chapter 7 : Conclusion

7.1 Introduction

The research addressed household energy-water urban nexus metabolism in Cape Town using a system dynamics approach. It was conducted by consulting literature on urban metabolism, energy-water nexus, household urban metabolism and household energy-water nexus, and ultimately conducted an assessment of households in the city of Cape Town using system dynamics modelling.

The main objective of this study was to assess the household energy-water urban nexus metabolism of Cape Town to identify intervention points for energy and water savings. This was achieved through the following research sub-objectives:

1. To undertake a critical review of the energy-water urban nexus metabolism at a household level.
2. To develop a system dynamics model of the energy-water urban nexus metabolism of Cape Town households.

This research analysed the energy and water requirements of different service activities for different household income levels, namely a low-income, low-middle-income, high-middle-income and high-income level. The analysis was based on the findings on points of intervention to minimise energy and water in their nexus at a household level in the city of Cape Town.

7.2 Key findings based on Objective 1

Urban metabolism is beneficial for understanding how resources flow within an urban space. However, the literature indicated a gap on which urban metabolism studies are concentrating, which is that only a single resource is considered. The literature highlights the need to understand resource flows in their nexus, since resource flows seldom occur independently, but rather interact with other resource flows. Therefore, insight for sustainable urban development management and planning can be achieved by using urban metabolism as a base to define a more integrated and broader nexus system with multiple flows.

Stellenbosch University https://scholar.sun.ac.za

In urban metabolism, water is considered one of the largest flows in a city, whereas energy accounts for the flow with the largest interaction with water at this scale. Water is used to produce energy, and energy is used in the transportation and treatment of water. However, energy-water urban nexus studies have largely been conducted only at this macro scale. Important drivers of energy and water consumption are private households that can directly regulate energy and water. Understanding resource flows at a household level proved vital, as it provided more detail in understanding flows of water and energy in a city at a micro scale. Furthermore, in contrast to city level, at micro-household level energy was predominantly used for water and not the inverse of water for energy. The literature revealed that energy was mainly used for water heating purposes in a household. This is why this research refers to the energy-water nexus and not the water-energy nexus, since it is energy for water, not the inverse.

The urban nexus from an urban metabolism perspective would prove beneficial for understanding energy and water flows in households. However, a gap identified in the literature was a definition of the household energy-water urban nexus metabolism, which this study defined as the links between energy and water flows at the household level. The literature on the urban nexus and urban metabolism flows of energy and water informed the conceptualisation of energy and water flows in a household that was developed. From this conceptualisation and additional literature providing the context of the city of Cape Town households' energy and water flows, a framework for the Cape Town household energy-water urban nexus metabolism was developed. The framework identified the services that can occur in the nexus of energy and water of Cape Town households. These services in the households' energy-water urban nexus metabolism included bathing, showering, cooking, laundry, dishwashing and swimming.

While nexus studies are generally widely accepted, there seemed to be multiple methods for understanding and applying nexus integration. Based on the literature, system dynamics modelling was identified as the best process for assessing the energy-water urban nexus metabolism at a household scale due to the following reasons:

- System dynamics modelling proved beneficial by focusing on the identified, articulated problem by analysing feedback relationships among various constituents that were time-dependent.
- The system dynamics approach utilises long simulation periods to understand long-term management options for both energy and water.

Stellenbosch University https://scholar.sun.ac.za

- System dynamics models may contribute to overcoming obstacles that may hinder the development and implementation of more holistic policies.

7.3 Key findings based on Objective 2

The purpose and articulated problem for the system dynamics model was to find out where energy and water savings can be maximised where they are linked in a household in order to ensure that Cape Town households have continuous and sustainable energy and water supply, where energy and water are explicitly understood to be municipal electricity and municipal water. Based on the simulated results of the developed household energy-water urban nexus metabolism (EWNEX) model, the following findings were observed:

- The total energy requirement and total water requirement of nexus services in households are not directly proportional to each other. Of the four identified income groups, high-middle-income households required the largest total energy but the second-largest total water. High-income households had the second-highest total energy requirements, but the second-lowest water requirements. Low-middle-income households required the highest total amount of water, but only the second-lowest total energy. This shows that the dynamics, as well as which and how specific service activities are utilised to satisfy household needs are important, and that a household can be more energy-intensive within the nexus or more water-intensive in the nexus.
- A household can be more energy intensive within the nexus or more water intensive based on the activities utilized to satisfy the services required. For example, in high-middle-income households it was identified that in terms of energy requirement, machine dishwashing, front-loaded laundry and top-loaded laundry were all the same. However, while the laundry services had the same water requirement, the machine dishwasher required significantly less water, indicating that the machine dishwasher requires more energy to heat less water. However the temperatures at which the water required for the different service activities plays an important role since more energy would be required to heat water to a higher temperature and generally water required for laundry is cooler than that used for machine dishwashing.
- For all households, services that contributed towards personal hygiene showed the biggest energy-water nexus and therefore identified to be high-leverage intervention points for energy and water savings. For low-income and low-middle-income households, the bathing service showed the biggest nexus of energy and water. For

Stellenbosch University https://scholar.sun.ac.za

high-middle-income and high-income households, showering showed the biggest nexus. This is backed up by literature that indicates that heated water is predominantly linked to personal hygiene.

- For all income groups, the cooking service showed the smallest energy-water nexus. Therefore interventions in this service will have the smallest effect on water and energy savings. This result was interesting since the literature indicated that across all household income levels, the cooking service accounted for the second-largest energy consumption.
- The allocated electricity budget for water heating purposes is a limiting factor with regard to how much heated water is required. A decrease in the percentage of electricity budget allocated for water heating purposes reduces both water and energy requirements for a household. However, this does not mean that if a household's total energy requirement is higher, its water requirement will be high as well. High-income households have a larger electricity budget compared to low-middle-income households, and the total energy requirement corresponds to this. Still, low-middle-income households have a significantly greater total water requirement. This requirement only indicates that the activities used to satisfy the services for high-income households require more energy compared to low-middle-income households. This just further emphasises that a household can be more energy-intensive in the nexus or more water-intensive in the nexus.

7.3.1 Methodological contribution

This research served as a methodological contribution towards household energy-water nexus studies and household urban metabolism studies utilising system dynamics modelling. This methodological contribution provided:

- A captured model structure of household energy-water urban nexus metabolism in terms of municipal electricity and water.
- A hypothesis of the dynamics that govern household energy-water urban nexus metabolism in the form of CLDs.
- Results based on context-specific causal feedbacks that occur in Cape Town households with regard to energy and water requirements.
- Simulations over a long period to identify high-leverage long-term intervention points with regard to household energy and water savings in their nexus.

Stellenbosch University https://scholar.sun.ac.za

- Quantitative graph trends and quantitative data produced from the developed models prove useful when comparing the requirements of different income groups and different services used. This showed to be beneficial for policy recommendations.

While the research provided a system dynamics approach towards understanding household energy-water urban nexus metabolism in Cape Town by contributing in the aforementioned ways, the model lacked the dynamics of finer details. As was pointed out in the results, the different temperatures to which water is heated and at which it is used for every service activity were not captured. Understanding how and why water is heated differently and to different temperatures also forms an integral part of understanding the nexus better. Furthermore, in the EWNEX model, the effect on both water and energy savings affects all services in the same manner (savings for all service activities are proportionally the same). However, in reality savings may occur in different proportions, depending on whether the service is considered to be a comfort service or a necessity. Savings of either energy or water could also occur by changing from one activity to another within the same service to satisfy the service. For example, to save energy, a household may decide that instead of using a front-loaded washing machine for laundry, it would do a load of laundry by hand-washing it. These types of behaviours are too small for the EWNEX model to capture. Therefore, a more appropriate approach towards understanding household energy-water urban nexus metabolism would be one that can account for these types of fine-grained behaviours and dynamics.

7.4 Recommendations for sustainability

The system dynamic modelling process is unique, since the policy analysis forms part of the process, making recommendations easier to identify. Therefore, based on the system dynamics process of problem articulation, the dynamic hypothesis, formulation and development of the EWNEX model, the simulated results and policy analysis, the following intervention points for minimising energy (specifically electricity) and water use in their nexus at a household level in Cape Town were identified:

- Personal hygiene was identified as an area of high-leverage intervention points for minimising energy and water in their nexus. Therefore, households of all income groups should shift their efforts towards either a reduced bathing and showering frequency, or reducing the amount of water used per bath or shower. This will require active behavioural change by all users. Low-income and low-middle-income households showed the biggest nexus for bathing. Therefore, usage behaviours with regard to this service should be a focus point. Showering showed the biggest nexus for high-middle-

Stellenbosch University https://scholar.sun.ac.za

income and high-income households, and therefore these household groups should focus on this service.

- In times where drought is prevalent, along with reducing the usage of the identified high-leverage intervention activities, a shift towards the reduction of activities or actively using water more sparingly for activities that are more water-intensive in the nexus (such as hand dishwashing for low-income households) is encouraged. If electricity load-shedding is prevalent, a shift towards reducing activities that are more energy-intensive in the nexus (such as machine dishwashing for high-income households) is encouraged. In both cases, energy and water are minimised in their nexus. However, they are minimised in different proportions.
- An economic mechanism to encourage energy-saving behaviours could be a reduction in a household's electricity budget allocated for water heating purposes. This can be done by investigating other energy carriers such as solar or gas.
    - The installation of solar water heaters across all household groups will have a direct impact on the municipal electricity requirement of the households. These installations will not necessarily decrease the households' overall energy requirement, but the change from predominantly municipal coal-derived electricity to renewable solar energy is a positive switch. While solar water heaters are preferred since they use a renewable energy source, gas heaters may prove more economical, especially for the lower-income households.
- While alternative energy carriers can be identified and installed as technical incentive mechanisms to lessen the dependence on municipal electricity requirement, alternative water sources for activities requiring heated water cannot be used. While water-saving technologies such as low-flow taps can be installed as a technical mechanism for water savings, a general shift of behaviour towards active water savings is vital in addition to the installed technologies.
- While the WiseOrWaste scenario indicated that the allocated budget for water heating purposes showed no impact on water and energy requirements, suggesting that increasing water restriction levels may have very little impact on energy and water savings in its nexus. However as studies by Brick *et al.* (2018) have indicated, increasing water price may still result in a reduced overall total water demand across all household income levels (Brick *et al.*, 2018). Therefore water restriction levels may still prove beneficial when considering total water consumption, as it can be a means to

Stellenbosch University https://scholar.sun.ac.za

incentivise water saving behavioural changes at a household level through economic repercussions.

7.5 Limitations and recommendations for future research

This research was limited by the following aspects:

- The uMAMA team collected its data during the 2018 Cape Town drought, therefore it may not be a true reflection of households' consumption in a non-drought context. Future studies should attempt to compile consumption data of energy and water over a longer period, through periods experiencing no drought and in drought contexts. This will provide more insight into how consumption behaviours change due to environmental pressures. Furthermore, it would be beneficial to understand how the availability of water or lack thereof affects every individual activity.
- The data was collected during a specific time of the year, which skewed the results towards current behaviour. Future studies could include data collected throughout different seasons in order to get a better understanding of energy and heated water consumption for warmer and cooler seasons. The collected data could be incorporated into the system dynamics model and could provide a more detailed policy analysis specific to seasons where, for example, consumption may be high but environmental factors such as drought are prevalent.
- This research considered only formal households. Informal households and low-income households make use of a more significant proportion of energy carriers that are not electricity. Therefore, future studies could gain further insight by expanding the system dynamics model to include other energy carriers used for water heating purposes in a household. These include solar and gas, which are often used for heating geysers. However, the use of wood should also be investigated. Paraffin and coal for water heating purposes are also included in these contexts.
- Future studies concerning household energy-water urban nexus metabolism should explore approaches that can capture finer-grained behaviours and dynamics of the system, for example, agent-based modelling, in order to understand the dynamics at play in more detail.
- Stovetop cooking was assumed to use already heated water for cooking. However, this is not always the case. Water will often be heated and cooled as it stands and reheated during stovetop cooking activities. Therefore, future studies could expand on this by considering the energy that is also required during cooking activities to heat water.

Stellenbosch University https://scholar.sun.ac.za

However, system dynamics modelling may not be the most appropriate tool for capturing this type of finer-grained dynamics. This suggests that approaches that can capture these types of fine-grained behaviours may be better suited when analysing the household energy-water urban nexus metabolism.

- As mentioned, the cooking service contributed the least energy and water requirement in their nexus which contradicted the literature. This could be since only energy and water flows were considered where it was directly linked, i.e. for heating water and not the entire service activity. It is therefore recommended that future studies consider all energy and water requirements in order to satisfy a service and not only where they are directly linked. This would include considering things such as all energy required for cooking or cold water (unheated) used for laundry.
- The study was limited to municipal electricity use, and other energy carriers such as solar and gas, which are also used for water heating purposes, were not included in the scope of this research. However, as renewable energy technology such as solar water heaters become more accessible, it is vital to capture and include these carriers as well.
- Lastly, this research highlights the importance of urban nexus metabolism studies and understanding the interdependence of resources. Future studies could therefore benefit from expanding the household energy-water urban nexus metabolism framework to include food or waste (or both) in order to understand the needs and requirements of households more holistically.

Stellenbosch University https://scholar.sun.ac.za

References

Arouri, M., Nguyen, C. & Youssef, A. Ben. 2015. Natural Disasters, Household Welfare, and Resilience: Evidence from Rural Vietnam. *World Development*. 70:59–77.

Bai, X. 2007. Industrial Ecology and the Global Impacts of Cities. *Journal of Industrial Ecology*. 11(2):1–6.

Bai, X. & Heinz, S. 2011. Urban ecology and industrial ecology. In *The Routledge Handbook of Urban Ecology*. 26–37.

Barlas, Y. 1996. Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*. 12(3):183–210.

Barrera, P.P., Carreón, J.R. & De Boer, H.J. 2018. A multi-level framework for metabolism in urban energy systems from an ecological perspective. *Resources, Conservation and Recycling*. 132:230–238.

Beloin-Saint-Pierre, D., Rugani, B., Lasvaux, S., Mailhac, A., Popovici, E., Sibiude, G., Benetto, E. & Schiopu, N. 2017. A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. *Journal of Cleaner Production*. 163:223–240.

Berman, H., Shwom, R. & Cuite, C. 2019. Becoming FEW Conscious : A Conceptual Typology of Household Behavior Change Interventions Targeting the Food-Energy-Water (FEW) Nexus. *Sustainability*. 11(5034):2–24.

Beyers, C. & Swilling, M. 2016. Economy-wide material flow accounting for the South African economy. In M. Swilling (ed.). *Greening the South African Economy*. Cape Town: University of Cape Town Press.

Biesiot, W. & Noorman, K.J. 1999. Energy requirements of household consumption : a case study of The Netherlands. *Ecological Economics*. 28:367–383.

Bleischwitz, R., Johnson, C.M. & Dozler, M.G. 2014. Re-Assessing resource dependency and criticality. Linking future food and water stress with global resource supply vulnerabilities for foresight analysis. *European Journal of Futures Research*. 15(34).

Booysen, M.J., Visser, M. & Burger, R. 2019. Temporal case study of household behavioural response to Cape Town ' s " Day Zero " using smart meter data. *Water Research*. 149:414–420.

Brick, K. & Visser, M. 2018. Green Nudges in the DSM toolkit : Evidence from Drought-Stricken Cape Town. Master's thesis. University of Cape Town.

Brick, K., DeMartino, S. & Visser, M. 2018. Behavioural Nudges for Water Conservation :

Stellenbosch University https://scholar.sun.ac.za

Experimental Evidence from Cape Town. University of Cape Town.

Broto, V.C., Allen, A. & Rapoport, E. 2012. Interdisciplinary Perspectives on Urban Metabolism. *Journal of Industrial Ecology*. 16(6):851–861.

Brunner, P.H. 2007. Reshaping urban metabolism. *Journal of Industrial Ecology*. 11(2):11–13.

Cairns, R. & Krzywoszynska, A. 2016. Anatomy of a buzzword: The emergence of ' the water-energy-food nexus ' in UK natural resource debates. *Environmental Science and Policy*. 64:164–170.

Carreón, J.R. & Worrell, E. 2018. Urban energy systems within the transition to sustainable development. A research agenda for urban metabolism. *Resources, Conservation and Recycling*. 132:258–266.

Chen, B. & Chen, S. 2015. Urban metabolism and nexus. *Ecological Informatics*. 26:1–2.

Chhipi-Shrestha, G., Hewage, K. & Sadiq, R. 2017. Water – Energy – Carbon Nexus Modeling for Urban Water Systems : System Dynamics Approach. *Journal of Water Resources Planning and Management*. 143(6):1–11.

Chini, C.M., Schreiber, K.L., Barker, Z.A. & Stillwell, A.S. 2016. Quantifying energy and water savings in the U.S. residential sector. *Environmental Science and Technology*. 50(17):9003–9012.

City of Cape Town. 2015. *Cape Town State of energy*. City of Cape Town.

City of Cape Town. 2018. *Water Outlook 2018 report*. City of Cape Town.

City of Cape Town. 2019. *Our shared water future: Cape Town's water strategy*. City of Cape Town.

Currie, P.K. & Musango, J.K. 2016. African Urbanization: Assimilating Urban Metabolism into Sustainability Discourse and Practice. *Journal of Industrial Ecology*. 21(5):1262–1276.

Currie, P.K., Musango, J.K. & May, N.D. 2017. Urban metabolism: A review with reference to Cape Town. *Cities*. 70:91–110.

Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., Song, X., Jia, B., Wanyun, X. & Yang, Q. 2018. Water-energy nexus: A review of methods and tools for macro-assessment. *Applied Energy*. 210:393–408.

Davis, S. & Durbach, I. 2010. Modelling household responses to energy efficiency interventions via system dynamics and survey data. *Operations Research Society of South Africa*. 26(2):79–96.

Department of Economic and Social Affairs Population Division. 2017. *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables*. (ESA/P/WP/248). New

Stellenbosch University https://scholar.sun.ac.za

York.

Department of Energy. 2018. *South African Energy Sector Report*. Pretoria.

Department of Energy. 2019a. *The South African Energy Sector Report: 2019*. Pretoria.

Department of Energy. 2019b. *South Africa Yearbook 2018/19: Energy*. Pretoria.

De Stercke, S., Mijic, A., Buytaert, W. & Chaturvedi, V. 2018. Modelling the dynamic interactions between London ' s water and energy systems from an end-use perspective. *Applied Energy*. 230:615–626.

Dhungel, R. & Fiedler, F. 2014. Price Elasticity of Water Demand in a Small College Town: An Inclusion of System Dynamics Approach for Water Demand Forecast. *Air, Soil and Water Research*. 7:77–91.

Dietz, T., Gardner, G.T., Gilligan, J., Stern, P.C. & Vandenbergh, M.P. 2009. Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences*. 106(44):18452–18246.

Duan, C. & Chen, B. 2020. Driving factors of water-energy nexus in China. *Applied Energy*. 257(113984).

Duran-Encalada, J.A., Paucar-Caceres, A., Bandala, E.R. & Wright, G.H. 2017. The impact of global climate change on water quantity and quality : A system dynamics approach to the US – Mexican transborder region. *European Journal of Operational Research*. 256(2):567–581.

Dyner, I., Smith, R.A. & Peña, G.E. 1995. System Dynamics Modelling for Residential Energy Efficiency Analysis and Management. *The Journal of the Operational Research Society*. 46(10):1163–1173.

Endo, A., Yamada, M., Miyashita, Y., Sugimoto, R., Ishii, A., Nishijima, J., Fujii, M., Kato, T., Hamamoto, H., Kimura, M., Kumazawa, T. & Qi, J. 2019. Dynamics of Water–Energy–Food Nexus Methodology, Methods, and Tools. *Current Opinion in Environmental Science & Health*. 10(004).

EUROSTAT. 2001. *Economy-wide Material Flow Accounting (EW-MFA): Compilation guide 2001*. Luxembourg.

Ewing, K. & Mammon, N. 2010. Cape Town DenCity: Towards Sustainable Urban Forms. In 1st ed. M. Swilling (ed.). *Sustaining Cape Town; Imagining a livable city*. Stellenbosch: Sun Press. 41–58.

Fan, J.-L., Kong, L.-S., Wang, H. & Zhang, X. 2019. A water-energy nexus review from the perspective of urban metabolism. *Ecological Modelling*. 392:128–136.

Ferrão, P. & Fernandez, J. 2013. *Sustainable urban metabolism*. Cambridge: MIT Press.

Stellenbosch University https://scholar.sun.ac.za

Fisher-Jeffes, L., Gertse, G. & Armitage, N.P. 2015. Mitigating the impact of swimming pools on domestic water demand. *Water SA*. 41(2):238–246.

Fletcher, A.J. 2017. Applying critical realism in qualitative research: methodology meets method. *International Journal of Social Research Methodology*. 20(2):181–194.

Gasson, B. 2002. The ecological footprint of Cape Town: unsustainable resource use and planning implications. *National Conference of the South African Planning Institution*. Durban

Georgescu-Roegen, N. 1986. The Entropy Law and the Economic Process in Retrospect. *Eastern Economic Journal*. 12(1):3–25.

Gerbens-Leenes, P. 2016. Energy for freshwater supply , use and disposal in the Netherlands : a case study of Dutch households. *International Journal of Water Resources Development*. 32(3):398–411.

Giampietro, M. 2018. Perception and representation of the resource nexus at the interface between society and the natural environment. *Sustainability*. 10(2545):1–17.

Goodland, R. & Ledec, G. 1987. Neoclassical economics and principles of sustainable development. *Ecological Modelling*. 38(1):19–46.

Hamiche, A.M., Stambouli, A.B. & Flazi, S. 2016. A review of the water-energy nexus. *Renewable and Sustainable Energy Reviews*. 65:319–331.

Hansen, L. 1994. Water and Energy Price Impacts on Residential Water Demand in Copenhagen. *Land Economics*. 72(1):66–79.

Harder, R., Dombi, M. & Peters, G.M. 2016. Perspectives on quantifying and influencing household metabolism. *Journal of Environmental Planning and Management*. 60(2):178–203.

Hargreaves, T. 2011. Practicing behaviour change : Applying social practice theory to behaviour change. *Journal of Consumer Culture*. 11(1):79–99.

Hedbrant, J. 2001. Stockhome: A Spreadsheet Model of Urban Heavy Metal Metabolism. *Water, Air, & Soil Pollution: Focus*. 1:55–66.

Hoad, K. & Kunc, M. 2017. Teaching system dynamics and discrete event simulation together: a case study. *Journal of the Operational Research Society*. 5682:1–11.

Hoekman, P. & Von Blottnitz, H. 2017. Cape Town's Metabolism: Insights from a Material Flow Analysis. *Journal of Industrial Ecology*. 21(5):1237–1249.

Hoff, H. 2011. Understanding the Nexus. Background Paper for the Bonn 2011 Conference. *Stockholm Environment Institute*. Stockholm

Hussien, W.A., Memon, F.A. & Savic, D.A. 2017. An integrated model to evaluate water-

Stellenbosch University https://scholar.sun.ac.za

energy-food nexus at a household scale. *Environmental Modelling and Software*. 93:366–380.

Ioannou, A.E. & Laspidou, C.S. 2018. The Water-Energy Nexus at City Level : The Case Study of Skiathos. In *3rd EWaS International Conference on Insights on the Water-Energy-Food Nexus*. Greece

Jetha, A., Pransky, G. & Hettinger, L.J. 2016. Capturing complexity in work disability research : application of system dynamics modeling methodology. *Disability and Rehabilitation*. 38(2):189–194.

Kennedy, C. & Hoornweg, D. 2012. Mainstreaming Urban Metabolism. *Journal of Industrial Ecology*. 16(6):780–782.

Kennedy, C., Cuddihy, J. & Engel-yan, J. 2007. The Changing Metabolism of Cities. *Journal of Industrial Ecology*. 11(2):43–59.

Kenway, S. 2012. The water-energy nexus and urban metabolism - Connections in cities. Urban Water Security Research Alliance Technical Report 100. *Urban Water*. (100):1–68.

Kenway, S. 2014. The energy- water nexus and urban metabolism : What lessons can we learn after the Australian Millennium Drought ? In *Global Water Forum*. 1417–1423.

Kenway, S.J., Scheidegger, R., Larsen, T.A., Lant, P. & Bader, H.P. 2013. Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings*. 58:378–389.

Liu, J., Wang, R. & Yang, J. 2005. Metabolism and Driving Forces of Chinese Urban Household Consumption. *Population and Environment*. 26(4):325–341.

Liu, J., Hull, V., Godfray, H.C.J., Tilman, D., Gleick, P., Hoff, H., Pahl-Wostl, C., Xu, Z., et al. 2018. Nexus approaches to global sustainable development. *Nature Sustainability*. 1(9):466–476.

Maani, K. & Cavana, R. 2007. *Systems Thinking, System Dynamics: Managing Change and Complexity*. 2nd ed. Auckland: Pearson.

Madonsela, B., Koop, S., VanLeeuwen, K. & Carden, K. 2019. Evaluation of Water Governance Processes Required to Transition towards Water Sensitive Urban Design — An Indicator Assessment Approach for the City of Cape Town. *Water*. 11(292).

Mekonnen, M.M. & Hoekstra, A.Y. 2016. Four billion people facing severe water scarcity. *Science Advances*. 2(2).

Metabolism of Cities. 2018. *About*. [Online], Available: https://metabolismofcities.org/page/about [2019, April 23].

Musango, J. & Currie, P. 2018. Cape Town's plans for what happens after Day Zero just won't

Stellenbosch University https://scholar.sun.ac.za

work - Here's why. *SyndiGate Media Inc* (Cape Town). 18 March.

Musango, J., Currie, P. & Robinson, B. 2017. *Urban Metabolism for Resource-Efficient Cities: from theory to implementation*. Paris.

Newell, J.P. & Cousins, J.J. 2015. The boundaries of urban metabolism: Towards a political – industrial ecology. *Progress in Human Geography*. 39(6):702–728.

Niselow, T. 2019. *Load shedding through the years and how Eskom has struggled to keep the lights on*. [Online], Available: https://www.fin24.com/Economy/Eskom/sunday-read-load-shedding-through-the-years-and-how-eskom-has-struggled-to-keep-the-lights-on-20190324 [Downloaded January 26 2020].

Obeng-Odoom, F. 2016. *Untamed Urbanisms*. A. Allen, A. Lampis, & M. Swilling (eds.). London: Routledge: Taylor & Francis Group.

Oosthuizen, J. 2016. Investigating the effects of a green economy transition on the electricity sector in the Western Cape Province of South Africa : A system dynamics modelling approach. University of Setellenbosch.

Panjabi, M. 1979. Validation of mathematical models. *Journal of biomechanics*. 12(3):238–238.

Perrone, D., Murphy, J. & Hornberger, G.M. 2011. Gaining perspective on the water-energy nexus at the community scale. *Environmental Science and Technology*. 45(10):4228–4234.

Plappally, A.K. & Lienhard, J.H. V. 2012. Energy requirements for water production , treatment , end use , reclamation , and disposal. *Renewable and Sustainable Energy Reviews*. 16(7):4818–4848.

Porter, S.E. & Pitts, A.W. 2015. Critical Realism in Context. *Journal for the Study of the Historical Jesus*. 13:276–306.

Pruyt, E. 2006. What is System Dynamics? A Paradigmatic Inquiry. In *Proceedings of the 24th International Conference of the System Dynamics Society*. 1–29. Belgium.

Radcliffe, J.C. 2018. The water energy nexus in Australia – The outcome of two crises. *Water-Energy Nexus*. 1:66–85.

Renouf, M.A., Serrao-Neumann, S., Kenway, S.J., Morgan, E.A. & Low Choy, D. 2017. Urban water metabolism indicators derived from a water mass balance – Bridging the gap between visions and performance assessment of urban water resource management. *Water Research*. 122:669–677.

Renouf, M.A., Kenway, S.J., Lam, K.L., Weber, T., Roux, E., Serrao-Neumann, S., Choy, D.L. & Morgan, E.A. 2018. Understanding urban water performance at the city-region scale

Stellenbosch University https://scholar.sun.ac.za

using an urban water metabolism evaluation framework. *Water Research*. 137:395–406.

Røpke, I. 2009. Theories of practice — New inspiration for ecological economic studies on consumption. *Ecological Economics*. 68(10):2490–2497.

Rycroft, M. 2016. *Solar water heater rollout programme gains momentum*. [Online], Available: https://www.ee.co.za/article/solar-water-heater-rollout-programme-gains-momentum.html.

Sanders, K.T. & Webber, M.E. 2012. Evaluating the energy consumed for water use in the United States. *Environmental Research Letters*. 7(034034).

Schindler, S. 2017. Towards a paradigm of Southern urbanism. *City*. 21(1):47–64.

Spencer, F. 2010. Sustainable Energy. M. Swilling (ed.). *Sustaining Cape Town; Imagining a livable city*. 1st ed. Stellenbosch: Sun Press 135–158.

StatsSA. 2016a. *Provincial Profile: Western Cape*. Pretoria.

StatsSA. 2016b. *Community Survey 2016: Statistical release*. Pretoria.

StatsSA. 2019. *Mid-year population estimates*. Pretoria.

Steg, L. & Vlek, C. 2009. Encouraging pro-environmental behavior : An integrative review and research agenda. *Journal of Environmental Psychology*. 29(3):309–317.

Sterman, J. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. S. Isenberg (ed.). Boston: Jeffrey J. Shelsfud.

Sterman, J.D. 2002. *System Dynamics: Systems Thinking and Modeling for a Complex World*. (ESD-WP-2003-01.13). Boston.

Stevenson, A. Ed. 2010. *Oxford Dictionary of English*. Oxford University Press.

Strydom, A. 2019. Understanding household energy metabolism in the city of Cape Town. Stellenbosch University.

Strydom, A., Musango, J.K. & Currie, P.K. 2019. Conceptualizing Household Energy Metabolism : A Methodological Contribution. *Energies*. 12(4125):1–19.

Strydom, A., Musango, J.K. & Currie, P.K. 2020. Connecting energy services, carriers and flows: Rethinking household energy metabolism in Cape Town, South Africa. *Energy Research and Social Science*. 60(101313).

Swilling, M., Hajer, M., Baynes, T., Bergesen, J., Labbe, F., Musango, J., Ramaswami, A., Robinson, B., et al. 2018. *The Weight of Cities: Resource requirements of future urbanization*. Stellenbosch.

United Nations. 2015a. *Transforming our world: the 2030 Agenda for Sustainable Development*. New York.

United Nations. 2015b. *Sustainable Development Goals*. New York.

Stellenbosch University https://scholar.sun.ac.za

United Nations. 2017. *New Urban Agenda*. Quito: Habitat3.

United Nations Department of Economic and Social Affairs. 2014. *World Urbanization Prospects: The 2014 Revision*. New York.

Ventana Systems Inc. 2007. *Vensim User's Guide Version 5*. 5th ed. United States of America.

Villarroel Walker, R., Beck, M.B., Hall, J.W., Dawson, R.J. & Heidrich, O. 2014. The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. *Journal of Environmental Management*. 141:104–115.

Wachsmuth, D. 2012. Three Ecologies: Urban Metabolism and the Society-Nature Opposition. *The Sociological Quarterly*. 53(4):506–523.

Wang, S., Cao, T. & Chen, B. 2017. Urban energy–water nexus based on modified input–output analysis. *Applied Energy*.

Ward, S. & Walsh, V. 2010. *Cape Town Energy Case Study*. Cape Town.

World Council on City Data. 2015. *Created by Cities, for Cities*. [Online], Available: https://www.dataforcities.org/about-wccd.

World Health Organization. 2013. *How much water is needed in emergencies*. Leicestershire.

Zhang, Y. 2013. Urban metabolism : A review of research methodologies. *Environmental Pollution*. 178:463–473.

Zhang, C., Chen, X., Li, Y., Ding, W. & Fu, G. 2018. Water-energy-food nexus : Concepts , questions and methodologies. *Journal of Cleaner Production*. 195:625–639.

Zhang, P., Zhang, L., Chang, Y., Xu, M., Hao, Y., Liang, S., Liu, G., Yang, Z. & Wang, C. 2019. Food-energy-water (FEW) nexus for urban sustainability : A comprehensive review. *Resources, Conservation & Recycling*. 142:215–224.

Zhang, Y., Yang, Z. & Yu, X. 2015. Urban Metabolism : A Review of Current Knowledge and Directions for Future Study. *Environmental Science & Technology*. 49:11247–11263.

Zhang, Y., Li, Y. & Zheng, H. 2017. Ecological network analysis of energy metabolism in the Beijing-Tianjin-Hebei (Jing-Jin-Ji) urban agglomeration. *Ecological Modelling*. 351:51–62.

Zheng, H., Wang, X., Li, M., Zhang, Y. & Fan, Y. 2018. Interregional trade among regions of urban energy metabolism: A case study between Beijing-Tianjin-Hebei and others in China. *Resources, Conservation and Recycling*. 132:339–351.

Appendix A: Initial values and parameters of household income groups for the EWNEX system dynamics model

Low-income household group

Service	*Service activity*	*Parameter*	*Initial value*	*Unit*	*Source*
Showering	Showering	Showering frequency	3	Shower/week/person	uMAMA data
		Showering water consumption	15	Litre/shower	uMAMA data
		Average number of people per household	3	Person	StatsSA (2019)
		Showering electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
Bathing	Bathing	Bathing frequency	15	Bath/week/person	uMAMA data
		Bathing water consumption	36	Litre/bath	uMAMA data
		Average number of people per household	3	Person	uMAMA data
		Bathing electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data

Stellenbosch University https://scholar.sun.ac.za

Cooking	Kettle	Kettles boiled per week	28	Kettle/week	uMAMA data
		Capacity of kettle	1,7	Litre/kettle	uMAMA data
		% of kettle filled	0,5	Dmnl	uMAMA data
		Electricity consumption per kettle	0,04	kWh/kettle	uMAMA data
	Stovetop	Stovetop use frequency	5	Hour/week	uMAMA data
		Stovetop water consumption per use	1	Litre/hour	uMAMA data
		Stovetop electricity usage per litre	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
Dishwashing	Hand dishwashing	Hand dishwashing frequency	19	Load/week	uMAMA data
		Hand dishwashing water consumption	22	Litre/load	uMAMA data
		Hand dishwashing electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data

	Machine dishwashing	Machine dishwashing frequency	0	Load/week	uMAMA data
		Machine dishwashing water consumption	22,5	Litres/load	uMAMA data
		Electricity consumption per machine dishwashing load	0,94	kWh/load	uMAMA data
Laundry	Hand-washing	Hand laundry frequency	4	Load/week	uMAMA data
		Hand laundry water consumption	25	Litre/load	uMAMA data
		Hand laundry electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
	Front-loaded	Front loader use frequency	0	Load/week	uMAMA data
		Front-loader water consumption	100	Litre/load	uMAMA data
		Electricity consumption per front-loaded load	0,94	kWh/load	uMAMA data

	Top loader use frequency	1	Load/week	uMAMA data
Top-loaded	Top-loader water consumption	100	Litre/load	uMAMA data
	Electricity consumption per top-loaded load	0,94	kWh/load	uMAMA data

Parameter	***Initial value***	***Unit***	***Source***
Monthly electricity budget	406,57	kWh/month	uMAMA data
% of the electricity budget used for water heating purposes	19%	Dmnl	uMAMA data
% of the water budget for heated water services	26%	Dmnl	uMAMA data
Monthly total water budget	11 790	Litre/month	uMAMA data

Low-middle-income household group

Service	***Service activity***	***Parameter***	***Initial value***	***Unit***	***Source***
Showering	Showering	Showering frequency	7	Shower/week/person	uMAMA data
		Showering water consumption	24	Litre/shower	uMAMA data
		Average number of people per household	3	Person	StatsSA (2019)
		Showering electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
Bathing	Bathing	Bathing frequency	20	Bath/week/person	uMAMA data
		Bathing water consumption	40	Litre/bath	uMAMA data
		Average number of people per household	3	Person	uMAMA data
		Bathing electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
Cooking	Kettle	Kettles boiled per week	30	Kettle/week	uMAMA data
		Capacity of kettle	1,7	Litre/kettle	uMAMA data

		% of kettle filled	0,5	Dmnl	uMAMA data
		Electricity consumption per kettle	0,04	kWh/kettle	uMAMA data
	Stovetop	Stovetop use frequency	4	Hour/week	uMAMA data
		Stovetop water consumption per use	1	Litre/hour	uMAMA data
		Stovetop electricity usage per litre	4 × 23 ÷ 34 124	kWh/litre	uMAMA data
Dishwashing	Hand dishwashing	Hand dishwashing frequency	18	Load/week	uMAMA data
		Hand dishwashing water consumption	22	Litre/load	uMAMA data
		Hand dishwashing electricity usage	4 × 23 ÷ 34 124	kWh/litre	uMAMA data
	Machine dishwashing	Machine dishwashing frequency	0	Load/week	uMAMA data
		Machine dishwashing water consumption	22,5	Litre/load	uMAMA data

		Electricity consumption per machine dishwashing load	0,94	kWh/load	uMAMA data
Laundry	Hand-wash	Hand laundry frequency	3	Load/week	uMAMA data
		Hand laundry water consumption	25	Litre/load	uMAMA data
		Hand laundry electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
	Front-loaded	Front loader use frequency	0	Load/week	uMAMA data
		Front-loader water consumption	100	Litre/load	uMAMA data
		Electricity consumption per front-loaded load	0.94	kWh/load	uMAMA data
	Top-loaded	Top loader use frequency	2	Load/week	uMAMA data
		Top-loader water consumption	100	Litre/load	uMAMA data

Stellenbosch University https://scholar.sun.ac.za

	Electricity consumption per top-loaded load	0,94	kWh/load	uMAMA data

Parameter	*Initial value*	*Unit*	*Source*
Monthly electricity budget	504,26	kWh/month	uMAMA data
% of the electricity budget used for water heating purposes	27%	Dmnl	uMAMA data
% of the water budget for heated water services	16,3%	Dmnl	uMAMA data
Monthly total water budget	20 430	Litre/month	uMAMA data

Stellenbosch University https://scholar.sun.ac.za

High-middle-income household group

Service	***Service activity***	***Parameter***	***Initial value***	***Unit***	***Source***
Showering	Showering	Showering frequency	13	Shower/week/person	uMAMA data
		Showering water consumption	37	Litre/shower	uMAMA data
		Average number of people per household	3	Person	StatsSA (2019)
		Showering electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
Bathing	Bathing	Bathing frequency	10	Bath/week/person	uMAMA data
		Bathing water consumption	27	Litre/bath	uMAMA data
		Average number of people per household	3	Person	uMAMA data
		Bathing electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
Cooking	Kettle	Kettles boiled per week	25	Kettle/week	uMAMA data
		Capacity of kettle	1,7	Litre/kettle	uMAMA data

		% of kettle filled	0,5	Dmnl	uMAMA data
		Electricity consumption per kettle	0,04	kWh/kettle	uMAMA data
	Stovetop	Stovetop use frequency	4	Hour/week	uMAMA data
		Stovetop water consumption per use	1	Litre/hour	uMAMA data
		Stovetop electricity usage per litre	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
Dishwashing	Hand dishwashing	Hand dishwashing frequency	11	Load/week	uMAMA data
		Hand dishwashing water consumption	22	Litre/load	uMAMA data
		Hand dishwashing electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
	Machine dishwashing	Machine dishwashing frequency	1	Load/week	uMAMA data
		Machine dishwashing water consumption	22,5	Litre/load	uMAMA data

		Electricity consumption per machine dishwashing load	0,94	kWh/load	uMAMA data
Laundry	Hand-wash	Hand laundry frequency	2	Load/week	uMAMA data
		Hand laundry water consumption	25	Litre/load	uMAMA data
		Hand laundry electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
	Front-loaded	Front loader use frequency	1	Load/week	uMAMA data
		Front-loader water consumption	100	Litre/load	uMAMA data
		Electricity consumption per front-loaded load	0,94	kWh/load	uMAMA data
	Top-loaded	Top loader use frequency	1	Load/week	uMAMA data
		Top-loader water consumption	100	Litre/load	uMAMA data
		Electricity consumption per top-loaded load	0,94	kWh/load	uMAMA data

Stellenbosch University https://scholar.sun.ac.za

Parameter	***Initial value***	***Unit***	***Source***
Monthly electricity budget	600,76	kWh/month	uMAMA data
% of the electricity budget used for water heating purposes	36%	Dmnl	uMAMA data
% of the water budget for heated water services	20,2%	Dmnl	uMAMA data
Monthly total water budget	15 660	Litre/month	uMAMA data

Stellenbosch University https://scholar.sun.ac.za

High-income household group

Service	*Service activity*	*Parameter*	*Initial value*	*Unit*	*Source*
Showering	Showering	Showering frequency	18	Shower/week/person	uMAMA data
		Showering water consumption	34	Litre/shower	uMAMA data
		Average number of people per household	3	Person	StatsSA (2019)
		Showering electricity usage	4 × 23 ÷ 34 124	kWh/litre	uMAMA data
Bathing	Bathing	Bathing frequency	4	Bath/week/person	uMAMA data
		Bathing water consumption	17	Litre/bath	uMAMA data
		Average number of people per household	3	Person	uMAMA data
		Bathing electricity usage	4 × 23 ÷ 34 124	kWh/litre	uMAMA data
Cooking	Kettle	Kettles boiled per week	21	Kettle/week	uMAMA data
		Capacity of kettle	1,7	Litre/kettle	uMAMA data

Stellenbosch University https://scholar.sun.ac.za

		% of kettle filled	0,5	Dmnl	uMAMA data
		Electricity consumption per kettle	0,04	kWh/kettle	uMAMA data
	Stovetop	Stovetop use frequency	4	Hour/week	uMAMA data
		Stovetop water consumption per use	1	Litre/hour	uMAMA data
		Stovetop electricity usage per litre	4 × 23 ÷ 34 124	kWh/litre	uMAMA data
Dishwashing	Hand dishwashing	Hand dishwashing frequency	7	Load/week	uMAMA data
		Hand dishwashing water consumption	22	Litre/load	uMAMA data
		Hand dishwashing electricity usage	4 × 23 ÷ 34 124	kWh/litre	uMAMA data
	Machine dishwashing	Machine dishwashing frequency	2	Load/week	uMAMA data
		Machine dishwashing water consumption	22,5	Litre/load	uMAMA data

Stellenbosch University https://scholar.sun.ac.za

		Electricity consumption per machine dishwashing load	0,94	kWh/load	uMAMA data
Laundry	Hand-wash	Hand laundry frequency	0	Load/week	uMAMA data
		Hand laundry water consumption	25	Litre/load	uMAMA data
		Hand laundry electricity usage	$4 \times 23 \div 34\ 124$	kWh/litre	uMAMA data
	Front-loaded	Front loader use frequency	2	Load/week	uMAMA data
		Front-loader water consumption	100	Litre/load	uMAMA data
		Electricity consumption per front-loaded load	0,94	kWh/load	uMAMA data
	Top-loaded	Top loader use frequency	1	Load/week	uMAMA data
		Top-loader water consumption	100	Litre/load	uMAMA data
		Electricity consumption per top-loaded load	0,94	kWh/load	uMAMA data

Stellenbosch University https://scholar.sun.ac.za

Parameter	***Initial value***	***Unit***	***Source***
Monthly electricity budget	554,79	kWh/month	uMAMA data
% of the electricity budget used for water heating purposes	31%	Dmnl	uMAMA data
% of the water budget for heated water services	20,8%	Dmnl	uMAMA data
Monthly total water budget	17 370	Litre/month	uMAMA data