Assessing the environmental sustainability of the urban ecosystem using Material Flow Analysis: the case of Riyadh housing stock

By

Naif Saud R. Albelwi

Supervised by:

Prof. Alan Kwan

Prof. Yacine Rezgui

Cardiff School of Engineering
Cardiff University
Cardiff, Wales, United Kingdom
December 2019

Thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD)

ACKNOWLEDGEMENTS

I would like to express my gratitude and praise to Allah for his help and guidance throughout this journey.

I am most grateful to my employer, Taibah University who provided me with the scholarship that made my graduate study in the U.K. possible.

I would like to express my sincere gratitude to my advisor, Professor Alan Kwan for his help, continued guidance, encouragement, and thoughtful supervision during my PhD study. My special thanks also go to my second advisor, Professor Yacine Rezgui, for his support and insightful suggestions throughout my PhD study.

My late parents, may Allah have mercy upon them, provided me with the guidance and inspiration that make me who I am today. Although the time I had with my mom was short, I still enjoy a lifetime of love, as her memories of endless love pour like the rain upon me.

Special thanks are due to my brothers, Muhammad and Abdulmajid for encouraging me to pursue my graduate studies, and for their guidance, encouragement and inspiration; all of which are deeply appreciated. Also, special thanks are extended to all my brothers and sisters for their support and encouragement.

Finally, I would like to thank my family and my wife, Shuaa, for their unending love and support during my studies. I extend special love and appreciation to my kids Anis, Ahmad, Basil, and new baby Saud, for their patience during my PhD journey. I dedicate this thesis to my family.

LIST OF PUBLICATIONS

Journals (under review):

- The paper entitled ‘‘Material Flow Analysis-based Assessment of Urban Ecosystem Sustainability: A Case Study of Riyadh” (Under submission)- Journal of Cleaner Production- Elsevier Journal.
- The paper entitled ‘‘Dynamic Material Flow Analysis based environmental framework to assess urban development” (Under submission)- Sustainable Cities and Society - Elsevier Journal.
- The paper entitled ‘‘Integrating MFA with LCA to evaluate urban development polices” to be submitted to Journal Energy - Elsevier Journal.

Conference paper:

- Albelwi, N., Kwan, A. and Rezgui, Y., 2017. Using Material and Energy Flow Analysis to Estimate Future Energy Demand at the City Level. Energy Procedia, 115, pp.440-450..
- Albelwi, N., Kwan, A. and Rezgui, Y., 2017. Temporal Trends of Energy Consumption and CO2 Emissions in Riyadh, Saudi Arabia. International Journal of Energy Production and Management, 2(2), pp.165-172.

ABSTRACT

In 2018, 55% of the global population resided in urban areas, and it is predicted that by 2050 this percentage will reach 68%. The consumption of materials, energy, and water resources is an inextricable consequence of population growth. This is especially apparent in urban areas, where there are significant investments in infrastructure to support urban development. Cities experiencing rapid growth face tremendous challenges, not only in providing the services required, but also to assure that development is sustainable. Urban material flow analysis (MFA) is becoming a popular framework. It links the interaction between urban activities and the environment, by quantifying the material flows that go into the urban system and the impacts of the use of resources, such as air pollution, and solid waste. To date, MFA has primarily focused on accounting for the annual direct mass and energy flows throughout the city. Therefore, it does not form a proper basis for assessing environmental sustainability within an urban system. Contrary to the MFA methodology, the Life Cycle Assessment (LCA) methodology not only examines mass, direct material and energy exchanges with the environment, but also provides a cradle-to-grave assessment of resource use and environmental impacts from a life cycle perspective.

With high rate of urban population growth, massive investments in infrastructure are needed and proposed to support urban development. Unfortunately, integrative, system-level tools are lacking for urban planners and decision-makers to assess the environmental sustainability of urban development. This thesis proposes an expanded MFA framework synthesizing additional critical urban indicators; including biophysical (i.e., land use) and socio-economic indicators. The aim being to extend MFA beyond an accounting framework, and towards a strategic planning framework. It also outlines the role of LCA in assessing urban flows, and in the evaluation of urban development scenarios, as significant changes currently being made to support 2050 urban infrastructure. The proposed framework involved three consecutive stages.

The first stage evaluated the potential use of MFA to assess the sustainability of urban systems. It involved a systemic review to evaluate how MFA can offer system-based perspectives from which to understand the interaction between the urban system and the surrounding environment. After this, MFA was applied to the domestic sector of Riyadh, Saudi Arabia, based on a set of indicators suggested by the literature. The years selected for analysis were 1996, 2006, and 2016 due to data availability. Temporal trends of resource consumption were established and results reported as gross values and on a per capita basis, to create clarity of understanding around the trends. The embodied energy and environmental impact of each MFA component was assessed using the LCA

method. The environmental impacts were classified into five categories: climate change, particulate matter formation, freshwater ecotoxicity, water consumption potential, and fossil fuel potential.

The second stage was motivated by studying the long-term impact of the built environment. A dynamic model of the in-use stock based on MFA was developed in this stage, thereby extending the model to include in-use services. The foundation of the analysis was the floor area devoted to housing stock. The input parameters of the model were based on socioeconomic indicators, and intensity factors (e.g., floor area per capita, energy use intensity). Then, LCA was introduced to the model to assess GHG emissions associated with energy (stationary/mobile) and water demands. The rationale was that with a clearer understanding of the impacts associated with resource demand, well-informed decisions can be made to address any increases in GHG emissions.

The third stage extended the scope of the analysis to include assessment of climate change mitigation policies. Initially, it reviewed current initiatives in Saudi Arabia to address the issue of climate change. Then, a set of mitigation policies were identified, and the impact of each policy investigated, and results reported against a base-scenario.

The results at each stage helped provide insights into the impact of the built environment in the context of Saudi Arabia. They also demonstrated that the proposed integrative approach can be used to quantify and assess urban flows, while conceptualizing the social and economic characteristics of the city. The findings emphasised that the framework combining stock dynamic and LCA can play a significant role in assisting the formulation of policies related to urban sustainability and climate change mitigation. Although the assessment was limited in its scope, the results afford a strong foundation for future holistic assessment.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Meaning
ADA	Riyadh Development Authority
CED	Cumulative Energy Demand
DMFA	Dynamic Material Flow Analysis
ECRA	Electricity & Cogeneration Regulatory Authority
EIO-LCA	Economic Input-Output Life Cycle Assessment
GASTAT	General Authority for Statistics
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MEDSTAR	Metropolitan Development Strategy for Arriyadh Region
NWC	National Water Company
OECD	Organization for Economic Cooperation and Development
SEEC	Saudi Energy Efficiency Centre
OECD	Organization for Economic Cooperation and Development
SDG	Sustainable Development Goals
SWCC	Saline Water Conversion Corporation
UM	Urban Metabolism

Chapter 1
Introduction

Chapter 1 introduces the concept that motivated this research, namely urban growth and its related impacts. It presents the background of the global context of urban population growth, then discusses the role of Material Flow Analysis (MFA) in providing an understanding of the magnitude of this global problem. The chapter then outlines the research aims, objectives, and the research questions in the context of sustainable development. It concludes with a discussion of the research design, and the research contributions, and provides the framework of the thesis' organization.

1.1 Background

In 2018, 55% of the global population resided in urban areas; by 2050, this figure is expected to reach 68% (UN, 2018). Cities with a high rate of urban growth face tremendous challenges, including increases in material and energy flows entering and exiting the urban system (Pauliuk, Sjöstrand and Müller, 2013). The consumption of materials, energy, and water resources is inextricably linked to population growth, which has a unique impact in urban areas, especially due to the significant investments in infrastructure that have been made to support urban development.

The use of MFA has become increasing popular, as it provides a framework that can be used to account for the flows of mass and energy through a city (Huang *et al.*, 2012; Makarichi, Techato and Jutidamrongphan, 2018; Islam and Huda, 2019). MFA is defined as "a systematic assessment of the flows and stocks of materials within a system defined in space and time" (Brunner and Rechberger, 2016). It provides indicators regarding how (un)sustainable urban systems are and can be a valuable tool for developing public environmental policies. This form of analysis is widely applied at the national level; however, it remains poorly employed at the local level, especially in developing countries, despite the existence of encouraging recent studies, most of which were conducted on a national level. The Organization for Economic Cooperation and Development (OECD) recommended that MFA should be used to study the flows of resources and materials into, through, and out of a specific system, applying the principles of conservation of matter (OECD, 2008). The results of an MFA can be expressed through indicators that compare all inputs, stocks, and outputs. It, therefore, allows the appraisal of the entire physical processes of cities and can be linked with economic and social processes, over time. However, while MFA provides a snapshot of the system under study, these snapshots do not provide information regarding the temporal evolution of the system. Adding a temporal trend dimension is therefore necessary to better understand the complexity of urban systems, as comprehending the temporal dimension of an MFA facilitates a recognition of the evolution of the system.

On the global scale, building stock comprises a significant part of the economy and plays a central role in the consumption of energy and materials (Tanikawa *et al.*, 2015). Therefore, understanding the dynamic dimension of building stock is important, as it can serve as a basis for urban development, in terms of floor area demand, energy and materials, and waste management. While there is a growing body of research concerning building stock, it has only been conducted in developed countries, and there is a paucity of research regarding the building stock of developing countries.

As well as its benefits, it is important to recognize the shortcomings of MFA, one of which is the fact that MFA is considered to be an accounting tool, not an assessment tool (Zhang, Yang and Yu, 2015). However, it does provide an understanding of a system, and additional assessment methodologies can be employed to interpret the results obtained. One important such tool is life cycle assessment (LCA). Connecting LCA and MFA is a new approach, and few studies have been published on this topic. This integration of approaches assists in providing an in-depth understanding of urban systems from a life cycle perspective. LCA approach does not end with the mass, direct material, and energy exchanges within the environment, as it provides accounting of resource use and the associated environmental impacts, from the extraction of raw materials, processing and manufacturing, the use of the product, and the disposal of the product after ends of its useful life. However, the definition of the boundaries concerned must be made explicit, and how far upstream the analysis should extend remains problematic in LCA.

1.2 Motivation

Cities experiencing rapid growth face tremendous challenges, not only in providing the services necessary to meet this growth but also in ensuring that the growth occurs in a sustainable manner. Associated with the increase in urban population size is the increased consumption of materials and energy to meet demand. The reduction of energy use lies at the heart of any attempt to plan for more sustainable cities, due to the fact that the world’s energy resources are becoming depleted, and to the associated major problems that cause climate change. Managing urban growth is a key challenge of the 21st century (Cohen, 2006). Rapid urban growth is usually associated with tremendous challenges, including increases in materials and energy flow entering and exiting urban systems (Kennedy, Cuddihy and Engel-Yan, 2007).

The MFA approach, with its notion of flows and accumulation, has encouraged researchers and city officials around the world to employ it as a basis for evaluating the sustainability of different urban systems, such as the transportation sector (Nichols and Kockelman, 2015; Butt et al., 2018); the housing sector (Bergsdal et al., 2007; Pauliuk, Sjöstrand and Müller, 2013; Sandberg et al., 2017); and the city as one system (Martínez, 2015; Sharib et al., 2017; Gonzalez-Garcia et al., 2018). In this study, sustainability is defined from the perspective of efficiency in urban flows over the studied period.

The potential contribution of MFA to the evaluation of the urban development, and the sustainability of cities is well established in the extant literature (see for example, Bao et al., 2010; Weisz and Steinberger, 2010; Laner, Rechberger and Astrup, 2014; Sharib et al., 2017). However, while there is a number of studies focussed on various cities around the globe, they were primarily conducted in developed countries, with only a few exceptions conducted in China (Hu et al., 2010; Colombier and Li, 2012; Zhao, 2012), and South America (Piña and Martínez, 2014).

The contribution and application of MFA remain poorly addressed in the context of developing countries, despite some recent encouraging studies (Vilaysouk, Schandl and Murakami, 2017). This lack of studies conducted in the context of developing countries inspired the present research, which seeks to provide a model that can compute direct and indirect energy, and the related emissions in the built environment, and analyse different scenarios to achieve the desired reduction in energy use and emissions by future stock. Integrating the LCA with the stock dynamic model, based on the MFA approach, is critical for understanding and developing meaningful policies targeting the environmental impacts of resource consumption in the built environment.

Moreover, in a country such as Saudi Arabia, which has experienced a rapid increase in its urban population, policies that are based on a systematic understanding are essential, due to the scarcity of resources. The capital city of the country, Riyadh, is the largest population centre located on the Arabian Peninsula, and its population has grown from almost one million in 1980 to nearly seven million in 2018 and is expected to reach 8.2 million by 2029. This increase in population is the most noticeable feature of Riyadh, and has engendered the growth of other sectors.

1.3 Research goals and objectives

The overall goal of this research is to establish a robust method to progress the MFA framework beyond an accounting model, towards a strategy tool. To accomplish this goal, the research proposes the integration of three extant methods: MFA, stock dynamic, and LCA, in a systematic approach using Riyadh city in Saudi Arabia as a case study.

The objectives involved in achieving this goal are as follows:

1. To review current approaches and methods that evaluate and assess the impact of the built environment.
2. To determine the energy and material flows of Riyadh, Saudi Arabia using MFA approach.
3. To enhance the MFA framework by synthesizing critical factors including biophysical, socio-economic, and quality of life indicators and assess the direct/indirect impacts of urban flows
4. To further develop the stock model for better understanding of the long-term dynamics of housing stock and related resources demand.
5. To assess different climate change mitigation policies to achieve the required reduction in GHG emissions.

1.4 Intellectual merit

This research contributes to the currently limited scientific understanding of the potential use of MFA in the context of developing countries. Through the use of an integrated, system-level approach, it also provides a better understanding of how urban development can increase the environmental impacts of the built environment. This research provides a structure for improving the MFA framework, applied to domestic sector in Riyadh, the capital city of Saudi Arabia. First, it enhances the MFA data by synthesizing the critical factors, including biophysical, socio-economic, and quality of life indicators, with the goal of evolving MFA beyond an accounting framework towards a strategic planning framework. The MFA framework is applied to three time periods (1996, 2006, 2016) to investigate how these indicators relate to one another, and how they change over time. Second, building upon the data obtained from the MFA study, this research uses a stock dynamic approach to determine the demand for housing floor area, and the related demand for energy, water and materials, in Riyadh's development over the coming decades. Third, this research provides an integrated stock dynamic and an LCA model to assess the environmental impact of the future development of the housing stock. The novel aspect of the research is the combination of the stock dynamic and LCA methods into a common framework, and the application of this framework to produce the first study that assesses the impact of housing stock and urban development in a developing country with a high rate of population growth.

The results of this research will assist policy makers and planners with the investigation of the impact of future development, and with producing effective policies for sustainable urban development.

1.5 Research questions

The following research questions are sequential in nature. The research questions involved are:

1. What are the environmental impacts of an urbanizing population?
2. What are the most influential factors through which these impacts occur?
3. How will the demand for housing floor area, and the related construction materials in Riyadh, develop over the coming decades, considering the ongoing urbanization?
4. How can dynamic stock models be extended to include both direct and indirect energy consumption and carbon emissions, and what are the critical assumptions and variables concerned?
5. What will the environmental impacts related to housing stock development be?
6. How can the stock dynamic model be applied to assess climate change mitigation policies?

The first two questions (1, 2) concern the study of the overall performance of Riyadh's urban ecosystem, while the next three questions (3, 4, 5) concern Riyadh's housing stock, and the final question (6) concerns urban development policies. The study develops an urban MFA framework to address the first two questions. Building upon the data obtained from the MFA framework, a stock dynamic model is then developed to support questions 3, 4, 5, and 6. Table 1-1 outlines the relationship between the study's objectives, research questions, the methods selected, and the related chapters.

Table 1-1 Relationship between the study's objectives, questions, methods, and chapters.

Objective	Research questions (RQs)	Method	Chapter
To review current approaches and methods that evaluate and assess the impact of the built environment at city level. To determine the energy and material flows of Riyadh, Saudi Arabia, using an MFA approach. To analyse the trends of resource consumption and material flows. To enhance the MFA framework by synthesizing critical factors, including biophysical, socio-economic, and quality of life indicators. To assess the direct and indirect impacts of urban flows.	RQ1 What are the environmental impacts of an urbanizing population?	Literature review/ MFA	Two, Four
	RQ2 What are the most influential factors through which these impacts occur?	MFA-LCA model	Four
To evaluate the dynamics of Riyadh's housing stock, and the corresponding stocks and flows of construction materials. To develop the stock model to enable a better understanding of the long-term dynamics of housing stock, and the related resource demands. To assess the direct and indirect impacts related to housing stock.	RQ3 How will the demand for housing floor area, and the related construction materials in Riyadh, develop over the coming decades, considering the ongoing urbanization?	Stock dynamic model	Five
	RQ4 How can dynamic stock models be extended to include both direct and indirect energy consumption and carbon emissions, and what are the critical assumptions and variables concerned?	Hybrid stock dynamic LCA model	Five
To investigate pathways to reducing GHG emissions related to housing stock. To assess different climate change mitigation policies that seek to achieve the reduction required in GHG emissions.	RQ5 What will the environmental impacts related to housing stock development be? RQ6 How can the stock dynamic model be applied to assess climate change mitigation policies?	Hybrid stock dynamic LCA model	Six

1.6 Research design

This thesis provides a valuable understanding of MFA and its application for studying the built environment. The work of this thesis in this regard involves four consecutive stages, which are summarized below. Figure 1-1 depicts the stages of construction of the framework.

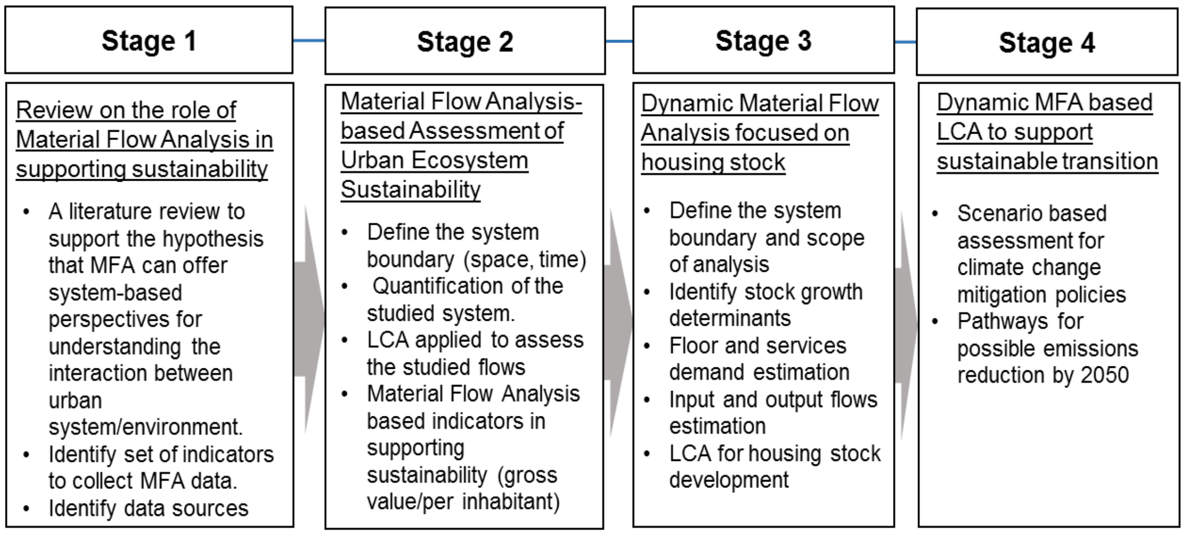


Figure 1-1 Overview of research stages.

Stage 1: In the first stage, the potential use of an MFA to assess the sustainability of urban systems is explored. Also, this stage involves reviewing the application of MFA in the context of sustainable development and outlining the gap in the literature regarding MFA and its application, especially in developing countries. Moreover, a set of indicators that assist with data collection for MFA study are identified from the literature.

Stage 2: MFA-based assessment of urban ecosystem sustainability.

After establishing that MFA can offer system-based perspectives for understanding the interaction between an urban system and the surrounding environment, this stage applied MFA to the city of Riyadh, Saudi Arabia and data is collected based on a set of indicators suggested by the extant literature when an MFA is applied at an urban level. The years selected for examination are 1996, 2006, and 2016, due to the data availability. The selection of Riyadh as a case study helps in filling the gap in the literature regarding MFA and its application, especially in developing countries. The results are reported as gross value, and on a per capita basis, to allow for a better understanding of the temporal trends.

Data concerning socioeconomic and biophysical indicators is also collected to describe the built environment of the city, and the characteristics of its population. An LCA is then applied, and the embodied energy and environmental impact of each MFA component assessed to determine the component with the highest impact on the city system's performance. The environmental impacts are reported according to five categories, including climate change, and water resource use.

Stage 3: A DMFA-based environmental framework is employed to assess urban development, and specifically the case of housing stock in Riyadh.

Motivated by the study of the long-term impact of the built environment, a generic stock dynamic based on the DMFA approach is applied and extended to include in-use services. The model's basis of the analysis is the floor area of the housing stock. The input parameters to the model are based on socioeconomic indicators and intensity factors, such as floor area per capita, and energy use intensity. The results provide insights regarding how the stock and its related demand develops in the future and provide a deeper understanding of the dynamics of the factors that govern materials and energy demands. An LCA is then combined with the stock dynamic to assess the greenhouse gas (GHG) emissions related to energy (stationery/mobile) and water demands. The rationale concerned is that a better understanding of the impacts associated with resource demand will enable the making of well-informed decisions to tackle the increase in GHG emissions.

Stage 4: Hybrid stock dynamic-LCA model to evaluate climate change mitigation

This stage builds on the findings obtained in Stage 2. A review is conducted of the current initiatives in Saudi Arabia that seek to tackle the issue of climate change, and a set of mitigation policies is defined. The impacts of each policy are investigated, and the results reported against a base scenario.

1.7 Contributions of this study

The merits of this research, and its contributions to the existing literature, can be summarized as follows:

1. It extends the current MFA framework to enable the assessment of the sustainability of urban systems in the context of a developing country, namely that of Riyadh, Saudi Arabia. The proposed framework integrates a set of indicators that describe the evolution of the built environment, and changes in the population's social characteristics over time using a static MFA;

2. It expands the scope of the analysis provided by the MFA approach by combining the MFA results with an LCA;
3. The results of the urban MFA-LCA framework constitute the first attempt to provide an environment-based assessment of the built environment in Saudi Arabia;
4. The stock-dynamic model proposed constitutes the first application of this approach in the region concerned;
5. This study adds new knowledge to the extant literature regarding the application of the stock dynamic model in the context of developing countries;
6. This study furthers the application of the current stock dynamic model, which is based on an MFA, to environmentally assess the interplay between housing stock and material and energy flows, using an LCA.

1.8 Organization of the thesis

This thesis is divided into six chapters. The following is a brief description of the content of each chapter. Table 1-1 outlines the relationship between the study's objectives, research questions, the methods selected, and the related chapters.

Chapter 1. Introduction. This chapter provides an overview of the MFA framework and its role in assessing the sustainability of the built environment. It outlines the aims of the study, together with its objectives and research questions. It also discusses the contributions of the research to the existing body of knowledge in the field.

Chapter 2. Background and literature review. This chapter provides a review of the application of MFA, in the context of sustainable development, and discusses the findings of the systemic review of the extant literature in the field, identifying the gap in the literature regarding MFA and its application.

Chapter 3. MFA-based assessment of urban ecosystem sustainability. This chapter provides an overview of the contribution of MFA to the assessment of the sustainability of urban regions. It proposes a set of indicators based on an integrated approach tool that combines MFA, LCA, and biophysical and socioeconomic indicators to analyse the sustainability of the urban development of cities, considering environmental, social, and economic parameters. It commences by reviewing the issues surrounding urbanization, and the steps already taken towards sustainable development, and then analyses the environmental impact of urban growth and development in Riyadh, Saudi Arabia.

Chapter 4. A DMFA-based environmental framework for assessing urban development: The case of housing stock in Riyadh. This chapter provides an overview of the potential use of DMFA for assessing the dynamic of the built environment. It introduces the concept of the use of DMFA to evaluate the development of flows and stocks of floor areas and materials, using a residential sector in Riyadh as a case study. First, it provides a description of the development of this stock dynamic approach, and extends the current framework to include an energy parameter, namely energy related to household use and energy related to transportation use by households. It also introduces an integrated approach to the model that combines DMFA and LCA to assess the environmental impacts, and estimate the embodied energy related to housing stock input flows. The chapter concludes with a discussion of the model's implications and its limitations.

Chapter 5. Hybrid stock dynamic LCA model for evaluating climate change mitigation. This chapter provides an assessment of the current policies that seek to mitigate climate change. It shows the potential contribution of the stock dynamic model, combined with LCA, for evaluating these policies, demonstrating that it provides a systemic understanding of the impacts or benefits associated with the implications of these policies for achieving the emissions reduction required by 2050.

Chapter 6. Conclusion. This chapter concludes the study and provides the context of the development of the model used in this research. It also outlines the research questions and summarizes the findings of each chapter, relating the findings to the research questions. The main contributions of the study are summarized, and this chapter concludes with recommendations and avenues for future work.

Chapter 2

Background and literature review

This chapter provides a review of the application of MFA in the context of sustainable development. The findings of a systemic review of the extant literature are outlined and discussed, and the gap in the literature regarding MFA and its application identified.

2.1 Introduction

In recent years, the concept of urban MFA has been developed from various research disciplines as a framework for understanding cities from the viewpoint of the resources that enter into, and the wastes that flow out of urban stocks. Thus, the MFA approach enables a focus on resource inputs and waste outputs into and from a city.

The MFA method is commonly employed in urban metabolism (UM) studies, as a metrics for the assessment of the urban material flows and stocks (Kennedy, Pincetl and Bunje, 2011). The method uses a systems approach to establish a system-level understanding of urban system function, and has been applied to identify material flows at the national level, and later at a city level (Huang et al., 2012; Hunt et al., 2014). An MFA estimates the materials that enter a system, the stocks within it, and the resulting output flows (Binder, 2007)It assists decision-makers with the analysis of the flows and stocks within a given system, with the assessment of the importance of these flows, and with the control of these flows to achieve urban development goals (Bao et al., 2010). It also accounts for the energy flows required to support a society's demands, and the associated waste flows (Vásquez et al., 2016a)

Due to the current high urbanization rate and population growth, the study of the input, stock, and output of energy and materials in urban societies has received an increasing amount of attention from researchers around the world. By characterizing the flows in urban systems, researchers seek to reveal the causes of environmental and resource-related issues, in order to develop appropriate measures to counter them (Kennedy, Pincetl and Bunje, 2011; Hendriks et al., 2000). However, many questions arise when discussing the most appropriate tools for quantifying urban metabolic flows, as well as whether to use a stand-alone tool, or to integrate it with other approaches, or to develop new approaches entirely.

Globally, the building sector comprises an important part of the economy. It currently contributes one-third of the global GHG emissions (Dean et al., 2016). Moreover, the building stock itself comprises a significant part of the economy and plays a central role in the consumption of energy and materials. Therefore, understanding the dynamic dimension of building stock can serve as a basis for urban development policies to manage housing demand, as well as the demands of energy and materials, and waste management.

2.2 A systematic review of previous studies of MFA and its applications

In order to locate MFA studies that were of relevance to the present research, a systematic search was conducted on all the most popular scientific databases, namely Web of Science, Scopus, and Science Direct, as illustrated in Table 2-1.

Table 2-1 The keywords employed in the search, and the results of each round.

Research words	Database			
	Web of Science	Scopus	Science Direct	Research constraints
MFA & urban development	162	251	74	1. Time span: 2000-2018. 2. Limited to: Research in English, and limited to journal articles and conference proceedings
MFA & sustainable development	318	515	158	
MFA & urbanization	92	128	37	
Dynamic MFA & sustainable development	41	50	13	
MFA & building stock	124	105	40	
MFA & sustainable development & developing countries	26	30	12	

Within the systematic approach employed, two methods were used to identify the relevant academic and peer-reviewed journal articles. First, the following academic databases were selected as search tools: Web of Science, Science Direct, and Scopus. Then, the following keyword combinations were entered into the respective search engines: (1) MFA AND sustainable development, (2) MFA AND urban development, (3) MFA AND urbanization, (4) MFA AND building stock, (5) Dynamic MFA AND sustainable development, (6) MFA AND sustainable development AND developing country. The time span of the research was from 2000 to December 2018. This stage produced more than 1,000 articles, including duplicates. In order to delete the duplicates, all of the articles were loaded into a reference management programme, Mendeley.

The conventional literature review approach was then conducted to crosscheck and validate the relevance of the initial set of articles. First, by examining the title to select the relevant articles. Then, the title, abstract, and the content of the articles was examined manually with reference to five criteria: (1) MFA and its application in urban development, (2) MFA as a decision-making tool to support sustainability, (3) Urban MFA and urban resource consumption, (4) the environmental impact assessment of MFA at an urban scale, and (5) MFA as a tool to predict future resource requirements and associated impacts. This produced 331articles.

Overall, the search found that although there was a fairly robust body of existing literature within the scope of the present research, and on the three methods concerned individually, there was a gap in the research regarding the integration of MFA, stock dynamic, and LCA into one framework for assessing the sustainability of the built environment, especially in developing counties with a high rate of urban population growth (see Figure 2-1).

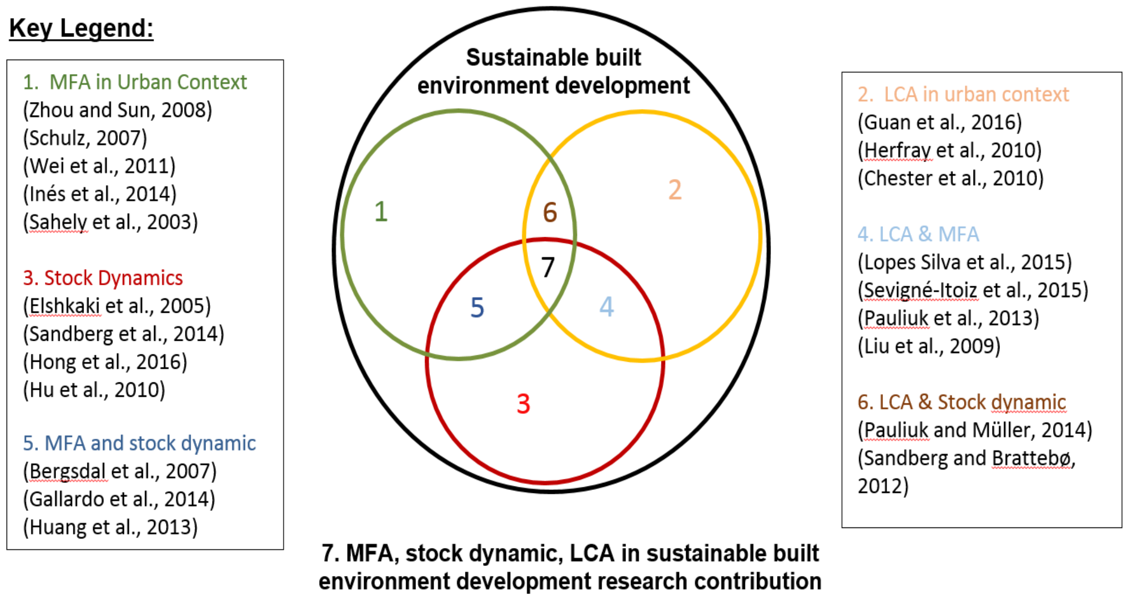


Figure 2-1 Literature review and research contribution.

The next step of the review employed VOSviewer scientometric software to identify the frequency (occurrence) of keywords in the text of the papers; these keywords were abstracted according to a set frequency (Waltman, Van Eck and Noyons, 2010). The similarity matrix of the keywords was computed using the co-occurrence relationship between any two keywords; VOSviewer uses association strength to obtain the similarity of any pairs of words, and then form a similarity matrix (Van Eck and Waltman, 2007)

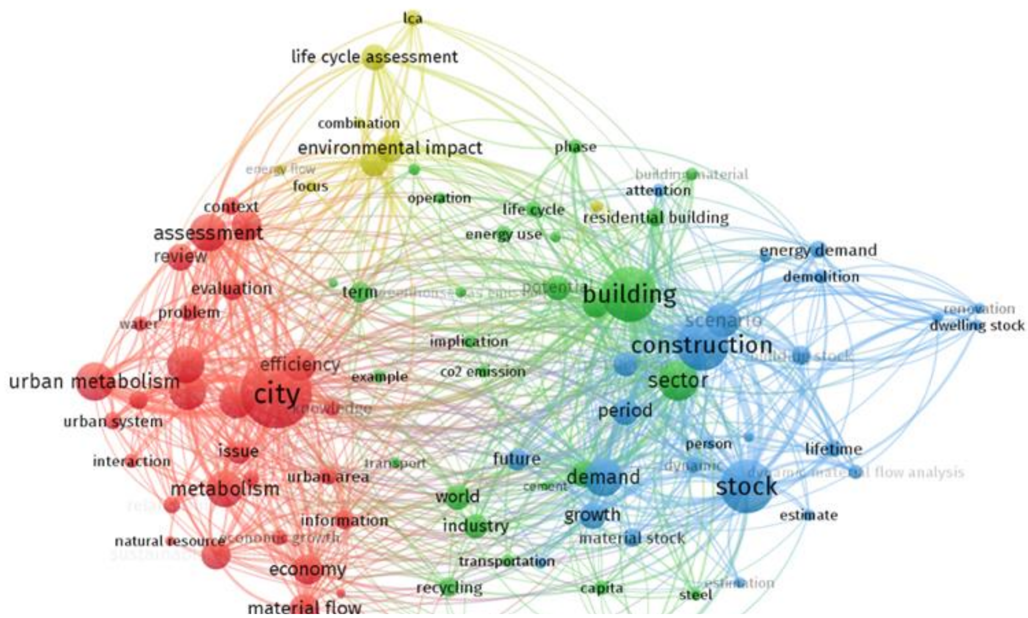


Figure 2-2 Clustering analysis of the literature.

This section of the thesis analyses the core keywords of the articles selected. As shown in Figure 2-2, four subgroups (clusters) were indicated, which are marked red, blue, green, and yellow for clusters one through four, respectively.

The co-words included items that contribute to the concept of MFA, such as ‘urban metabolism’, ‘city’, ‘energy’, ‘recycling’, ‘use stock’, ‘carbon dioxide (CO_2) emissions’, ‘energy use’, ‘environmental impact’, ‘building, ‘dwelling stock’, and ‘construction’. Table 2-2 summarizes the main findings of these studies, categorized according to their topics.

Table 2-2 Summary of main points in some of the literature selected.

Summary of the main points in Research Group 1 (MFA in an urban context)		
Author(s)/year	Study title	Notes
Zhou and Sun, 2008	Analysis of characteristics of regional material metabolism based on MFA: a case study of Chengyang district in Qingdao.	1. The application of MFA and its assessments of cities, especially in the developing world. Remains limited. 2. The literature review revealed that developing countries are under-represented in metabolic flow studies. 3. MFA alone is not sufficient to orientate environmental decisions, but should be construed as a first critical step in collecting the information required for these environmental management applications. 4. MFA can be conducted on different geographical scales. 5. MFA fails to provide decision-makers with the interpretation clues required to determine which flows must be controlled to achieve a greater environmental sustainability of the urban system.
Schulz, 2007	The direct material inputs into Singapore's development.	
Wei et al., 2011	The development and practice at a city level of MFA in China.	
Inés et al., 2014	Urban MFA: An approach for Bogotá.	
Sahely et al., 2003	Estimating the urban metabolism of Canadian cities: case study.	
Summary of the main points in Research Group 2 (LCA in an urban context)		
Author(s)/year	Study title	Notes
Guan et al., 2016	Quantification of building embodied energy in China, using an input–output-based hybrid LCA model.	1. LCA is used to account for the cumulative environmental impacts of products and services. 2. Performing LCAs can be resource and time intensive. 3. Comprehensive strategies that are LCA-based are likely to have a greater impact in moving cities towards the path of a green and smart economy than policies that rely on partial data serving as indicators of the whole system.
Herfray et al., 2010	LCA applied to urban settlements.	
Chester et al., 2010	LCA and urban sustainability.	
Summary of the main points in Research Group 3 (Stock dynamic)		
Author(s)/year	Study title	Notes
Elshkaki et al., 2005	Dynamic stock modelling: A method for the identification and estimation of future waste streams and emissions, based on past production and product stock characteristics.	1. Assessing the effect of different emission mitigation pathways requires a time dimension in the model. 2. The historic development of in-use stocks can be used to derive benchmarks for future development. 3. DMFA differs from static analysis, as it includes the investigation of stocks in society, so it is possible to explore future flows of emissions and wastes, based on past and future inflows and stock characteristics.
Sandberg et al., 2014	Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock.	
Hong et al., 2016	Building stock dynamics and its impacts on materials and energy demand in China.	
Hu et al., 2010	Dynamics of urban and rural housing stocks in China.	
Summary of the main points in Research Group 4 (LCA & MFA)		
Author(s)/year	Study title	Notes
Lopes Silva et al., 2015	Combined MFA and LCA approach used to evaluate the	1. A life cycle perspective is necessary for effective sustainability policies.

	metabolism of service polygons: A case study conducted on a university campus.	2. LCA methodology does not stop at the mass, direct material and energy exchanges with the environment. 3. MFA categorizes flows, but omits impact and indirect effects; combining LCA with MFA can bridge these gaps.
Sevigné-Itoiz et al., 2015	Methodology of supporting decision-making of waste management with MFA and consequential life cycle assessment (CLCA): Case study of wastepaper recycling.	
Pauliuk et al., 2013	Transforming the Norwegian dwelling stock to reach the 2 degrees Celsius climate target: Combines MFA and LCA techniques.	
Liu et al., 2009	Environmental consumption patterns of Chinese urban households, and their policy implications.	
Summary of the main points in Research Group 5 (MFA & stock dynamic)		
Author(s)/year	Study title	Notes
Bergsdal et al., 2007	DMFA of Norway's dwelling stock.	1. The studies emphasized the importance of considering dynamic behaviour when analysing the building stock. 2. The implications for downstream and upstream systems must be addressed and evaluated from the economic and environmental perspective. 3. In order to support strategy development in the sustainable built environment, a long-term perspective is required, and a DMFA is necessary.
Gallardo et al., 2014	DMFA examination of Chilean housing stock: long-term changes and earthquake damage.	
Huang et al., 2013	Material demand and environmental impact of building construction and demolition in China, based on DMFA.	
Liu et al., 2009	Environmental consumption patterns of Chinese urban households, and their policy implications.	

The following sections detail the main findings of the literature. These findings were observed when reviewing the articles selected.

2.2.1 The role of the built environment in sustainable development

The term 'the built environment' refers to man-made buildings that create the setting for human activity. Its scale can range from neighbourhoods to cities. From the sustainability point of view, the built environment can play a major role in moving towards a more sustainable future (Jones, Patterson and Lannon, 2007; Krausmann, Gingrich and Nourbakhch-Sabet, 2011; Tingley, Giesekam and Cooper-Searle, 2018). However, the increase in the size of urban populations, along with changes in the lifestyle of contemporary citizens, can have a significant negative impact on natural resources. For example, building-related activities constitute approximately 44% of the total material use, 30-40% of society's total energy demands, and one third of the total CO_2 emissions (Sartori et al., 2008; Condeixa, Haddad and Boer, 2017).

Several of the sustainability issues are related to the extensive mobilization of materials by urban development (Hendriks et al., 2000). This, in turn, engenders major transformations of the landscape of the Earth, due to the transfer of large stocks of material from hinterlands to urban areas. Moreover, sustainability issues and challenges are not globally balanced, and greater attention must be paid to developing countries. According to United Nation (UN) studies, the world population is expected to surpass 9 billion by 2050, and while 54% of the global population currently resides in urban areas, this percentage is expected to reach 66% by 2050 (UNDP, 2015). Subsequently, the demand for the expansion of the built area will emanate primarily from the rapid urbanization of developing countries over the next few decades. In these developing countries, rapid industrialization, among other factors, has caused fast-growing urbanization, and a doubling the building stocks in only 20-30 years (Yang and Kohler, 2008). If the depletion of increasingly scarce resources is taken into account, together with the problem of global warming, the consequences of the high urbanization rate in developing regions it is critical for steering the development of the built environment onto a more sustainable path.

2.2.2 MFA and the metabolism of the built environment

The MFA method is considered to be the earliest urban metabolism (UM) method (Goldstein et al., 2013), which is defined as " a means of quantifying the overall fluxes of energy, water, material, and wastes into and out of an urban region" (Sahely, Dudding and Kennedy, 2003). In this method, single or more comprehensive lists of metabolic flows, such as food, water, fuels, electricity, and construction materials, are accounted over the period of a year (Codoban and Kennedy, 2008). This method only quantifies a city's direct consumption, and ignores the embedded upstream processes required to provide a city with resources, and also omits the impacts of the downstream processes that handle a city's waste (Kennedy, Pincetl and Bunje, 2011).

The MFA approach is widely used in UM studies, since metrics for the assessment of urban materials, flows, and stocks are available (Barles, 2007). MFA measures the materials flowing into a system, the stocks and flows within it, and the resulting outputs from the system to other systems based on the principle of mass conversion, where mass in = mass out + stock changes (Sahely, Dudding and Kennedy, 2003).

The authors Brunner and Rechberger (2016) outlined seven general methodological steps of MFA. It begins with defining the problem and the goals of the study. Next, the relevant materials and system boundaries are selected. Then, the mass of flows and stocks are calculated with uncertainties considered. Finally, results need to be presented in a proper way to facilitate the implementation of goal-oriented decisions.

2.2.3 The need for a long-term systems perspective of sustainable built environment development

The built environment is characterized by a long service lifetime; therefore, a long-term perspective can provide an understanding of the dynamics of the system. It can also provide valuable information to support the implementation of sustainable strategies (Bergsdal et al., 2007). According to Brattebø et al. (2009), a systems approach to the built environment should be used, due to the long service life of built structures, and their significant mobilization of physical land monetary flows, such as materials, energy, emissions, and waste. Moreover, Müller (2006) concluded that stocks in use play an important role in understanding the long-term changes of societal metabolism since they better reflect the quality of life than inflows.

2.2.4 MFA and its application at the city level

Urban MFA is a way of characterizing the flows of materials and energy through and within cities. Because of the data-intensive nature of an MFA study, there are challenges associated with its methodology. For example, urban MFA studies only present results on either energy, water, or material flows at a particular point in time. This does not provide results on flow's evolution caused by a city's temporal dynamics.

An MFA generally aims to achieve the following objectives: (i) to delineate the system of material flows and stocks; (ii) to reduce the complexity of the systems, while concurrently maintaining the basis for decision-making; (iii) to quantitatively assess the stocks and flows of certain components of a metabolism; (iv) to present the system results in a comprehensible manner; and (v) using the results as a basis for managing the resources, to investigate the environment and wastes (Hendriks *et al.*, 2000).

The studies quantifying material flows at a city level vary considerably in terms of the nature and scale of the metabolic flows considered. Some analyses focussed on establishing a comprehensive material balance in specific cities, such in Vienna, Hong Kong, various Irish cities, and Lisbon, whereas other studies focussed only on specific metabolic flows, such as construction materials, while Kennedy, Cuddihy and Engel-Yan (2007) applied the approach to eight cities.

MFA applications at the cities level would provide valuable information that can be used for several purposes. For example, MFA can help cities determine their greenhouse gas (GHG) inventory which is used to establish cities ecological footprint (Kennedy, Baker and Brattebø, 2014b). Moreover, assessing flows related to housing stock (e.g. electricity, water, transportation) would help identify hotspot where policies should be focused. The number of resource flows that to be analysed depends on the context, data availability and key environmental challenges of a specific city (Kennedy, Baker and Brattebø, 2014b).

2.2.5 MFA and building stock modelling

Building stock modelling has been approached using Dynamic MFA in previous research, through the analysis of the floor area and building materials. Floor area is defined here as a measurement of the built environment (Sartori et al., 2008). When implementing a DMFA model, the system variables are functions of time (Bergsdal et al., 2007). A historical and future analysis of the system can be performed, and its dynamic behaviour can be understood (Hong et al., 2016).

For instance, Müller (2006) applied a DMFA to the Dutch dwelling stock for the period 1900-2100, relating the material stocks in use to service, with the central driving forces of the population (P) and its lifestyle. When applied to housing stock, lifestyle was elaborated further with the variables average size (area) of a dwelling (AD), and persons per dwelling (PD). These variables together, each expressed as a function of time, yielded the stock demand, or stock in use, for the floor area. This stock in use formed the physical link between resource demand and waste generation, or input and output, respectively (Müller, 2006).

Several other studies concerning building stock modelling employed the approach proposed by Müller (2006), to evaluate, for instance, the dynamic of the Norwegian residential stock (Bergsdal et al., 2007); to model construction, renovation, and demolition activities (Sartori et al., 2008), and to study the material and energy metabolism of built environment stocks (Brattebø et al., 2009). The model was also applied to study the dynamics of urban and rural housing stocks in China (Hu et al., 2010), and to study the urban housing system in Beijing (Hu, van der Voet and Huppes, 2010). In general, these studies concluded that it is possible to understand patterns in long-term development systems.

2.2.6 Integrating MFA with other tools: MFA and system dynamic

Due to the limited number of system variables in MFA studies, dynamic analysis and scenario modelling are relatively easy to perform and are commonly applied (Sandberg, Sartori and Brattebø, 2014c). Dynamic stock modelling combines MFA with system dynamics to investigate long-term trends in the different material cycles (Müller, 2006).

In a study conducted by Hu et al. (2010a, 2010b), the authors developed a dynamic building model, based on statistical data for the urban housing stock in rural and urban China in general, and Beijing in particular, focussing on construction and demolition wastes (C&D), as well as iron and steel. Meanwhile, Bergsdal et al. (2007) projected the amount of C&D waste and the related demolition activities in the residential sector in Norway, for a period of 23 years (1995–2018), based on statistical data of the building stock (floor area, age), and historical building material consumption. Due to the better availability of the relevant statistical data, most of the previous studies were focused on residential buildings,

The way that building stock was approached by DMFA in previous research was through the analysis of the floor area and building materials. The building stock demand over time, or also the floor area in use, S(t), is represented by a relationship between three parameters: population (P), persons per dwelling (PD), and the average size (area) of a dwelling (AD); these last two being the lifestyle parameters. Hence, for each year, the stock demand is represented by the following expression (Müller, 2006).

$$S(t) = P(t) \cdot \frac{A_D(t)}{P_D(t)} \qquad Equation\ (2.1)$$

Only a few studies connected MFA and dynamic stock modelling, in particular, to energy use and carbon emissions (Sandberg and Brattebø 2012; Sandberg et al. 2011; Liu et al. 2011; Kohler and Hassler 2002). A key challenge involved in this approach is that a substantial fraction of the total sectoral emissions could come from outside the MFA system, such as the emissions from electricity generation (Yin, Liu and Yuan, 2015). A generic approach regarding how to include both direct and indirect energy consumption and GHG emissions into MFA systems is lacking. Table 2-3 lists the MFA studies that applied the dynamic system approach.

Table 2-3 Metabolic flow studies using system dynamics.

Region	Notes	Source
China	Used a DMFA model to analyse the rural and urban housing systems in China, for the period 1900–2100, for several scenarios, assuming different development paths for population, urbanization, housing demand per capita, and building lifetime.	Hu, M. et al., 2010. Dynamics of urban and rural housing stocks in China. *Building Research & Information,* 38(3), pp.301–317.
Germany and Czech Republic	Presented a dynamic Type-Cohort-Time (TCT) stock-driven modelling	Vásquez, F. et al., 2016. Dynamic type-cohort-time approach for the analysis of energy reductions

	approach that considered demographic aspects, lifestyle-related issues, and building-specific characteristics for the analysis of energy reduction strategies in the building stock.	strategies in the building stock. *Energy and Buildings*, 111, pp.37–55. Available at: http://dx.doi.org/10.1016/j.enbuild.2015.11.018.
Caral, Peru; Lisbon, Portugal	Current work to assess the metabolism of several cities in different countries in Asia and South America.	Fernandez. J.E. Undated. Urban metabolism of ancient Caral, Peru. School of Architecture and Planning, Massachusetts Institute of Technology (MIT), USA. Unpublished.
Norway	A DMFA approach was applied to analyse the dynamic of both floor area and material used in residential housing. The population's demand for housing represented the driver in the system.	Bergsdal, H. et al., 2007. Dynamic material flow analysis for Norway's dwelling stock. *Building Research & Information,* 35(5), pp.557–570. Available at: http://www.tandfonline.com/doi/abs/10.1080/09613210701287588.
China	Incorporated the effects of earthquakes into a DMFA of the Chilean dwelling stock, by integrating a seismic vulnerability assessment into the dynamic modelling of the building stock.	Gallardo, C., Sandberg, N.H. and Brattebo, H., 2014. Dynamic-MFA examination of Chilean housing stock: long- term changes and earthquake damage. *Building Research and Information,* 42(3), pp.343–358. Available at: http://www.tandfonline.com/doi/pdf/10.1080/09613218.2014.872547.
Beijing	A DMFA was conducted for Beijing's urban housing system, with the demand for the stock of housing floor area employed as the driver.	Hu, M., van der Voet, E. and Huppes, G., 2010. Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing. *Journal of Industrial Ecology,* 14(3), pp.440–456.

2.2.7 The stock dynamics model and its uncertainties

In most of the above studies, it was assumed that the demand for housing stock is determined by the growth of the population, and the living standard represented. This is a reasonable assumption and was employed by many studies for projecting long-term trends in the housing stock (Bergsdal et al., 2007; Bergsdal, 2009; Hu et al., 2010; Hu et al., 2010; Gallardo, Sandberg and Brattebo, 2014a; Sandberg et al., 2017; Sandberg, Nord and Lausselet, 2018). However, it is not suitable to analyse the detailed short-term fluctuations, because the short term housing demand is also determined by business cycles (Niza, Rosado and Ferrdo, 2009). The other issue with the stock dynamic model concerns that fact that its results are not rigid predictions, rather they are possible scenarios. Finally, the implications for downstream and upstream systems must be addressed and evaluated from the economic and environmental perspective (Bergsdal et al., 2007).

2.2.8 MFA combined with LCA

LCA is a quantitative tool that is used to evaluate the potential environmental impacts and resources used throughout a product's lifecycle. It is becoming increasingly important as an investigative tool for evaluating the impacts of urban activities, and various LCA studies have been conducted regarding the environmental footprint of cities (Chester, Pincetl and Allenby, 2012).

LCA is an invaluable tool when comparing the environmental impacts of various products and processes. Although it has traditionally been applied almost exclusively to consumer goods and services, over the last decade its field of application has expanded to include infrastructure (Lopes Silva et al., 2015). The LCA framework is a system-based approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation.

Both MFA and LCA are methodologies that attempt to quantify flows of material and energy in complex systems at multiple scales, and can be incorporated into the urban MFA framework (Chester, Pincetl and Allenby, 2012). LCA is formalized in the ISO 14044 standards, which specify requirements and provide guidelines for LCA for businesses. Several software packages have been developed to conduct LCAs, including Gabi, developed by PE International, and SimaPro, developed by PRé.

The proposal to combine the MFA and LCA techniques has advantages, particularly in studies of complex systems, such as cities, regions, or economic sectors (Gabarrell et al., 2014). The combination of MFA/LCA is a new approach, and few studies have been published on the topic, although some MFA-LCA studies have been conducted in recent years, most of which focussed on waste management and GHG inventory. Table 2-4 lists come of the LCA studies conducted at a city level. Moreover, to the best of our knowledge, to date no MFA-LCA study concerning the building stock in Saudi Arabia has been published.

MFA can be employed to account for the direct material flows of the cities. While MFA provides aggregated indicators that are considered to be generic pressure indicators, it does not indicate specific environmental impacts (Liu, Wang and Yang, 2009). Integrating MFA results with LCA method enable the analysis and assessment of these impacts. However, there are several drawbacks in LCA. The most important issue is the collection of high-quality data as input data for LCA studies (Finnveden, 2000; Testa *et al.*, 2016). Also, defining the boundaries must be made explicit and how far upstream to take the analysis is still problematic in LCA.

Table 2-4 A sample of the LCA studies conducted at a city level.

City or city region	Notes / description	Focus	Source
New York	Comparing combined sewer overflow control strategies in New York (Bronx river).	EIO-LCA	De Sousa, M. R. C., Montalto, F. A. and Spatari. S. 2012. Using Life Cycle Assessment to Evaluate Green and Grey Combined Sewer Overflow Control Strategies. *Journal of Industrial Ecology.* Volume 16 (6) 901:913.
Los Angeles County, Denver City and County, Greater Toronto, New York City, Greater London, Geneva Canton, Greater Prague, Barcelona, Cape Town, Bangkok	Inventorying GHG emissions in the ten cities or city regions.	LCA	Kennedy, C, A., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havránek, M., Pataki, D., Phdungsilp, A., Ramaswami, A. and Villalba Mendez, G. 2010. Methodology for inventorying GHG emissions from global cities. *Energy Policy* 38 (4828:4837).
Norway	A dynamic stock model with an optimization routine to identify and prioritize buildings with the highest energy-saving potential. Applied LCA technique to extend the sectoral boundary beyond direct household emissions.	MFA-LCA	Pauliuk, S., Sjöstrand, K. and Müller, D.B., 2013. Transforming the Norwegian dwelling stock to reach the 2 degrees Celsius climate target: Combining material flow analysis and life cycle assessment techniques. *Journal of Industrial Ecology*, 17(4), pp.542–554.

2.3 Research needs and future directions

MFA is not an evaluation or assessment tool, rather it is an accounting instrument that can be employed to describe the metabolism of a system. With this system understanding, additional assessment methodologies and approaches can be employed to interpret the results. The results can be integrated into static or dynamic models. Previous authors suggested the linking of MFA and LCA to improve the understanding of how city processes and decisions trigger regional and supply chain effects, beyond the urban boundary (Chester, Pincetl and Allenby, 2012; Reyna and Chester, 2015). There is a growing need to integrate MFA with LCA to investigate the impact of urban development, especially in developing countries that experience a high rate of urbanization. The present research study sought to fill this gap by applying a DMFA-LCA framework to Riyadh, Saudi Arabia. Data related to MFA would be collected based on a set of indicators using locally generated data (please refer to chapter 4 and 5).

Riyadh is the largest population centre in the Arabian Peninsula. The population of Riyadh has grown from almost one million in 1980 to nearly six million at the time of writing and is expected to reach 8.2 million by 2029 (Riyadh Development Authority, 2016). Between 2004 and 2010, the population of Riyadh grew at a rate of 4% annually. The increase in the population remains the most notable feature of Riyadh and has engendered the growth of other sectors.

Chapter 3 **Overall Methodology**

In this chapter, a short overview of the methodology that will be used to achieve the objectives of this thesis will be outlined. It provides a general description of the overall approach to answering each of the research questions.

3.1 Introduction

This study was motivated by the need to assess the environmental sustainability of urban ecosystems, defined here as areas where the built environment covers a large proportion of the land surface (Pickett *et al.*, 2001). Based on this motivation, the study objectives and research questions were determined and presented in sections 1.3 and 1.5. The research questions have been employed as a basis upon which to design the study methodology. The literature review was conducted to help select the appropriate methodology for the analysis. It was found from the literature conducted in chapter (2) that MFA provides metrics for assessing urban ecosystem and tools such as LCA can be integrated with MFA to improve the understanding of how city processes (e.g. electricity, water) trigger regional and supply chain effects. Moreover, extending the scope of analysis to include additional critical urban indicators; including biophysical and socio-economic will provide information describing the built environment and characteristics of its population. The following sections provide an overview of the methodology applied in this thesis.

3.2 MFA-LCA approach

This relates to research questions (1) and (2) as these questions attempt to determine the environmental profile of the city under study. To this purpose, a combined MFA-LCA will be used to first quantify the overall resource consumption for the city understudy and then assess the related environmental impacts. Figure 3-1 shows the schematic representation of flows considered MFA-LCA approach. These flows represent the major flows of a city and contribute the most to a city's ecological footprint (Barles, 2010; Moore, Kissinger and Rees, 2013; Wilson, Tyedmers and Grant, 2013).

The MFA method applied in this thesis following the Eurostat (2001) methodology. Based on this methodology, the flows should be classified as input flows and output flows. Input flows can be energy, materials, and water while output flows can be solid waste, wastewater, and emissions to air. However, input and output flows in this method are classified as direct flows. In order to assess the indirect flows LCA will be used in this thesis to further the understanding of the environmental impacts of these flows.

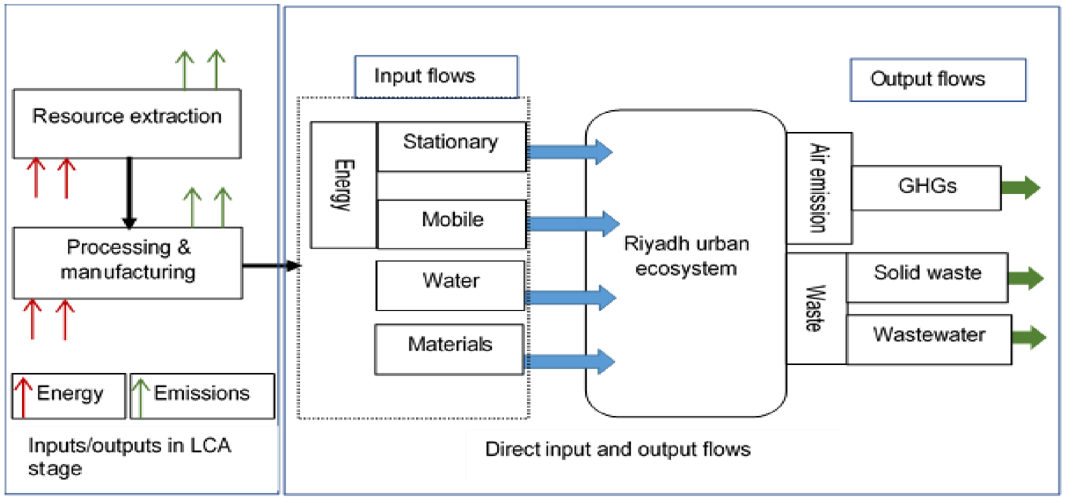


Figure 3-1 Schematic representation of flows considered MFA-LCA approach.

3.2.1 MFA of Riyadh's urban ecosystem

The urban ecosystem was defined earlier as areas where the built environment covers a large proportion of the land surface. Conducting MFA can be performed on different scales from global, national, or at city scale (Lopes Silva *et al.*, 2015). In several studies, MFA has been applied at the city level to provide an accounting of the total consumption of resources and the associated impacts in terms of GHG emissions (Ramaswami, Chavez and Chertow, 2012; Pauliuk, Sjöstrand and Müller, 2013b; Niza *et al.*, 2015; Dias *et al.*, 2018; Lavers Westin *et al.*, 2019). At the city level, this accounting is based on consumption data for products or services under study.

Because of the growing need for basic empirical data about cities' physical and environmental characteristics, there have been several attempts to create a set of indicators based on an MFA approach, in order to guide cities to achieve sustainability objectives (Kennedy and Hoornweg, 2012; Kennedy *et al.*, 2014; Mostafavi, Farzinmoghadam and Hoque, 2014; Conke and Ferreira, 2015). These studies attempted to address the issue of the lack of standardization in urban MFA and to establish principles for establishing system boundaries (Voskamp et al., 2016).

This thesis will use MFA-based framework of indicators to study the flows of material and energy in Riyadh, Saudi Arabia, for the years 1996, 2006, and 2016, thereby employing Riyadh as a test subject for the proposed framework. The selection of these years is based on data availability and it will help in recognising the temporal trends of resources consumption of the city. To assist with data collection, Table 3-1 shows the set of indicators that will be used in this study. The set of indicators developed from the literature as reported in (Kennedy and Hoornweg, 2012; Kennedy *et al.*, 2014; Mostafavi, Farzinmoghadam and

Hoque, 2014; Conke and Ferreira, 2015). The direct input and output flows of Riyadh will be determined based on this table. Further details on how each component is calculated is provided in Chapter 4.

Table 3-1 MFA flows and indicators

MFA component		Unit
Input flows	Source	
Energy (production)	Fuel oil	TJ
	Natural gas	TJ
	Primary energy factor	
	Distribution loss	%
Energy (stationary)	Electricity consumption (total)	GWh
	Residential	GWh
	Commercial	GWh
	Industrial	GWh
	Government and services	GWh
	Others	GWh
	Energy end-use	
	Air conditioning (AC)	%
	Heating	%
	Water heating	%
	Lighting	%
	Food preservation	%
	Others	%
Household fuel consumption	LPG	TJ
Energy (mobile)	Gasoline	TJ
	Diesel	TJ
	Jet fuel (kerosene)	TJ
Water flow	Water consumption total	kt
	Water production (wells)	kt
	Desalination	kt
	Distribution loss	%
Construction materials	Cement production	tonne/ year
	Steel	
	Aggregate	
Emissions	GHG of power generation	t-$CO_{2\ e}$
	GHG of energy use	t-$CO_{2\ e}$
	GHG of transport sector	t-$CO_{2\ e}$
Solid waste	Total municipal waste	tonne/ year
	Construction and demolition waste	tonne/ year
	Recycled waste	%
Wastewater	Total wastewater	ML
	Recycled wastewater	%

3.2.2 Socio-economic and biophysical indicators

Although the integrative framework is focused on the environmental side of the sustainability equation, extending MFA to include the social and economic dimensions of a society is an important step suggested by several studies for achieving meaningful results (Sinclair *et al.*, 2005; Kennedy, Cuddihy and Engel-Yan, 2007; Weisz and Steinberger, 2010; Chester, Pincetl and Allenby, 2012; Pincetl, Bunje and Holmes, 2012; Rochat *et al.*, 2013; Kennedy *et al.*, 2014; Pincetl *et al.*, 2014a; Fang *et al.*, 2017; Carbajo and Cabeza, 2019). However, the analysis of the social and economic aspects of sustainability is beyond the scope of this thesis. Instead, this study attempts to provide information on several indicators related to the social and economic status of the city. These indicators are selected based on a literature review.

Also, MFA typically assesses the flows resulting from the built environment and analyses their trends. However, understanding the characteristics of the built environment where the transformation of these flows occurs, is necessary to widen the understanding of the issues related to sustainable development. For the abovementioned reasons, this study will include socio-economic and biophysical indicators to provide a better understanding of trends of resources consumption by the city. Two steps are taken to develop the set of indicators required. The first involved reviewing the related literature to identify these indicators, and the second involved determining the appropriate sources of data collection.

One of the latest attempts to create a framework targeting sustainability objectives that is applicable worldwide is the United Nation Sustainable Development Goals (United Nations, 2016). Also, a multi-layered indicator set for studying urban energy and material flows was proposed by Professor Christopher Kennedy. The socio-economic and biophysical indicators will be selected based these two sources as they have been used in several recent and similar studies as in Pincetl et al*.* (2014), Kennedy et al. (2015), Facchini et al. (2017), and Gonzalez-Garcia et al. (2018). Based on these sources, this study will use the set of indicators as illustrated in Table 3-2. The inclusion of these indicators will help answer the research question (2).

Table 3-2 Socioeconomic and biophysical indicators

	Indicators
Socioeconomic indicators	Population
	Density
	Household size
	Household formation rate
	Housing stock
	Households
	Housing units density
	Dwelling type
	Floor of housing area per person
	Unemployment rate
	Average annual income in US dollars (USD)
	GDP per capita
	Household connections to public water network
	Household connections to public wastewater network
	Transport modes
	Automobile ownership
	Travel time (minutes/trip)
	% Wastewater treatment
	Solid waste per person/day
	Recycle solid waste
Biophysical indicators	Land area (sq. kilometres)
	Urbanized area (sq. kilometres)
	Heating degree days (18°C base)
	Cooling degree days (25°C base)
	Annual solar radiation (kWh/m^2/year)
	Annual precipitation (mm)
	Land area km^2 (developed areas)
	Land area km^2 (Vacant land areas)
	Building gross floor areas (m^2)
	Residential building gross floor areas (millions m^2)

3.2.3 LCA method

In this thesis, LCA method will be used to provide a quantitative assessment of environmental impacts of energy and material flows that are derived from the MFA study. This will help determine the overall interactions between the city ecosystem and the environment. The goal of conducting the LCA is to assess a city's environmental profile, taking into account the direct and indirect flows. The flows that contribute the most to the environmental impact in a city will be identified using the cradle-to-gate approach. The cradle-to-gate approach considers all energy consumption from the upstream stages, including raw material extraction to the final stage as a finished product (Dixit *et al.*, 2010). Since the upstream processes are a result of the city's demands, it is appropriate to select this approach instead of cradle-to-grave (full life cycle) (García-Guaita *et al.*, 2018).

3.2.3.1 The functional unit

The functional unit in a typical LCA study is defined as a reference unit that quantifies the performance of the system being studied (ISO, 2006). It also is used to compare the performance of different systems. However, in terms of cities, the choice of the functional unit is challenging, due to the different systems within the city, and selecting a unit that can quantify the performance of all of these systems would be practically impossible. However, several studies suggested the use of population factor to overcome this challenge. Therefore, the LCA analysis in this study will be performed according to per capita. The selection of this functional unit concurred with the approach of several previous studies (Goldstein *et al.*, 2013; Dias *et al.*, 2014; Roibás, Loiseau and Hospido, 2017; García-Guaita *et al.*, 2018).

3..2.3.2 System boundaries

As noted previously, the system boundary of the LCA stage in this study will be based on a cradle-to-gate approach. The selection of this system boundary provided a better understanding of the impact of urban growth and the demand of the associated services since the increase in demand engendered an increase in energy and emissions resulting from the production of these services. The primary data used for the lifecycle inventory for the flows studied will be taken from the MFA study.

3.2.3.3 Impact assessment

The LCA software, SimaPro, developed by PRé Sustainability, is widely used in LCA studies. It can be employed to handle the data resulting from the MFA stage, as evidenced by several studies, such as those conducted by Rochat et al. (2013), Lopes Silva et al. (2015), Sharib et al. (2017), García-Guaita et al. (2018), Gonzalez-Garcia et al. (2018), and Lavers Westin et al. (2019). The impact assessment method selected for this study was the ReCiPe2016, based on a midpoint perspective (Huijbregts et al., 2017). This is conducted by applying midpoint parameters, according to the ReCiPe 2016 (hierarchist perspective) method, which is based on a scientific consensus regarding the timeframe and plausibility of the impact mechanisms (Huijbregts et al., 2016). This method is commonly employed in life cycle impact assessments (LCIA), as it is the most up-to-date method. Similar studies also employed this method, including those conducted by Goldstein et al. (2013), García-Guaita et al. (2018), and Gonzalez-Garcia et al. (2018), which will support a comparison with these studies.

This stage will translate the inventory data (inputs and outputs) into environmental impact scores, using different characterization factors. There are 17 midpoint categories, including global warming (GW), ozone depletion (OD), fine particulate matter ($PM_{2.5}$), terrestrial acidification (TA), freshwater eutrophication (FE), and fossil resource scarcity (FS), as illustrated in Figure 3-2. Together, these impact categories provide a complete and comprehensive synopsis of the environmental problems associated with cities.

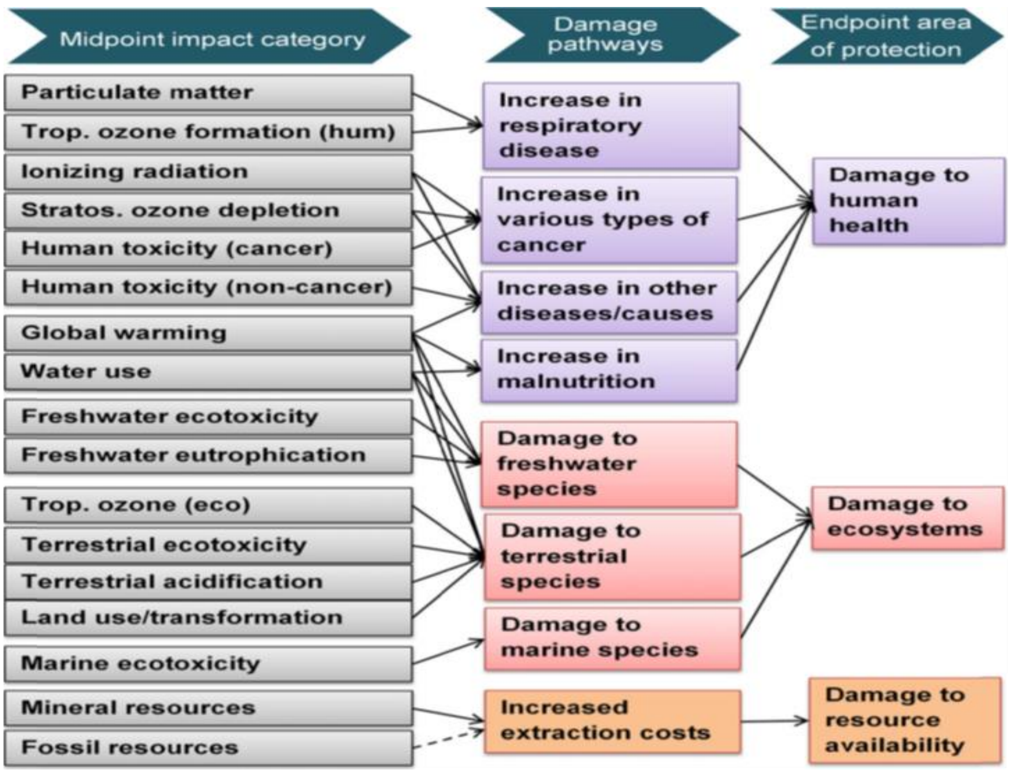


Figure 3-2 Overview of the ReCiPe2016 impact categories. (Source: Huijbregts et al., 2017).

In this study, however, the assessment was based on only five impact categories: climate change, particulate matter formation, freshwater ecotoxicity, water consumption potential, and fossil fuel potential. The impacts selected provided a comprehensive assessment of the relationship between urban material flows and the environment (Goldstein *et al.*, 2013). Moreover, the impact categories selected provided an opportunity to compare the results of the present study with those of similar studies, such as those conducted by Goldstein *et al.* (2013), García-Guaita *et al.* (2018), and Gonzalez-Garcia *et al.* (2018).

In addition to assessing the environmental impacts of the direct flows, LCA will be used to estimate the embodied energy based on a cradle-to-gate boundary. This boundary can be defined as the energy consumed up to the use phase. While this embodied energy can be divided in two parts, initial embodied energy, and recurring embodied energy (Ramesh, Prakash and Shukla, 2010), this study only considered the initial embodied energy and did not consider the entire life cycle of the system studied.

The components of material flow considered to assess embodied energy are water production, energy production, and construction material production. The initial embodied energy (EE_i) is expressed as follows:

$$EE_i = \sum m_i . M_i \qquad \textit{Equation 3.1}$$

Where m_i is quantity of the materials studied, and M_i is the energy content.

The embodied energy values will be calculated in SimaPro using the Cumulative Energy Demand (CED) method (also known as primary energy consumption). Using this method will enable determining the energy intensity of energy and material flows understudy (Röhrlich *et al.*, 2000). Further details on estimating the embodied energy for each MFA component are given in Chapter (4).

3.3 Dynamic MFA-LCA approach

The method presented here is related to research questions (3, 4, 5). The MFA-LCA approach presented in section 3.2 quantifies and assess the flows and stocks in a defined system (defined here as the city ecosystem) for a given time. To further the understanding of the city's ecosystem, this thesis will develop a hybrid Dynamic MFA-LCA method and applied to the housing stock in the city of Riyadh, Saudi Arabia. This step takes advantage of the valuable information provided by the MFA-LCA approach in section 3.2 in that it will shed light on how the system performs over time.

3.3.1 System definition

The model proposed in Figure 3-3, consists of three sub-systems, as indicated in In subsystem (1) A_p represents floor area per capita. The rectangles represent processes, while the oval shape depicts flows and the hexagons show drivers or determinants. Moreover, the dashed lines show the influence between variables. These variables include: A: floor area, dA/dt: stock accumulation of floor area, dAin/dt: input flow of floor area, dAout/dt: output flow of floor area, M: materials stock, dM/dt: sock accumulation of materials, dMin/dt: input flow of materials, dMout/dt: output flow of materials. The factors characterised as determinants are population (P), per capita floor area (Ap), and building lifetime.

For sub-system (2), service intensity factors are introduced. The extension of the stock dynamic model here considers energy and water consumption to be related to dwelling stock. The factors used are based on historical per capita values. Using intensity values to estimate resources (e.g., material, energy, water etc.) consumption has been the main method reported in the literature (Lanau *et al.*, 2019). Demand associated with increased stock can be estimated either by per capita (Kapur *et al.*, 2008; Pauliuk, Wang and Daniel B Müller, 2012; Zucaro *et al.*, 2014; Pardo Martínez, 2015), by per square metre of built area (Sandberg and Bratteb, 2012; Sandberg *et al.*, 2016), or per GDP (Xiang, Xu and Sha, 2013; Fishman, Schandl and Tanikawa, 2015). In this study, an intensity per capita factor was used. Adopting this approach permits evaluation of dwelling stock over time (Fang *et al.*, 2017; Göswein *et al.*, 2019; Lanau *et al.*, 2019).

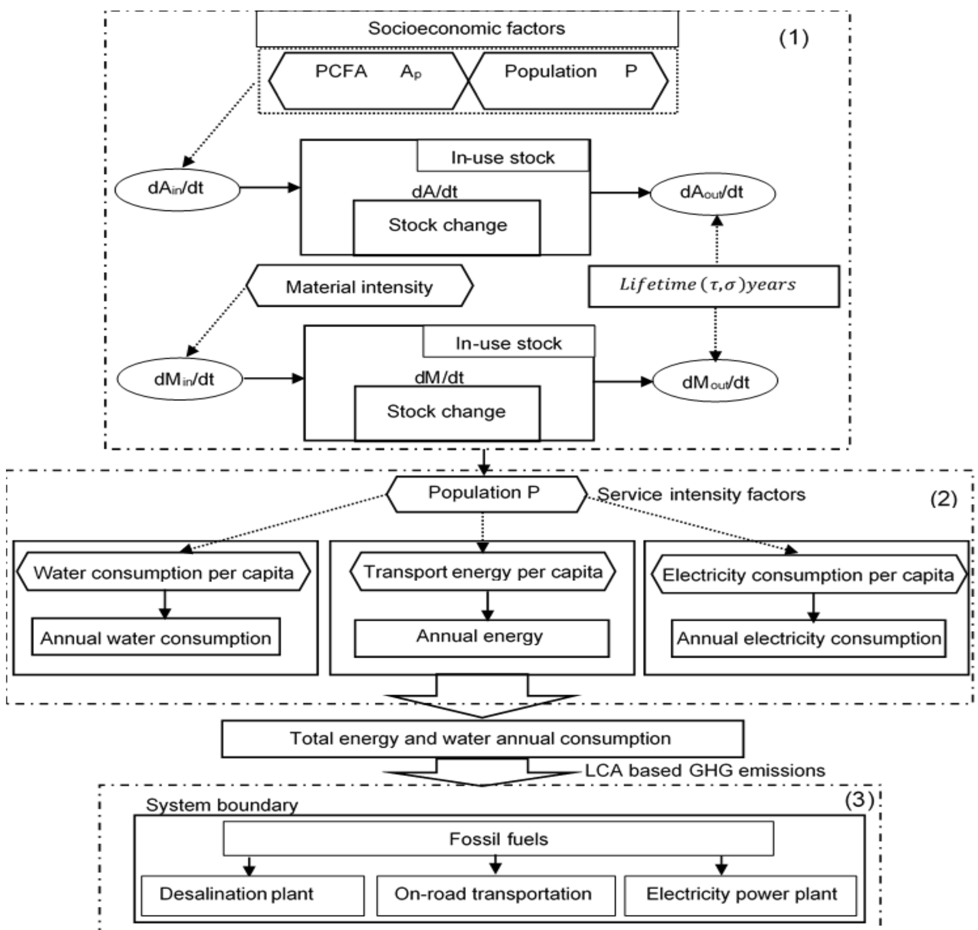


Figure 3-3 System definition for the integrative approach.

(1): Stock dynamic model, (2): extended service intensity factors, (3): LCA on background processes. Hexagons represent input parameters, rectangles represent processes, ovals represent flows

Resource intensity provides measurement of materials and energy needed for the production of a unit of a good or service (Müller, 2006). In this thesis, the intensity-of-use (floor area) is defined as floor area demand per capita.

Data on intensity per square metre is rarely available in the Saudi context. In this study, the main drivers forces of the model are population (*P*) and lifestyle, as represented by floor area per capita (A_p) and shown in equation (3.2).

$$A(t) = P(t) \cdot A_p(t)$$ Equation (3.2)

To determine the input and output flows for floor area, information about the building's lifetime needed to be added. There is no data available regarding building lifetime in Saudi Arabia; therefore, a normal distribution is used with the default mean lifetime τ and standard deviation equal to 40 years and 8 years, respectively, as shown in equation (3.3).

$$L(t,t') = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(t-t'-\tau)^2}{2\sigma^2}}$$ Equation (3.3)

Building upon data from equation (3.3), the probability that housing units built in year t will be demolished in year t is determined by equation (3.4).

$$\frac{dA_{out}(t)}{dt} = \int_{t_0}^{t} L(t,t') \cdot \frac{dA_{in}(t')}{dt} dt'$$ Equation (3.4)

In equation (3.5), the future floor area inflow is determined by adding demand for new housing and outflow of floor area together. Up to this point, the model deals with inflows and outflows affecting stock changes in floor area.

$$\frac{dA_{in}(t)}{dt} = \frac{dA(t)}{dt} + \frac{dA_{out}(t)}{dt}$$ Equation (3.5)

By adding two more parameters, we can estimate corresponding materials and energy. Equation (3.6) determines the dynamics of corresponding materials (stocks and flows), by introducing a material intensity parameter (M_{in}).

$$\frac{dM_{in}(t)}{dt} = \frac{dA_{in}(t)}{dt} \cdot M_A(t)$$ Equation (3.6)

Equation (3.7) determines material outflow based on the probability that materials entering the system in year t would exit the system as outflow in year t.

$$\frac{dM_{out}(t)}{dt} = \int_{t_0}^{t} L(t,t') \cdot \frac{dM_{in}(t')}{dt} dt' \qquad \text{Equation (3.7)}$$

Equation (3.8) determines the balance equation for material stock.

$$\frac{dM(t)}{dt} = \frac{dM_{in}(t)}{dt} - \frac{dM_{out}(t)}{dt} \qquad \text{Equation (3.8)}$$

Similarly, by adding an energy intensity parameter (e_i), the corresponding energy flows (E) are determined as shown in equation (3.9) and the same approach is used for the water intensity parameter, as shown in equation (3.10)

$$E(t) = A(t) \cdot e_i(t) \qquad \text{Equation (3.9)}$$

As mentioned before, the use of energy intensity per square metre is widely applied in stock dynamic analysis (Pauliuk, Sjöstrand and Daniel B Müller, 2013; Pauliuk and Müller, 2014; Sandberg, Sartori, Magnus I. Vestrum, *et al.*, 2016, 2017; Vásquez, Amund N Løvik, *et al.*, 2016); however, intensity per capita is the preferred method in cases where detailed data concerning stock is lacking.

$$W(t) = A(t) \cdot w_i(t) \qquad \text{Equation (3.10)}$$

All data and assumptions related to the model parameters will be presented in chapter 5 along with the results.

For sub-system (3), this study advances the assessment by introducing in-use intensity parameters (electricity use, transportation energy use, and water) and a life cycle perspective assessment of the model considering both these parameters. The aim is to provide a system-based approach to environmentally evaluate the stock and its development to 2050.

LCA is introduced to assess the impacts associated with the flows provided by the city as a way to maintain a good quality of life. The results related to energy and water flows can be obtained from a stock dynamic model for use as an inventory to carry LCA. Applying LCA only provides an effective evaluation of the system at a given point in time, but it can also serve as a basis for determining different scenarios relating to development, policies, and technology to be assessed. The system's boundary is based on cradle to gate, and the functional unit is foregone in this part of the study. The selection of not including a functional unit is determined by several factors. As stated by Goldstein and others, defining a functional unit for LCA in urban areas is a complex challenge, because cities have different populations with different lifestyles and provide different service qualities (Goldstein *et al.*, 2013). While the functional unit was defined in section 3.2 as per capita, it was intended to serve the objective of conducting the LCA by assessing how the city is impacted by its inhabitants. Additionally, LCA was described as being used to assess the current status of the city without predicting figures for future development. However, there have been recent calls to advance the LCA methodologies applied to urban centres to afford better guidance for a functional unit for LCA to be applied to cities (Albertí *et al.*, 2017).

On the issue of the impact assessment, ReCiPe 2016, a hierarchical midpoint was chosen to assess climate change, as reported as GWP. The LCA calculation will be performed using SimaPro software.

A note must be made regarding integrating LCA with the stock dynamic model. Several studies have attempted this approach and the majority also applied LCA to quantify GHG in association with upstream activities (Pauliuk, Sjöstrand and Müller, 2013; Pauliuk and Müller, 2014b). However, there is a limitation imposed on this integration. The assessment of background processes (upstream) was based on datasets that are static in nature. As a consequence, these data do not capture changes in processes over time, such as the energy mix.

In Chapter 6, however, different scenarios will be developed based on this model to capture the impact of these changes. This will provide an answer to the research question (6).

Chapter 4 **MFA-based assessment of urban ecosystem sustainability**

This chapter provides an overview of the contribution of MFA to the assessment of the sustainability of urban regions. It proposes a set of indicators, based on an integrated approach tool that combines MFA, LCA, and biophysical and socioeconomic indicators, for analysing the sustainability of the urban development of cities, considering environmental, social, and economic parameters. The issues surrounding urbanization, and the steps currently taken towards sustainable development are reviewed, and the environmental impact of urban growth and development in Riyadh, Saudi Arabia, is analysed.

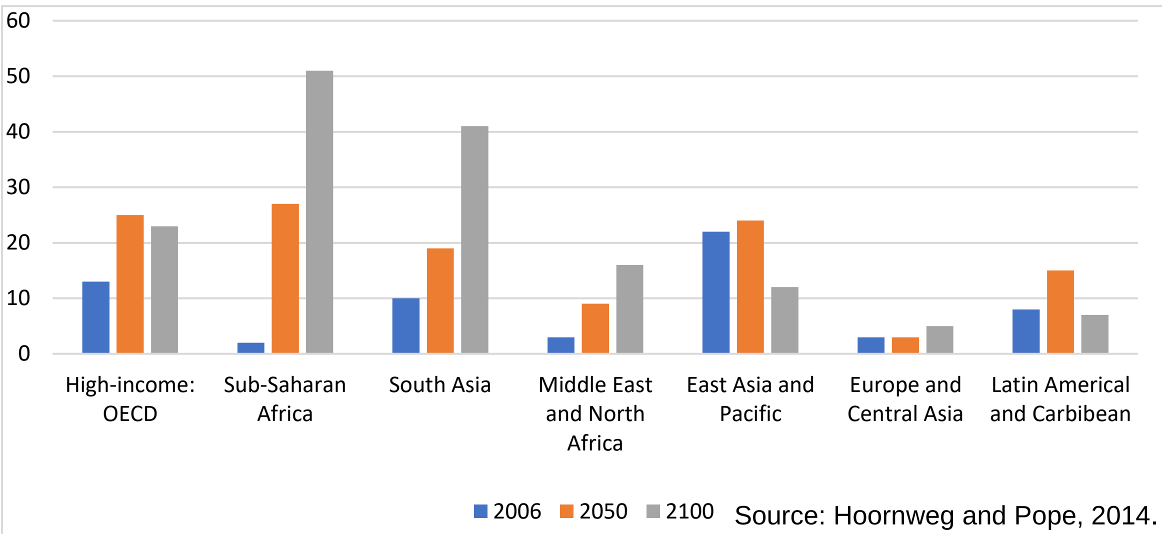
4.1 Background

During the 20th century, cities worldwide grew dramatically in terms of population and influence. In 1900, approximately 16% of the global population lived in urban centres. This percentage increased to 46.8% in 2000 (Klein Goldewijk et al., 2010). In the 21st century, the urban population is expected to increase to 60% by 2030 (United Nations, 2018), and some scholars argue that the urbanization of the world is an irreversible process (Baccini and Brunner, 2012). As Figure 4-1 shows, urban regions are located all over the globe. Moreover, cities are considered to be the most complex systems ever created by humans (Götz et al., 2017; Grimm et al., 2008; Hodson et al., 2012).

(Source: https://earthobservatory.nasa.gov/images/90008/night-light-maps-pen-up-new-applications

Figure 4-1 Earth by night in 2016.

Figure 4-2 shows the predicted rise in population of the world’s 101 largest cities by 2100 (World Urbanization Prospects, WUP, extrapolation), illustrating the shift in the relative influence of cities that is anticipated to occur during the 21st century, showing the world's cities with populations of five million or more. In 2006, there were 50 cities with populations of over five million. By 2050, that number is expected to increase to 122, with the number of cities of that size in East Asia beginning to decline, while those in sub-Saharan Africa are expected to increase from six in 2006 to 27 by 2050, making it the region with the most cities with a population of over five million. This trend is anticipated to continue to the close of the century, when there are expected to be 155 cities with populations in excess of five million, 51 in sub-Saharan Africa, and 41 in South Asia, while the number in East Asia is anticipated to plummet to just five. In demographic terms, the 21st century is expected to witness the relative decline of East Asia, especially China and Latin America, and the rise of Africa and South Asia (Hoornweg and Pope, 2014).



Source: Hoornweg and Pope, 2014.

Figure 4-2 Cities with population over five million, by region.

Cities, throughout history, have overcome limits on local energy availability, with connections to remote sources of food, water, fuel, and materials being a key feature of urbanization (Decker et al., 2000). This motivated many studies to attempt to analyse the ecological footprint of cities. One primary conclusion of these studies was that the carrying capacity of the ecosystem to support city development is becoming increasingly scarce, due to the rapid increase in urban population, and the intensified use of natural resources (Piña and Martínez, 2014). Therefore, the impact of urban development and city expansion has become the main argument in sustainable development discussions in recent years. One potential approach to assessing the sustainability of urban development, and the built environment in general, is MFA that seeks to estimate urban material and energy flows. It applies industrial ecology to the quantification of the flows of materials, such as construction materials and nutrients, and energy, as these flows enter, accumulate, and exit the urban system (Barles, 2009).

This chapter aims to evaluate the contribution of MFA-LCA approach to the assessment of the environmental sustainability of cities in developing countries by taking Riyadh, Saudi Arabia as a case study. To define the scope of the analysis the following two questions are posed:

1. What are the environmental impacts of an urbanizing population?
2. What are the most influential factors through which these impacts occur?

This chapter will provide a review of the role of MFA in recent studies related to sustainable development. Also, it will provide further details on the methods used to answer the research questions.

4.2 The role of MFA in assessing environmental sustainability

As stated before, the focus of this study will be on the environment side of sustainability. This study applies the concept of environmental sustainability as define by Morelli (2011) which is "condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity". Moreover, sustainable development is not easy to measure. In recent history, the UN has played a vital role, not only in defining what sustainable development is, but also in developing tools that many countries have adapted for their own pursuit of sustainability. In 1987, the World Commission on Environment and Development (WCED) published the Report of the world commission on environment and development our common future, which is described as the origin of the consideration of approaches to sustainability (Carbajo and Cabeza, 2019). Other global institutions that play a role in supporting sustainable development included the World Bank, and the International Organization of Standards.

Over the last few decades, numerous key international guidelines and codes of practice have emerged, including the consumption-based accounting indicators, Leadership in Energy and Environmental Design (LEED), and the Building Research Establishment's Environmental Assessment Method (BREEAM). Meanwhile, another important city-focussed agency is UN-Habitat, which, alongside the United Nations Development Programme and the Global Taskforce of Local and Regional Governments, developed the Sustainable Development Goals (SDG) Table 4-1, which have become widely accepted as a framework for cities to employ as a guideline for sustainable development transition. Moreover, within the built environment, there are currently more than 600 sustainability assessment rating systems worldwide (Poveda and Lipsett, 2014). The benefits of these frameworks are that they provide measures and indicators for sustainability assessment in that these indicators can be used yearly to show progress toward a set of targets and benchmark.

Table 4-1 The United Nations Sustainable Development Goals (SDGs)

Selected Sustainable development goals	
Goal 1. End poverty in all its forms everywhere	Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Goal 10. Reduce inequality within and among countries
Goal 3. Ensure healthy lives and promote well-being for all at all ages	Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Goal 12. Ensure sustainable consumption and production patterns
Goal 5. Achieve gender equality and empower all women and girls	Goal 13. Take urgent action to combat climate change and its impacts
Goal 6. Ensure availability and sustainable management of water and sanitation for all	Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all	Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development	

The SDGs that are relevant to the scope of the present study are summarized and presented in Table 4-2, which also provides examples of MFA studies related to each goal. A summary of the role of MFA in achieving the relevant goal is discussed below.

Table 4-2 SDGs and assessment measures of MFA application for achieving them.

Select SDGs	Examples of MFA studies	Assessment measures from MFA studies	Assessment measures set by UN SDGs
Goal 6: Ensure the availability and sustainable management of water and sanitation for all.	López-Villarreal *et al.,* 2014; Montangero *et al.,* 2007	Pollutant concentration. Water consumption by source.	Population connected to at least secondary wastewater treatment. Water exploitation index by type of water source.
Goal 7: Ensure access to affordable, reliable, sustainable, and modern energy for all.	He *et al.,* 2017; Hoque *et al.,* 2012; Khonpikul *et al.,* 2017; Sandberg and Bratteb, 2012	Primary energy intensity. Carbon emissions. Total carbon emissions. Energy intensity of materials. Consumption of non-renewable materials.	Primary energy consumption. Final energy consumption in households per capita. Energy productivity. Share of renewable energy in gross Final energy consumption by sector. GHG intensity.
Goal 9: Build a resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.	Bai *et al.,* 2019; Kapur *et al.,* 2009; Meng *et al.,* 2017; Pauliuk *et al.,* 2012; Shi *et al.,* 2012	Per-capita annual consumption of material stock of buildings and infrastructure. Embodied carbon emissions. Average annual net addition of in-use. Material intensity factors.	Gross domestic expenditure on Research and Development (R&D) by sector. Share of buses and trains in total passenger transport. Average CO_2 emissions per km from new passenger cars.
Goal 11: Make cities and human settlements inclusive, safe, resilient, and sustainable.	Browne *et al.*, 2005; García-Guaita *et al.,* 2018; Gonzalez-Garcia *et al.,* 2018; Li *et al.,* 2015; Voskamp *et al.,* 2016	Total input of materials per year. Total output flows per year. Production and use of energy per type of use. GHG emissions per capita.	Overcrowding rate by poverty status. Difficulty in accessing public transport by level of difficulty and degree of urbanization. Exposure to air pollution by particulate matter. Recycling rate of municipal waste. Population connected to at least secondary wastewater treatment. Share of buses and trains in total passenger transport.
Goal 12: Ensure sustainable consumption and production patterns.	Giljum *et al.*, 2011; Liu *et al.*, 2009; Wolff and Schönherr, 2011	Material consumption per household. GHG emissions from household consumption. Material consumption of cities. Water footprint of cities.	Resource productivity and domestic material consumption (DMC). Average CO_2 emissions per km from new passenger cars. Circular material use rate. Recycling rate of waste excluding major mineral wastes. Primary energy consumption.
Goal 13: Take urgent action to combat climate change and its impacts.	Byrne and O'Regan, 2016; Dahlbo *et al.,* 2015; Lavers Westin *et al.,* 2019; Milford *et al.,* 2013; Pauliuk and Müller, 2014; Pauliuk *et al.,* 2013;	Total material stock in-use. Total emissions per year. Energy stationary and energy mobile consumption. Transport modes. Transport CO_2 from all modes of transport.	GHG emissions. GHG emissions' intensity of energy consumption. Climate related economic losses by type of event. Primary energy consumption. Final energy consumption. Share of renewable energy in gross final energy consumption, by sector. Average CO_2 emissions per km from new passenger cars.

4.2.1 MFA potential for assessing SDG goal (6)

In their study, López-Villarreal et al. (2014) developed an MFA-based model to study and evaluate the sustainability of the surrounding watershed, with a focus on pollutant trading strategy in the watershed. The use of MFA enabled them to track the pollutant behaviour in the watershed, and facilitated better practices for assuring water quality standards, as well as the avoidance of the creation of places with high pollutant concentrations.

Meanwhile, Montangero et al. (2007) indicated that MFA proved to be an effective tool for analysing resource flows, and evaluating the impact of different consumption patterns, as well as solid waste, wastewater, and wastewater reuse practices on resource consumption and environmental pollution. They employed a previously developed MFA tool by Montangero (2006) to assess the impact of changes in Hanoi’s environmental sanitation and agricultural practices on groundwater abstraction and phosphorus recovery in peri-urban agriculture. Applying an MFA in this context facilitated the identification of the most influential parameters that could assist in designing effective measures. This study constituted an example of the effectiveness and usefulness of MFA results and recommendations, for instance, it demonstrated that by promoting the improvement of the water distribution system, and increasing the recycling rate of grey water, the groundwater abstraction could be reduced by a third.

4.2.2 MFA potential for assessing SDG goal (7)

The study conducted by Khonpikul et al. (2017) employed MFA and an input/output analysis (IOA) to evaluate the options available for improving and evaluating the trade-off between economic and environmental performance in the livestock and feed production supply chain in Thailand. In this study, an MFA model facilitated the assessment of direct and indirect resource consumption, namely energy and water, and demonstrated the significance of an MFA model for developing scenarios to evaluate the effectiveness of the improvement options.

Meanwhile, Hoque et al. (2012) used an MFA to evaluate and analyse patterns of the resource consumption construction sector in Catalonia, Spain. Another goal in the use of MFA is to pinpoint opportunities for improving material selection, processing, reusing, and recycling, in order to promote better sustainable practices in resource use. The results of this study showed that MFA provided a comprehensive evaluation of the resource consumption in the construction sector that could prove to be useful for developing future strategies to improve the energy efficiency of others involved in the sector. For example, energy-intensive materials, such as metal, plastic, wood, glass, and ceramic represented 15% of the total material input, in terms of mass; however, they accounted for 69% of the total exergy input in the sector. This signified the importance of improving the manufacturing stage for optimizing efficient resource use.

In another study, He et al. (2017) developed an MFA model intended to analyse the energy consumption and carbon emissions of steelmaking plants in China. The study concluded that the model was a reliable instrument for characterizing material flows and stocks within different systems, and that MFA is convenient for studying changes in energy consumption and carbon emissions. Moreover, it demonstrated that MFA can be used to forecast future flows and emissions, along with empirical and scenario analyses. The results of the study revealed that reducing coal consumption is the primary requirement for achieving a significant reduction in carbon emissions, and improving energy efficiency.

Meanwhile, Shi et al. (2012b) studied the increased demands of building and infrastructure in China, and what this demand requires in terms of the large amounts of construction materials involved. They applied an MFA framework to forecast future steel and cement demand, and associated resource consumption and CO2 emissions. The study highlighted the importance for societies to address the issue of the consumption of limited raw materials, and an MFA framework was developed to help provide guidelines to protect the environment and mitigate global warming. The study sought to determine the amount of steel and cement required for the building and transportation infrastructure in the future, together with the associated emissions, and concluded that the MFA results could be used to guide officials to better control the consumption of steel and cement, and to reduce CO2 emissions, thereby progressing towards a low carbon–dematerialization society. For example, one scenario developed in this study demonstrated that extending the lifetime of buildings and infrastructure can reduce resource consumption and CO2 emissions. Another example in the study that illustrated the contribution of MFA to the field showed that the amount of material demand and the CO2 emission peak changed, depending on the lifetime scenarios, which indicated the usefulness of MFA for forecasting the amount and timing of a peak, and for policy making.

4.2.3 MFA potential for assessing SDG goal (9)

The study conducted by Meng et al. (2017) developed an integrative framework that included MFA, Cumulative Energy Demand (CED), an exergy analysis (EXA), an Energy Assessment (EMA), and emissions (EMI) to examine the energy efficiency of the high speed urban bus transportation systems in the city of Xiamen, China, comparing the results with conventional bus transport. The author applied an MFA approach to evaluate the efficiency of public urban systems, and used environmental accounting (EMA, EMI, LCA) approaches to assess the environmental sustainability of the systems. The use of the MFA approach highlighted a potential source, namely material recycling, for reducing the direct and indirect demand of abiotic materials and water materials by 5% and 9% of the total demand for the system studied. The study also employed an MFA approach to compare between the two systems, namely the high speed urban bus transportation, and conventional bus transport, in terms of their direct/indirect material demand. The results showed that the NBT, the conventional transport system, was 5.4 times higher than the high speed, BRT, system in terms of material intensity, and 2.7 times higher in terms of its water demand.

Meanwhile, Pauliuk, Wang and Müller (2012) developed a stock-driven DMFA model to forecast production and iron ore consumption in the Chinese steel cycle, up to 2100, seeking to assess the environmental impact of building up and maintaining the in-use stock in the context of a circular economy. In the study, a combination of historical data regarding iron stocks, along with historical patterns of stock development, were employed as the core for developing the model to quantify the steel demand until 2100. The DMFA results indicated that, in order to meet circular economy goals, three conditions must be addressed: (1) a large degree of mature in-use stock, (2) a move towards implementing recycling, and (3) waste management that recycles scrap into the same product category from which it came.

In another study, Bai et al. (2019) used an MFA framework to systematically calculate the material stock of infrastructure, and to extend their analysis to include the embodied carbon emissions from 1997 to 2016. The authors also analysed the spatial-temporal characteristics of the stock of 31 provinces in China. The results demonstrated that there was an increase of 24.5% of the total emissions of the whole country from 1997 to 2016, and found that the material stock in the buildings, and its embodied carbon emissions, were larger by far than those involved in the transportation infrastructure. The study concluded with guidelines based on the MFA study, and development strategies that sought to lower carbon emissions in accordance with the resource characteristics.

In addition, Kapur et al. (2009) employed an MFA to develop a country-level stock and flow model that sought to analyse the cement cycle within the infrastructure in the United States (US) by characterizing the stocks and flows of cement from a lifecycle perspective, and assessing the underlying environmental and resource use implications. By applying an MFA, the study helped to quantify and understand cement flows, and the type and amount of raw materials extracted and consumed to produce cement. It also provided important information regarding the input and output flows of cement that are added to the in-use stock every year. While it acknowledged the value of the current MFA application for studying infrastructure systems, it also used an integrated assessment framework focussing on the end of life stage of the system studied. The MFA results demonstrated that in the infrastructure of the US, an average of 81 million metric tons per year of clinker were consumed, and approximately 140 million metric tons per year of raw materials. The study concluded by emphasizing the significance of applying MFA to the evaluation of the sustainability of infrastructure. The MFA applied in this study helped to quantify the raw materials required to produce cement, the production residues generated during the production phase, the share of cement use involved in the replacement of old stock and the addition of new stock, and the amount of time cement remained in use until it reached the end of its life.

Finally, Browne, O'Regan and Moles (2005) applied two sustainability metric tools, namely MFA and the integrated sustainable cities assessment method (ISCAM) to an Irish settlement. The MFA was employed to measure the resource use efficiency in the town of Tipperary, while the ISCAM method was employed to simulate alternative scenarios, and to calculate the divergence of current trends from more sustainable scenarios. The MFA was applied to household food and waste, and in the case of the relevant data being unavailable at a local level, it was necessary to apply a top-down or bottom-up approach. The results showed that there was high metabolic efficiency, and the study concluded that to assess sustainable development effectively, it is critical to develop a methodology that can model all elements of sustainable development. It suggested integrating MFA, ISCAM, and the ecological footprint to assess sectoral sustainability.

4.2.4 MFA potential for assessing SDG goal (11)

The study conducted by Li, Dong and Ren (2015) focussed on China's resource dependent cities concept, and proposed a countermeasure for the sustainability transition, applying MFA to quantitatively assess the environmental benefit of the measures involved, which included material/waste recycling, heat exchange, and other measures that sought to close the loops in the system. The MFA approach employed was able to calculate the quantity of materials exchanged, and the consumption/emissions avoided. The results demonstrated that in terms of resource saving and waste reduction, the MFA outcomes highlighted that approximately 1.43 million tons of material, and 18 thousand tonne of coal equivalent (tce) energy was exchanged in the network, and in return there was a decrease of raw material by 1.47 million tonne/year and fossil fuel by 102.71ktce/y, respectively. Meanwhile, using resource saving and waste reduction measures, the CO2 emissions were reduced by 1028 kt- CO2/y. The study concluded that decisions based on MFA can assist with planning the best location for public waste recycling and treatment facilities, and that MFA helps to optimize the recycling boundary and route of various wastes.

In another study, Voskamp et al. (2016) employed an MFA of the city of Amsterdam to analyse the UM of the city, seeking to gain insights regarding the city's metabolism using the Eurostat method, and to identify areas for modifications to the method that would enhance its performance. First, an MFA based on the Eurostat method was performed, and the results demonstrated that fossil fuels and fossil fuel products dominated the material balance, with 58% of total imports, and 61% of total exports. Next, a modified Eurostat method was employed to perform the second MFA. The seven modifications included adding drinking water and wastewater flows; accounting for storm water and groundwater entering the sewer; incorporating renewable energy; categorizing waste according to its origin, type, process, and location of treatment; incorporating materials and energy recovered from waste as a local sourcing category; classifying import and export flows in less aggregated categories; and explicating throughput flows. In the modified urban MFA, additional inputs and outputs appeared that reflected the inclusion of the water flows, and the results revealed that approximately 92% of the drinking water ended up at wastewater treatment plants, which the authors attributed to nonrevenue water and household losses. The comparison of the urban Eurostat MFA and the modified MFA demonstrated that the latter quantified a large amount of additional inputs and outputs. Moreover, the modified method included the calculation of the locally generated renewable energy that could provide insights into the biophysical flows that, in the city, had begun to sustain the local economy. The study concluded that the modified urban Eurostat MFA provided better and more detailed information concerning the city's metabolism than the urban Eurostat MFA.

Meanwhile, Gonzalez-Garcia et al. (2018) proposed an integrative multi-criteria approach consisting of MFA, LCA, and Data Envelopment Analysis (DEA). This approach was applied to 26 representative Spanish cities to identify the non-sustainable cities by considering several indicators based on the three dimensions of sustainability. An MFA was used to quantify the material and energy flows of the cities concerned, and to build an inventory to feed information to the LCA stage. To assist with data collection in the MFA stage, the study employed indicators developed in previous studies, including those conducted by the World Bank (2008); Shen et al. (2011); Chrysoulakis et al. (2013); Kennedy et al. (2014); the European Commission (2015); Michael et al. (2014); and Petit- Boix et al. (2017). The result of combining an MFA with an LCA enabled the embedded environmental burdens of the input/output flows to be assessed, and the results were integrated with other environmental tools, such as an LCA, to quantify and environmentally assess the direct and indirect input and output flows of the cities concerned. Using per capita as a function unit, the MFA-LCA results revealed that the global warming potential of the cities studied ranged from 3.7 tonne CO2eq to 32.7 tonne CO2eq, which indicated that some of the cities needed to initiate plans to reduce their GHG emissions that were targeted by the most metabolic flows responsible for the high GHG emissions. The study concluded that to better analyse cities' sustainability, an integrative approach that considers the environmental, social, and economic parameters is required.

In another study, García-Guaita et al. (2018) developed a simplified UM-MFA-LCA approach to analyse the city of Santiago de Compostela in Spain that was based on seven primary flows; input flows: energy, transportation, food and drink, water and output flows: wastewater, municipal solid waste, and airborne emissions. Although MFA facilitates the easy comprehension of the material flows within a defined system, alone it cannot assess the environmental impacts associated with these flows. In this study, an MFA was employed to define and quantify the energy and metabolic flows, then an LCA was applied to estimate the associated environmental impacts. Due to the absence of data at the local level studied, the authors employed several ratio-based downscaling factors to represent the case study. For example, number of dwellings was used to estimate product consumptions, namely water and food, while gross domestic product (GDP) was used to estimate fossil fuel and energy consumption, and population factor was used to estimate the municipal solid waste generation. The MFA-LCA results found that the total GHG emissions estimated in 2015 was 9 tonne CO2 eq/inhabitant, and that the greatest contribution to climate change and ozone layer depletion was the production and use of transport fuels. Meanwhile, coal and diesel were found to be relevant in terrestrial acidification, freshwater eutrophication, and human toxicity. This type of analysis easily identified the hotspots of each flow, which facilitated the consideration of improvement measures to guide the progression towards a sustainable society, and to reduce the per capita of the environmental impact.

4.2.5 MFA potential for assessing SDG goal (12)

In their study, Giljum et al. (2011) proposed a set of complementary resource use indicators based on combining existing measures for resource use. The indicators suggested covered the resource input flows of materials, water, and land, as well as the GHG emissions. The study also emphasized the importance of adopting a life cycle perspective when examining these indicators, as it facilitated the consideration of indirect resource consumption, and captured possible shifts of environmental impacts related to domestic production and consumption to other parts of the world. The authors suggested applying an MFA to draw indicators related to material consumption, and proposed the concept of 'water footprinting' as an indicator of water use and water consumption. The study concluded that while the set of indicators suggested could be implemented in a reasonable timeframe, extra resources should be devoted to improving the availability of the data.

Meanwhile, Wolff and Schönherr (2011) employed a combination of qualitative and quantitative methods to evaluate the effectiveness of policy instruments that aimed to improve the sustainability of household consumption. In this study, the term 'policy instruments' referred to all tools and rules applied by the local government to support and affect social change to enhance sustainable consumption. The study employed an MFA to assess the impact of these polices, analysing data concerning the changes in consumption and production patterns that were attributed to policy instruments. The resulting changes were then contrasted with a baseline scenario. The results found that MFA has a potential ex post explanatory power, as well as providing a transparent means of evaluating and exploring alternative pathways to a more sustainable consumption society in the future. However, the authors explained that in cases where the link between resource consumption and its impact was extended, or too diffuse, it might not be possible to establish or determine the causality, therefore the aim of the evaluation should shift to the output flows as a rough proxy of the impacts.

In another study, Liu, Wang and Yang (2009) applied an integrative method that compared between MFA and LCA to analyse the environmental consumption patterns of Chinese urban households from 1985 to 2000. An MFA was employed to account for the material metabolism processes of Chinese urban households, but because MFA provides aggregated indicators that are considered to be generic pressure indicators, and does not indicate specific environmental impacts, the LCA method was utilized to analyse and assess these impacts. This study provided another example of the fact that combining MFA with LCA enables the determination of 'hot spots' in resource consumption from an environmental perspective, and provides science-based guidelines for decision makers. In this study, household consumption items were categorized into eight clusters, namely food, clothing, household facilities, medical services, transport, recreation, residence, and miscellaneous commodities. In order to calculate the material stocks of a household, the study employed a method consisting of multiplying ownership numbers for different consumption clusters obtained from the Statistical Yearbooks of China by their material constituents. The results of the MFA demonstrated that the amount of material flow continued to increase from 1985 to 2000, with water constituting the largest portion of household material flow. The study employed a process-based LCA to analyse select materials related to the four consumption clusters, and the results were expressed as a single score, called the 'environmental potential index' (EPI). The results revealed that the total household environmental impact increased nearly fourfold from 1.85 EPI in 1985, to 6.40 EPI in 2000. While the EPI of all four clusters witnessed an increase, the EPI for appliances and transportation consumption increased faster than that for food and housing consumption. While approximately 80% of the EPI resulted from food and housing consumption, in 2000 the EPI for transportation and housing consumption became the main source of household environmental impact. The study acknowledged that factors such as climate, economic development, and household income and size, living conditions, infrastructure, and policies have significant impact on household environmental consumption patterns, and concluded that in order to meet population demand in a sustainable manner, integration methods such MFA and LCA can be useful for determining guidelines that govern or control current consumption patterns.

4.2.6 MFA potential for assessing SDG goal (13)

In a study conducted by Uihlein, Poganietz and Schebek (2006), the authors developed a carbon flow model, 'CaboMoG', based on MFA that was able to identify carbon flows, carbon sources, and sinks in the German anthroposphere. The study suggested that policies that aim to reduce CO_2 emissions must build a scientifically-based inventory of CO_2 sources and sinks, and that MFA is an important tool for creating such an inventory. The model proposed involved accounting for carbon flows from and to the atmosphere and lithosphere, as well as imports and exports. In order to model the carbon flows and stocks, the mass flow was quantified and then multiplied by the carbon intensity for each flow. The results demonstrated that fossil energy carriers are the main sources of carbon, and that the importers of energy carriers were responsible for 82% of the total carbon import to Germany. Meanwhile, carbons related to non-energy use were found to be significantly higher than energy use, at 386 million tonne CO_2 and 230 Mt CO_2, respectively. When considering the reduction of carbon emissions, the findings of this study highlighted the importance of accounting for both energy and non-energy use, and demonstrated that, in order to combat climate change and its impacts, an MFA-based assessment could be employed to assess the possibilities of targeted carbon management to reduce CO_2 emissions. The study concluded that such an MFA-based model could analyse the options available to achieve CO_2 emission reduction targets, and provide an optimization of these options.

Meanwhile, Pauliuk, Sjöstrand and Müller (2013) proposed a model that combined MFA and LCA to create a new dynamic stock model that sought to identify energy saving potential, and prioritize buildings with the highest potential. The study was modified by several factors related to buildings and their role in climate change mitigation. Globally, around 25% of fine energy consumption is from households. The International Energy Agency (IEA) reported that there is a need for a global revolution in the way that energy is supplied and used, a statement driven by the requirement to limit global warming to 2 degrees Celsius (oC), which requires a 50% to 85% reduction of global GHG emissions by 2050. Considering this goal, the IEA estimated that increasing energy efficiency could contribute around 50% of the energy saving overall.

The building sector constitutes a potential contributor to energy efficiency, and this study investigated factors such as building codes, lifestyle changes, and domestic use energy savings to identify which combinations of these factors had the potential to help reduce the carbon footprint of the housing sector in Norway by 50% by 2050. The proposed model included three stages. First, a physical model of heating energy demand was published and applied to several archetypes of existing buildings, to new buildings with current codes and standards, and to the proposed renovation measures. Then, a DMFA was employed to model the transformation of the housing stock by 2050, based on demolition and renovation rates. The results obtained were fed into an LCA stage to model the carbon footprint of the entire dwelling stock. Finally, a set of scenarios was developed to estimate the energy saving potential by 2050. These scenarios were based on changing the model parameters related to household lifestyle, efficiency measures, and turnover rates. Following the example of previous studies (Bergsdal et al., 2007; Hu et al., 2010), a stock-driven approach was used to build the dynamic model, in which the floor area was determined by the population and persons per dwelling, which represented the lifestyle of the population. In order to estimate the energy demand for each end use type (heating, domestic hot water, and appliances), a specific energy consumption per square metre and year for each type, multiplied by stock heating floor area was applied.

In the LCA employed in this study, a CED method was used as an impact assessment method for the carbon footprint. In the final stage, different scenarios were created to capture different consumption patterns, together with different stock growth scenarios. The results revealed that in 2010, the heating energy demand of nonrenovated single-family houses was approximately 40% of the total stock, and that 33% of the total direct energy consumption came from single-family houses built before 1970. The two scenarios developed were assessed using the same model, with parameters such as increasing the u-values for windows, and increasing wall and ceiling thickness used in the development of each. The study found that if the stock was to be completely transformed by renovation to achieve the passive house standard, the sectoral carbon emissions might drop by around

40%, despite a projected population growth of 50% between 2000 and 2050. Moreover, the study found that by applying the most ambitious reduction measures, 60% of the 2000 level could be saved by 2040. This indicated that the housing stock has a huge potential to contribute to energy reduction. Nevertheless, it would be extremely challenging to achieve the 50% reduction in carbon emission required to limit global warming to 2oC, and other factors such as changes in lifestyle and dwelling size are required. The study concluded that their use of a DMFA-based model demonstrated its usefulness for assessing the impact of climate change mitigation measures, and for illustrating the route that would eventually engender success.

In another study, Milford et al. (2013) developed a stock-based MFA approach to estimate future emissions in the steel sector, and to evaluate all of the abatement options. The study sought to explore different routes to achieving the global emission reduction target set by the International Panel on Climate Change (IPCC) that has become law in many countries. As previous noted, the target states that global emissions must be cut by at least 50% of 2000 levels by 2050. The basic analysis developed in this study was based on emission intensity multiplied by mass flow. An LCA was integrated into the model to assess the impact of the upstream processes, based on life cycle inventory data obtained from the World Steel Association. The results demonstrated that in a ‘business-as-usual’ (BAU) scenario, the annual emissions peak in 2025 would achieve levels almost 25% higher than those in 2008. Meanwhile, the ‘energy efficiency’ scenarios proposed demonstrated emission reductions of up to 20%, compared with the BAU scenario. The study concluded that energy efficiency measures alone cannot meet emission reduction targets, and should also include material efficiency measures.

Meanwhile, Lavers Westin et al. (2019) proposed a hybrid MFA-LCA method to quantify the environmental impact of urban consumption in three cities in Sweden. Because 80% of global energy consumption, and 75% of global GHG emissions are caused by cities, it is critical to recognize the environmental impact of urban consumption, in order to develop effective polices that address the problem. Combining MFA and LCA is useful for developing such polices. In the study, the total consumption for each region was quantified using an MFA model that employed data regarding trade, transportation, production, and employment. This data was categorized into products using a classification method called ‘combined nomenclature’ (CN) that is used in the European Union (EU) for trade. In order to assess the environmental impact, a scaled-up mass of the representative products was multiplied by the impact coefficient per kilogram of product. The study analysed the impact according to midpoint indicator categories, namely climate change, acidification, eutrophication, photochemical ozone formation, and resource use, and the results obtained from the hybrid MFA-LCA approach were used to establish hotspot identification criteria. The adoption of this approach made it possible to identify the product categories with a high environmental impact in multiple impact categories. In terms of developing policies that address climate change, targeting the hotspots of urban consumption, integrating MFA with LCA can show policy-makers and consumers where high-impact consumption occurs, in order to minimize the impact. The results of the study demonstrated that fuel was a hotspot in all three cities, and vehicles in one city. The study concluded that an MFA-based assessment can be employed to identify hotspots and develop environmental policies accordingly.

In an earlier study, Byrne and O'Regan (2016) stated that there is an increasing interest in sustainability transitions in urban and rural regions that seek to tackle issues related to climate change, public health concerns, and environmental degradation. Using Ballynagran in Ireland as a case study, an MFA was developed to calculate the potential of the community to generate its energy requirements from the resources available within the community. The benefits from energy upgrades and building retrofitting were also assessed using the same approach. The study sought to explore the potential routes to becoming a zero CO2 community by 2025, and the methods developed to address this aim consisted of three stages that provided a better accounting approach for renewable energy, GHG emissions, and energy saving potential in rural communities. An MFA approach was employed to calculate the total amount of electricity, gas, and other fuels consumed by the community, and the CO2 emissions were calculated. Using conversion factors obtained from the IPCC, data from several sources was employed, together with certain assumptions, to estimate the potential renewable energy generation, as well as energy savings, in the housing stock. The results demonstrated that renewable sources, such as energy crops food and garden waste, solar and wind power, and geothermal power had the potential for energy generation. The results also revealed that MFA has the potential to highlight for a community the possible means of producing energy from resources within the community. The study concluded that increasing awareness and interest among the population, and providing financial support, are critical to the success of sustainability transition to tackle climate change issues in both urban and rural regions.

Meanwhile, Dahlbo et al. (2015) proposed a combination of MFA, LCA, and environmental life cycle costing (ELCC) for holistically assessing the performance of the construction and demolition waste (C&DW) management system. In the study, an MFA was employed to evaluate material and energy recovery rates, and an LCA was used to assess climate change impacts and ELCC. The MFA approach was used to calculate material and energy recovery rates from the outputs of the sorting and separation processes, and an LCA was employed to estimate the potential impacts, in terms of climate change of C&DW management. In addition, the use of an LCA approach made it possible to determine the waste fractions and activities causing the most impact. The results revealed that, according to the MFA, a recovery rate of 73% was the closest that could be achieved to the target 80% recovery rate required to reach the 70% recycling rate of C&DW. The LCA results demonstrated that recovery of metals, the energy recovery of SRF, and landfilling were the main contributors to climate change in the C&DW system. The results also showed that the route to reducing the climate change impact was connected with the recycling of metals and the recovery of wood. For example, one scenario demonstrated that changes in waste composition could reduce the climate change impact, because of the increased volume and energy recovery of wood. From a sustainability perspective, the study concluded that the use of an MFA not only provided a description of the waste flows that enabled the recovery rates of the system to be calculated, but also enabled other tools to be used, such as an LCA, which increased the critical nature of the results, in terms of developing climate change policies.

In another study, Pauliuk and Müller (2014) combined MFA and LCA to provide insights into the roles of in-use stocks in developing climate change mitigation policies. In-use stocks include the built environment (building and infrastructure), and artefacts (machinery and durable consumer goods). The model proposed in this study was based on a stock-driven approach that employed population, stock per capita, and lifetime as driving factors to estimate the flows of final demand. Applying a DMFA also enabled the tracking of material content and energy demand for each housing type and product. In order to assess the embodied impact of materials and products, an LCA was used to extend the proposed mode to capture the impacts occurring outside the system. Three cases constituted of the three sectors of buildings, transport, and industry were used to test the outcome of the model. Buildings, transport, and industry accounted for 33%, 23%, and 36% of global energy and process-related GHG emissions in 2006, respectively. The results of the study demonstrated that several scenarios existed for reducing emissions by stock decoupling, which in this context meant energy efficiency, material efficiency, and moderate lifestyle changes. In the case of transportation, improving car design and engine efficiency could achieve around a 30% reduction of baseline emissions, and lowering car ownership and travel distance could potentially reduce the baseline emissions by 25%. In terms of dwelling stock, in a scenario in which the entire stock was renovated to passive house standards, 30% of baseline emissions could be saved by 2050. However, such an ambitious scenario is difficult to implement. Instead, this study suggested that by reducing floor area per person, along with reducing energy use in hot water generation, appliances, and lighting, the 2oC benchmark could be achieved. The study concluded that climate change policies that focus on short-term reductions of sectoral emissions may cease proceeding when faced with a short-term increase in emissions. However, this increase is necessary to achieve a meaningful emission saving in the long term. Finally, the stock DMFA model proposed showed the potential contribution of the MFA method to determining effective and meaningful measures to tackle climate change issues, especially when combined with other tools, such LCA, to widen the scope of the analysis.

To summerise the abovementioned studies, it is clear from the extant urban material flow studies that for any city to sustain the lifestyle of its people, there is a reliance on flows of energy and materials. It also evident that these flows are affected by the living standards of the city's populace, which are explained in terms of socioeconomic indicators, and by the conditions of the built environment, which are explained in terms of biophysical indicators. Moreover, applying an LCA to capture and report the embodied impact, such as embodied energy and embodied GHGs, of input and output flows enables the environmental impacts of a city to be determined. However, there is a gap in the literature, as there is a current lack of studies of cities in the developing world using such an integrative approach, and to the best of our knowledge, no reported study has attempted to assess and quantify resource flows and wastes in developing world cities using the integrative approach proposed in this study (please refer to Figure 3-1), although the need for such an analysis was highlighted by Weisz and Steinberger (2010), Beloin-Saint-Pierre et al. (2017), and Kissinger and Stossel (2019).

4.3 MFA-based urban sustainability indicator sets

As previously noted, due to the vast resources and capital investment involved, cities have a great potential to play a positive role in planning for sustainability. However, cities face significant challenges in their efforts to achieve sustainability, arising from the need to ensure that all of the city's population has access to the same quality of services. Moreover, due to the increasing number of disasters related to climate change, cities must increase the resilience of their infrastructure to combat these hazards. In addition, a growing population places increased pressure on urban centres, as new development and new infrastructures must be constructed to meet demand, and replace the old and deteriorating infrastructure, which in turns creates economic and environmental challenges. Therefore, any attempt to evaluate or provide a measurement tool for assessing the sustainability of the built environment should consider the flows of energy and materials, and the resulting emissions and wastes. The anticipated worldwide growth in urban centres offers cities the chance to take the lead in creating a more sustainable world (Kennedy et al., 2011; Li et al., 2018; Kissinger and Stossel, 2019). Therefore, in recent decades, many approaches have been developed to provide indicators and measures to help guide cities through the transition period. Before reviewing these efforts, it is necessary to clarify several critical points.

It is challenging to define a city, as cities are extremely diverse in nature, and are dependent on several criteria that differ from one country to another. Studies concerning urban systems tend to use the administrative limit as the system's boundary (Sahely, Dudding and Kennedy, 2003; Kennedy, Cuddihy and Engel-Yan, 2007; Ngo and Pataki, 2008; Barles, 2009; Zhang, Yang and Yu, 2009; Huang and Chen, 2009; Chester, Pincetl and Allenby, 2012; Moore, Kissinger and Rees, 2013b; Piña and Martínez, 2014; Voskamp et al., 2016; Kissinger and Stossel, 2019).

Another point that requires clarification concerns the debate regarding the definition of urban sustainability. The 1992 Rio de Janeiro Conference is considered by many to mark the turning point in the discourse of sustainability, and the shift of focus to applying the concept of sustainable development to nations and cities (Bartelmus, 2003; Päivinen et al., 2012). At this conference, the concept of integrating several factors when sustainable development is sought was introduced. These factors include economic, social, environmental, and governability aspects.

Finally, the term 'urban sustainability' is employed throughout this study, but different approaches to urban sustainability exist in the previous literature in the field. Some studies built their approach on the environmental dimension (for example, Zellner et al., 2008; Li et al., 2016), while others attempted to include bio-physical dimensions (for example, Kennedy, Cuddihy and Engel-Yan, 2007; Moore, Kissinger and Rees, 2013). Meanwhile, studies such as those conducted by Kennedy et al. (2014), Gonzalez-Garcia et al. (2018), and Kissinger and Stossel (2019) proposed set of indicators that encompassed social, economic, and environmental dimensions. However, the suitability of such indicators remains challenging, as cities differ in their characteristics.

In the present study, the term 'urban sustainability' is treated as a measurable process for improving the status quo of the built environment. This process is measured through a proposed set of indicators that are grouped into four categories: socio-economic indictors, bio-physical indicators, MFA-based indicators, and LCA-based indicators. Most importantly, while this framework applied at the urban level, its focus limited to the domestic sector.

Moreover, if sustainability goals were implemented, relying on measuring only one of the sustainability pillars could oversimplify the challenge and engender unexpected consequences. For example, climate change mitigation policies that are built on reducing resource consumption could ultimately ignore the unintended impacts of these measures, or the social and economic changes necessary for these measures to succeed. The integrative environmental indicators suggested in this study create a better understanding of the complicated relationship between population activities, the services required, the built environment, and the material and energy throughput.

As previously stated, the city is a complex system, and for this reason, it is critical to understand its flows of material and energy over time. In recent years, there has been an increase in the number of MFA studies. A search of the SCOPUS database using the keywords {Material flow analysis} AND {urban} revealed that in 2010 alone, there were 12 studies. This number increased to 34, 29, 42 in the years 2015, 2016, and 2017, respectively. Yet, there is no reported study of Saudi Arabian cities, although efforts to tackle climate change are arguably more importantly in an economy that is described as carbon-intense (Alyousef and Abu-ebid, 2012; Alkhathlan and Javid, 2015). Moreover, extending an MFA, which is widely employed to assess urban development, to capture the embodied environmental impact and the socio-economic parameters in cities could assist in identifying paths to implementing sustainable development goals. The following section provides a detailed description of the methodology.

4.4 Methodology

Having identified the main components of the integrative approach suggested for this study, this section describes the methods employed for each component, detailing the methodology and data sources concerned, and discussing the evaluation of the sustainability of the urban ecosystem based on the MFA approach.

4.4.1 Socio-economic and biophysical indicators

While the core analysis of this study seeks to assess the energy and material flows in a developing city, assessing the socioeconomic and the built environment conditions of what can be called the primary factor responsible for these flows, namely people, is vital for understanding how cities develop, and what factors impact this development the most. Two steps were taken to develop the set of indicators required. The first involved reviewing the related literature to identify these indicators, and the second involved determining the appropriate sources of data collection.

In this study, numerous sources were employed to collect the data for Riyadh for years 1996, 2006, and 2016, as illustrated in Table 4-3.

Table 4-3 Socioeconomic and biophysical indicators.

	Indicators	**Data sources**
Socioeconomic indicators	Population	• Population Study of Riyadh City, 2016; Riyadh Urban Indicators, 2017 • Riyadh Urban Observatory (http://www.ruo.gov.sa/) • Riyadh Municipality open data https://opendata.alriyadh.gov.sa • The Statistical Yearbook published by General Authority for Statistics (GASTAT) • Riyadh in number report, 2016 (in Arabic), Riyadh Chamber of Commerce • Final reports of the Metropolitan Development Strategy for Arriyadh Region (MEDSTAR) • Investment Climate in Riyadh (A periodical issued by the Riyadh Development Authority)
	Density	
	Household size	
	Household formation rate	
	Housing stock	
	Households	
	Housing units density	
	Dwelling type	
	Floor of housing area per person	
	Unemployment rate	
	Average annual income in US dollars (USD)	
	GDP per capita	
	Household connections to public water network	
	Household connections to public wastewater network	
	Transport modes	
	Automobile ownership	
	Travel time (minutes/trip)	
	% Wastewater treatment	
	Solid waste per person/day	
	Recycle solid waste	
Biophysical indicators	Land area (sq. kilometres)	
	Urbanized area (sq. kilometres)	
	Heating degree days (18°C base)	https://www.degreedays.net/ (OERK: King Khaled International Airport, SA (46.72E,24.93N))
	Cooling degree days (25°C base)	https://www.degreedays.net/ (OERK: King Khaled International Airport, SA (46.72E,24.93N))
	Annual solar radiation (kWh/m^2/year)	(Myers *et al.*, 2002; Hepbasli and Alsuhaibani, 2011)
	Annual precipitation (mm)	The Statistical Yearbook published by General Authority for Statistics (GASTAT)
	Land area km^2 (developed areas)	Riyadh Urban Observatory http://www.ruo.gov.sa
	Land area km^2 (Vacant land areas)	
	Building gross floor areas (m^2)	
	Residential building gross floor areas (millions m^2)	

4.4.2 MFA-based indicators

MFA approach will be employed to study the urban ecosystem of Riyadh and to estimate its inventory, with a focus on material and energy flows. When modelling these flows, some MFA studies consider cities as an individual unit, which is known as a black-box approach. This study took into consideration consumption activities according to their types, such as buildings, transportation, and energy production, which is known as a grey box approach. The conceptual framework of Riyadh's urban system, considering the main flows, and inputs and outputs, is shown in Figure 4-3.

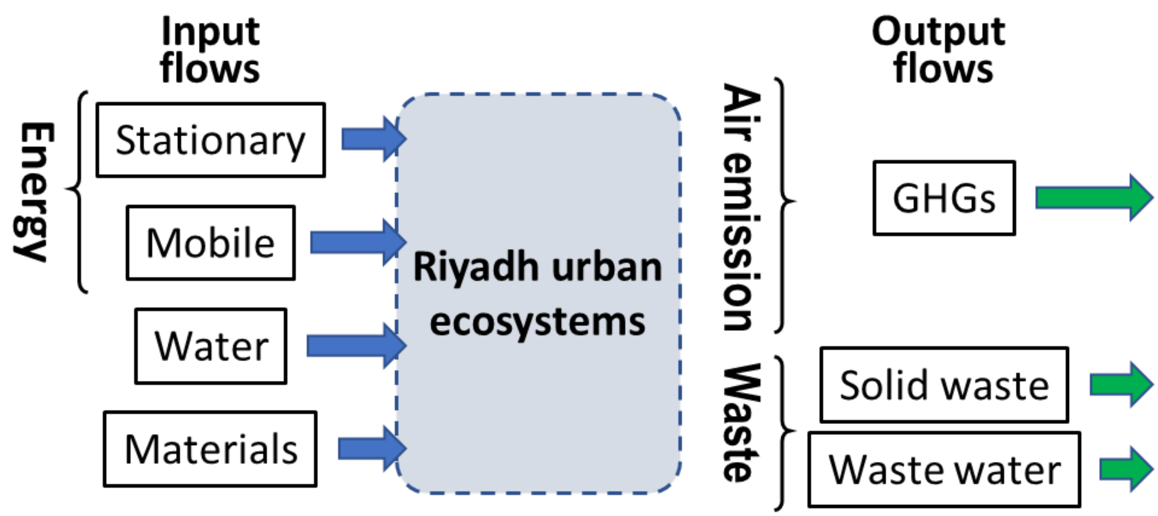


Figure 4-3 Concept of the main flows as inputs and outputs.

In terms of modelling the material and energy flows, a linear approach built on data concerning the demand for services, and socioeconomic values to estimate stocks and flows, is most effective approach for visualizing and illustrating the interaction between the cities and the environment (Condeixa, Haddad and Boer, 2017). Because of the growing need for basic empirical data about cities' physical and environmental characteristics, there have been several attempts to create a set of indicators based on an MFA approach, in order to guide cities to achieve sustainability objectives (Kennedy and Hoornweg, 2012; Kennedy *et al.*, 2014; Mostafavi, Farzinmoghadam and Hoque, 2014; Conke and Ferreira, 2015). These studies attempted to address the issue of the lack of standardization in urban MFA and to establish principles for establishing system boundaries (Voskamp et al., 2016).

As stated in previous studies, the application of MFA at an urban level requires the use of varied consumption data concerning the services and products by which the urban activities are supported, together with data related to the conversion of consumption flow data into quantities of materials and energy used to support the urban activities, and the waste resulting from the consumption. As discussed previously, it is clear from recent systemic reviews on the subject of urban MFA that more MFA case studies of cities in developing countries are required, especially the cities that are categorized as possessing a high rate of population growth and resource demand. This study developed an MFA-based framework of indicators to study the flows of material and energy in Riyadh, Saudi Arabia, for the years 1996, 2006, and 2016, thereby employing Riyadh as a test subject for the proposed framework.

An MFA approach was employed to apply a relevant set of flow indicators to help to quantify the flows that pass into and out of Riyadh, which was defined geographically according to the administrative boundary of the city. In the MFA approach, weight-based calculations, in tonnes, determine the annual contributions of the flows studied through the city, and the annual stock that provides a simplification of a complex task (Hunt et al., 2014). The categorization of the input and output flows was based on the Eurostat approach developed by the Statistical Office of the European Communities and Eurostat (2001). Several studies have applied this approach for MFA study for Hamburg, Lisbon, London and Vienna (Montangero 2003; Browne et al. 2009; Niza et al. 2009. While these cases are reported in Europe, few cases in developing countries have used the same approach such as Bogotá, Colombia (Piñan et al. 2014); Cairo, Egyept (Magdy 2014); and Amman, Jordan (Sugar, Kennedy, Hoornweg 2013).

This method is widely used in MFA studies as it provides a framework to measure inputs and outputs of the urban ecosystem (Barles, 2009). This approach, the city requires different resource inputs, such as water and energy, and emits different outputs, such as emissions and waste. The use of this approached helped to establish an understanding of the relationship between the city and the environment, in terms of the physical units that estimated the inputs, stocks, and useful outputs and wastes. While the categories reported in the Eurostat are aggregated, in this study the modelling of the urban flows took into consideration different consumption activities, such as housing, transport, and services. The inclusion of socio-economic and biophysical indicators in an MFA study assisted with this disaggregation. Table 4-4 illustrates the data collection approach and sources for each urban material flow component considered in this study.

As previously stated, the years selected for the analysis were 1996, 2006, and 2016. This was because of the data availability, and because it served the objective of this study to analyse the direct and indirect flows of the city, and assess the contribution of potential sustainability measures, namely changes in the energy mix, and increases in energy end-use efficiency.

The urban MFA data for each component included in this study was categorized as follows: input flows included energy production, energy stationery, energy mobile, construction materials, and water that entered the city's systems and originated from different sources. The output flows included solid waste, wastewater, and emissions disaggregated according to energy use type.

Following subsections will provide further details for each component describing methods used to quantify input and output flows for each one.

4.4.2.1 Energy stationary consumption

The input flows in the energy production component included two main categories: type and amount of fuels consumed to produce electricity, and the primary energy factor that calculates the total fuels required to produce one useful unit (kWh). The data concerning the direct energy consumption of each sector of the city, whether residential, commercial, industrial or services, was obtained from ADA, and the data regarding the energy mix was obtained from ECRA. The primary energy factor, which accounts for the amount of primary energy used to generate a unit of final energy, was reported to be 3.38 (Alyousef and Varnham, 2010). Moreover, data related to irradiance is not included and future research is recommended to assess and analyse its effects.

Output flows in the energy consumption component were modelled using SimaPro, which calculates the total emissions resulting from energy production, using the Ecoinvent database. The Ecoinvent database provides well-documented information about processes for thousands of products, including energy production in Saudi Arabia. The relevant processes were selected, and SimaPro was used to calculate the total emissions. In order to calculate the outflows, namely the emissions, it is necessary to enter the amount of energy required, after selecting the appropriate process, and to select a method for the impact assessment.

Table 4-4 Flows, indicators, and sources.

MFA component		Unit	MFA indicators	Approaches used to obtain data required	Data sources and guideline articles
Input flows	Source				
Energy (production)	Fuel oil	TJ	Total energy consumption	Locally generated data on energy sources used in Riyadh power plants, and reports on power generation efficiency.	Riyadh Development Authority (ADA), Electricity & Cogeneration Regulatory Authority (ECRA)
	Natural gas	TJ			
	Primary energy factor		Primary energy factor	Efficiency factor at power plant is used to estimate the fuel mass required to produce electricity.	Alyousef and Abu-ebid, 2012
	Distribution loss	%	Network efficiency	Locally generated data from several sources.	Electricity & Cogeneration Regulatory Authority (ECRA)
Energy (stationary)	Electricity consumption (total)	GWh	Final energy consumption		ECRA; ADA: reports of the Metropolitan Development Strategy for Arriyadh Region (MEDSTAR) in 1997, 2004, 2011; Riyadh Atlas, 1999; Social Studies (Executive Summary), 1987; The Statistical Yearbook published by General Authority for Statistics (GASTAT) (Chapter: Energy)
	Residential	GWh	Final energy consumption by sector		
	Commercial	GWh			
	Industrial	GWh			
	Government and services	GWh			
	Others	GWh			
	Energy end-use				Household Energy Survey, 2017; Household Energy Survey, 2018
	Air conditioning (AC)	%	Final energy consumption by end-use		
	Heating	%			
	Water heating	%			
	Lighting	%			
	Food preservation	%			
	Others	%			
Household fuel consumption	LPG	TJ	Household fuel consumption for heating and cooking	Data on per capita consumption of LPG obtained from household	Household Energy Survey, 2017; Household Energy Survey, 2018

				energy survey for Riyadh region.	
Energy (mobile)	Gasoline	TJ	Energy mobile consumption per transport modes	Sales data at regional scale were downscaled by population and using conversion factors from (IPCC, 2006); the fuel mass of petrol, diesel, and jet fuel were estimated.	Reports of MEDSTAR in 1997, 2004, 2011; Aldalbahi and Walker, 2015; ; Urban indicators of Riyadh, 2012; IPCC, 2006; Riyadh Urban Indicators, 2017
	Diesel	TJ			
	Jet fuel (kerosene)	TJ			
Water flow	Water consumption total	kt	Water consumption	Locally generated data on water consumption for all of the city, and for household use.	Reports of MEDSTAR in 1997, 2004, 2011); The Statistical Yearbook published by General Authority for Statistics (GASTAT) (Chapter: Agriculture, Water and Environment); annual report of the National Water Company (NWC)
	Water production (wells)	kt	Water flow by source		
	Desalination	kt			
	Distribution loss	%	System efficiency		
Construction materials	Cement production	tonne / year	Annual production of construction material	Cement production from cement plants within city boundary was obtained from The Statistical Yearbook published by General Authority for Statistics (GASTAT) (Chapter: industry).	The Statistical Yearbook, published by General Authority for Statistics (GASTAT), (Chapter: Industry)
	Cement	tonne / year	Total input of materials per year	Square metres of new built area were converted to mass of cement, steel, and aggregate, according to material intensity factors developed from bill of materials of different buildings.	Kennedy, Baker and Brattebø, 2014b; bill of materials of different buildings obtained from local firms
	Steel				
	Aggregate				
Emissions	GHG of power generation	t-CO_2 e	GHG emissions generated during power generation	Used SimaPro LCA software to estimate emission at power plant.	Annual Statistical Booklet on Electricity Industry, SimaPro 8.5
	GHG of energy use	t-CO_2 e	GHG emissions from energy use	Used emission factors for energy use, according to Riyadh energy mix obtained using SimaPro.	Annual Statistical Booklet on Electricity Industry, SimaPro 8.5

	GHG of transport sector	t-CO_{2e}	GHG emissions from transport sector use	Used default values reported by IPCC in Chapter 3 (Mobile Energy).	Kennedy, Baker and Brattebø, 2014b; IPCC, 2006
Solid waste	Total municipal waste	tonne / year	Generation of waste	Waste generated within city boundary.	Reports of MEDSTAR in 1997, 2004, 2011); Riyadh General Authority of Cleanness: https://clean.alriyadh.gov.sa/, Riyadh Urban Indicators, 2017
	Construction and demolition waste	tonne / year	Amount of construction waste within city's boundary	Generation of construction and demolition waste.	
	Recycled waste	%	Recycling rate of municipal waste	The percentage of recycled waste from the total solid waste.	
Wastewater	Total wastewater	ML	Amount of wastewater generated within city's boundary	Wastewater generated and collected within city's boundary.	Reports of MEDSTAR in 1997, 2004, 2011; Riyadh Urban Indicators, 2017
	Recycled wastewater	%	Recycling rate of collected wastewater	The recycled percentage of the wastewater collected.	

4.4.2.2 Energy mobile (transportation)

The input flows Most of the energy required for transportation in cities takes the form of petrol and diesel, which is primarily combusted in automobiles, trucks, and buses. In order to quantify the fuels consumed in the transportation sector, this study employed data regarding fuel sales, as reported in the annual report of Saudi Aramco, formally known as the Saudi Arabian Oil Company. In its annual report, fuel sales data per type is reported on a regional scale. The central region was selected, and the population factor used to downscale the data to the city level. This approach was suggested by several studies, such as those conducted by Niza, Rosado and Ferrdo (2009), Kennedy, Baker and Brattebø (2014c), and Facchini et al. (2017), and was employed in a number of recent studies (García-Guaita et al., 2018; Gonzalez-Garcia et al., 2018; Kissinger and Stossel, 2019). Another method that could have been used would involve multiplying the within-boundary vehicle kilometres travelled (VKT) by the fuel economy (L/km) for each vehicle grouping. However, due to the data constraints, this approach was not considered. Table 4-5 summarizes the main characteristics of the transport sector.

Table 4-5 Cars ownership and daily trips in Riyadh, 2016.

Vehicle ownership per 1000	Total daily trips	Average length
381	9 million/day	18 km/trip

Output flows from energy mobile component consists of two steps. First, the amount of energy consumed was converted to energy using the default factors from the IPCC Guidelines for National Greenhouse Gas Inventories, as shown in Table 4-6

Table 4-6 Energy content for select fuels.

Fuel type	Energy content (GJ)
1 cubic metre (m3) (motor gasoline)	34.66 GJ
1 cubic metre (m3) (diesel)	38.68 GJ
1 cubic metre (m3) (jet fuel/kerosene)	37.68 GJ

In the second step, the GHGs were calculated for each fuel type, following the procedures suggested by the IPCC guidelines (IPCC, 2006). The direct GHG emissions were estimated according to the default factors shown in Table 4-7, and using the following equation:

$GHG_{transport} = \sum_{transport\ fuel} C_{fuel} \cdot I_{fuel}$ *Equation 4.1*

Where C represents the total amount of fuel consumed, and I represents the emission factor associated with the same type of fuel.

Table 4-7 Default GHG emission factors (Source: IPCC 2006).

	CO_2 kg/TJ	CH_4 kg/TJ	N_2O kg/TJ
Global warming potential	1	21	310
Gas/diesel oil	74,100	3.90	3.90
Motor gasoline	69,300	3.80	5.70
Biodiesel (100%)	70,800	3.00	0.60
Natural gas liquids	56,100	92.00	3.00
Aviation gasoline	70,000	3.00	0.60
Kerosene type jet fuel	71,500	3.00	0.60

4.4.2.3 Water flows

Input flows of the water component consisted of data collection on the water sources and the end-uses of water within the municipal system. It should be noted that stormwater and rainfall is not considered in this study due to two reasons. First, there is a lack of data that can be used in modelling water flows of the city. Second, the stormwater network only covers about 26% of the total developed areas (Nahiduzzaman, Aldosary and Rahman, 2015). The input flows considered for this component are limited to the water supply to the city. Water flows of precipitation and urban runoff are not included in the analysis due to data constraint. However, even when all these flows included, the flows of water supply will dominate the flow quantity of water within a city (Kennedy, Baker and Brattebø, 2014a). In Riyadh, the two main sources of water supply are groundwater and desalination. Data related to water component are collected from the local authority, including from the National Water Company (NWC), and several published reports by the Royal Commission for Riyadh. Input flows associated with households consumption is determined based on a per capita indicator published by the Royal Commission for Riyadh.

Output flows included data on the wastewater collected within the city's boundary, and the GHG emissions associated with the water production from the ground, and desalination. The percentage of the total wastewater treated was estimated from information obtained from NWC, and ADA. The amount of water recycled and reused was estimated from the same sources. In terms of the GHG emissions, two sources were used: for emissions associated with water production from the ground, SimaPro software was employed, and the Ecoinvent database referred to. In order to calculate the emissions related to water production from desalination plants, two steps were undertaken. First, reports from the Saline Water Conversion Corporation (SWCC) were reviewed to identify the specifications and technologies employed in desalination plants, since desalination technologies differ in their environmental performance. For example, technologies such multi-stage flash, multi-effect distillation, or reverse osmosis have different specifications, and their energy intensity is also different (Raluy, Serra and Uche, 2006; Al-Karaghouli and Kazmerski, 2013; Darwish, Hassabou and Shomar, 2013). After identifying the specification of the desalination plants, secondary sources were consulted to estimate the GHG emissions per m3 of useable water.

4.4.2.4 Material (construction) flows

Input flows for this component concerned only those associated with construction materials, namely cement, steel, and aggregate. Since construction materials constitute the largest flows and stocks of materials in cities (Pauliuk, Wang and Müller, 2013; Kennedy, Baker and Brattebø, 2014c), this study focussed particularly on construction material, and selected cement, steel, and aggregate as they represent the largest share in buildings, in terms of weight, and environmental impact (Ramesh, Prakash and Shukla, 2010; Asif et al., 2017). The selection of these materials was justified by the fact they represent the major components of the building stock in Saudi Arabia, as evidenced by the latest national survey (Household Energy Survey, 2017). Moreover, cement, steel, and aggregate are all manufactured locally within Riyadh's urban limit. In order to quantify the flows of these three materials, this study adopted a bottom-up approach, based on archetypes. First, data concerning the classification of buildings was obtained from the Royal Commission for Riyadh City (RCRC), together with a housing survey from the General Authority for Statistics. Then, with the aid of local construction firms, and using bills of the materials, representative quantities of the material was established for each group. While this approach may not represent the current status of the built environment, it is justified by the fact that the main material used in the majority of buildings in Riyadh (98%) is reinforced concrete, according to the latest survey (Household Energy Survey, 2017).

The use of archetypes as a method to estimate material and energy flows at an urban level was employed in several previous studies (Surahman, Kubota and Higashi, 2015; Sharib et al., 2017; Stephan and Athanassiadis, 2017; 2018). Meanwhile, studies such as that conducted by Swan and Ugursal (2009) used this approach to model operational energy use, and the study by Stephan and Athanassiadis (2017) employed this approach to quantify the embodied energy and environmental requirements of building stocks. Based on the bills of materials acquired, a material intensity factor for the construction materials selected was developed.

A material intensity by floor area approach employs an average for material use per square metre of floor area and can provide a realistic estimate at the city level (Stephan and Athanassiadis, 2017). At the time of this study, there was no direct data available for the material intensity of Riyadh’s building stock. It was, therefore, essential to use the archetypical approach limited to housing stock. Other types of building and infrastructure were not included, due to the difficulty in obtaining the drawings and bills of quantities of such buildings. Moreover, residential land use is the predominant form of land use in the city, in terms of area (49%), excluding roads and open spaces, and is the type of land use currently exhibiting the most growth, according to the reports obtained from ADA (Study of Riyadh's land use, 2013). Figure 4-4 shows the housing stock age and Table 4-8 presents the data regarding housing types in Riyadh in 2016.

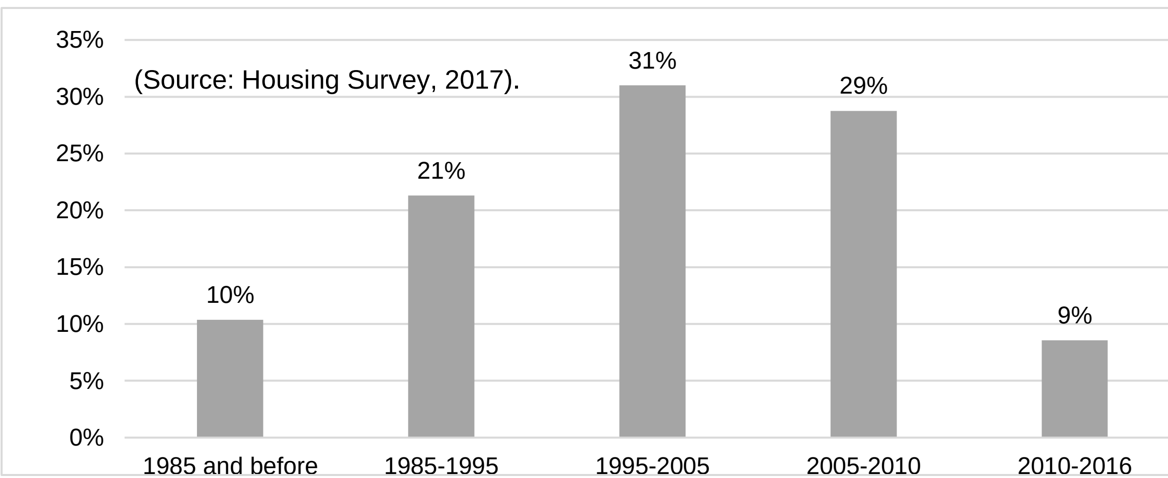


Figure 4-4 Housing stock age in Riyadh, 2016.

Table 4-8 Housing unit types in Riyadh, 2016. (Source: Housing Survey, 2017).

Housing unit type	Percentage (%)
Villa (detached house)	52%
Apartment	42%
Traditional house	2.5%
Others	3.4%

The housing stock age is presented. This figure indicates that the housing stock in Riyadh is relatively new and there is a significant increase in new housings (housings built after 2010 is about 9% of the total stock).

The average number calculated was then compared with similar studies, which, although not conducted within the Saudi context, shared similar building characteristics in terms of building type (residential), and construction features. In Riyadh, reinforced concrete buildings constitute approximately 98% of the entire building stock (General Authority for Statistics, 2017). The data presented in Table 4-9 and Table 4-10 shows the average material intensity developed in this study, and the values for the same materials reported in similar studies.

Table 4-9 Average material intensity (kg/m2) for the construction materials selected.

Cement	Steel	Aggregate
227	74	1283

Table 4-10 Comparison of material intensity values (kg/m^2) with similar studies.

Study title	Location	Building type	Structure type	Cement	Steel	Aggregate
Input, stocks, and output flows of the urban residential building system in Beijing city, China, from 1949 to 2008	China	Residential	Reinforced concrete	246	59	1042
Material demand and environmental impact of building construction and demolition in China, based on dynamic material flow analysis	China	Residential	Reinforced concrete	238	75	1451
Dynamic material flow analysis for strategic construction and demolition waste management in Beijing	China	Residential	Reinforced concrete	212	46	1291
Average (kg/m^2)				232	60	1261

The input flows and the in-use stock were determined using equations 4.2 and 4.3, both of which were based on data concerning floor area demand, and in-use. The residential floor area per capita was obtained directly from ADA, and in 2016 was estimated to be 41m^2/capita, a decrease from the 43m^2 reported in 2012. The input flows for year studied (t) was estimated using the following equation:

$$A(t) = A_{cap}.P_N \qquad \textit{Equation 4.2}$$

Where A is input floor area (m^2), A_{cap} is the floor area per capita, and P_n is the new population.

$$M(t) = A(t).m_i \quad \textit{Equation 4.3}$$

Where M is material flows, A is input floor area (m^2), and m_i is material intensity (kg/m^2).

These equations are able to capture the input flows corresponding to population demand, and were employed in similar previous studies (Bergsdal, Brattebø, Bohne, *et al.*, 2007; Sartori, Bergsdal, Müller, *et al.*, 2008; Hu, Bergsdal, *et al.*, 2010; Pauliuk and Müller, 2014; Wang *et al.*, 2015a). This approach does not consider the construction flows for buildings other than residential types, due to the lack of information available. However, limiting the scope to residential building did not affect the implications of this study, since it is the predominant type of in-use stock, hence any trends of material consumption would be captured. According to reports on the annual construction permits for all types of buildings, published online by the Ministry of Municipal and Rural Affairs, data concerning the Riyadh Municipality illustrated that from 1996 to 2016, on an annual basis, the input floor designated to residential use was 78% of the entire input floor on average area[1]. Moreover, while the focus is on the domestic sector, this can serve as a proxy for city level.

Output flows were estimated for both wastes to land and waste to air. Waste to land is considered to be the amount of construction waste within a city's boundary that is collected by the city's authority and sent to landfill. Data regarding construction waste was obtained from the Riyadh General Authority of Cleaning, which published this data on its website (https://clean.alriyadh.gov.sa). It should be noted that the data was only available for the year 2016, therefore temporal trends could not be established from primary sources. In terms of calculating the emissions resulting from the manufacture of these materials, the LCA software SimaPro was used, and the Ecoinvent database was consulted to estimate the GHG emissions for cement and steel. The Inventory of Carbon and Energy, known as the ICE database, a leading embodied energy and carbon database for building materials, was used to calculate the aggregate related emissions (Hammond and Jones, 2008).

The Ecoinvent database contains approximately 17,000 life cycle inventory (LCI) datasets in areas such as energy supply, transport, construction materials, wood, and waste treatment, and is considered to be the most comprehensive and transparent international LCI database. While these datasets may not represent the Saudi Arabia context, the SimaPro software provided the opportunity to modify the process selected to represent the

[1] https://www.momra.gov.sa/GeneralServ/statistic.aspx

local context. For example, a process such as ‘Cement, Portland {RoW} production’ can be modified in terms of the energy mix and fuel types used in the production stage to represent the area studied while retaining the technical aspect. Table 4-11 shows the factors used in this study to estimate the GHG emissions for the materials selected.

Table 4-11 GHG emissions factor for material production.

	Cement	Steel	Aggregate
(kg CO_2 e/kg)	0.92	2.25	0.0052
Source	SimaPro: Cement, Portland {RoW}| production | APOS, U	SimaPro: Reinforcing steel {RoW}| production | APOS, U	ICE database

4.4.3 LCA indicators

4.4.3.1 Environmental impacts of Riyadh’s urban material flows

this stage of the study, an LCA was performed to assess the environmental and human health impacts resulting from the input and output flows (MFA-based indicators). An LCA from a cradle-to-gate was performed to assess the environmental impact of the results produced by the indicators (inventory) driven by the MFA approach in the previous stage. The LCA was also employed to assess the environmental impacts associated with urban material and energy flows during the year of study, 2016. It should be noted that LCA was not preformed for past years (2006 and 1996). Conducting LCA study for years in the past will significantly increase uncertainty (Cellura, Longo and Mistretta, 2011; Lima, de Azevedo Caldeira-Pires and Cardoso, 2020).

The LCA scope, in this case, was limited to the upstream phase and did not consider the full cycle of these flows. This was partly due to the limited data, but more significantly because of the impact of upstream flows, and the use phase consumption of material and energy accounts for 80% to 90% of the total life cycle impact of the products and services (Anderson, Wulfhorst and Lang, 2015; Su and Zhang, 2016). The goal of conducting an LCA is to assess a city’s environmental profile, taking into account the direct and indirect flows. Meanwhile, the flows that contribute the most to the environmental impact in a city are identified using the cradle-to-gate approach. The cradle-to-gate approach considers all energy consumption from the upstream stages, including raw material extraction to the final stage as a finished product (Dixit *et al.*, 2010). The focus is on assessing the environmental impacts associated with the input flows: energy consumption, both stationary and mobile; construction materials; and water flows, together with those associated with the output flows: wastewater and solid waste treatment. This stage applied the impact assessment method selected to evaluate the environmental and human health impacts of these flows.

4.4.3.2 Impact assessment (LCIA)

The LCIA translates inventory data (inputs and outputs) into environmental impact scores, using different characterization factors. This study applied midpoint characterization factors to estimate the environmental impacts associated with the urban material and energy flows obtained in the previous stage. This study will consider only five impact categories: climate change, particulate matter formation, freshwater ecotoxicity, water consumption potential, and fossil fuel potential. These impact categories provide a comprehensive synopsis of the environmental problems related to cities (García-Guaita *et al.*, 2018).

4.4.3.3 Life cycle inventory (LCI)

As noted previously, the system boundary of the LCA stage in this study was based on a cradle-to-gate approach. The selection of this system boundary provided a better understanding of the impact of urban growth and the demand of the associated services since the increase in demand engendered an increase in energy and emissions resulting from the production of these services. The primary data used for the lifecycle inventory for the flows studied were taken from the MFA study. As discussed previously, MFA is considered to be an accounting method and can be employed in an LCI stage (Rincón *et al.*, 2013). The flows studied are reported in total and per capita as presented in Table 4-12

Table 4-12 Lifecycle inventory data of the flows studied for the year 2016.

MFA component	Source	Unit	Total	Per capita
Energy (production)	Crude oil	TJ	304,633	
	Diesel	TJ	54,348	
	Natural gas	TJ	356,120	
Energy (stationary)	Electricity consumption (total)	GWh	58,769	9,032 kWh
Household fuel consumption	LPG	TJ	6,554	1.01 GJ
Energy (mobile)	Gasoline	TJ	259,131	39 GJ
	Diesel	TJ	157,055	24 GJ
	Jet fuel (kerosene)	TJ	39,764	6.11 GJ
Water flow	Water consumption total	kt	832,655	127 ton
Construction materials	Cement	ton	4,004,136	615 kg
	Steel		1,297,224	199 kg
	Aggregate		22,597,800	3,473 kg
Emissions	GHG of energy use	kt-CO_{2e}	47,354	7.28 ton
	GHG of transport sector	t-CO_{2e}	32,962	5.07 ton

	GHG material production		6,720	1.03 ton
Solid waste	Total municipal waste	kt	2,731	0.42 ton
	Construction waste	kt	3,650	0.56 ton
Wastewater	Total wastewater	kt	375,451	58 ton

4.4.3.4 Embodied energy

The components of material flow considered to assess embodied energy are water production, energy production, and construction material production. The initial embodied energy is expressed as follows:

$$EE_i = \sum m_i . M_i \qquad \textit{Equation 4.4}$$

Where m_i is quantity of the materials studied, and M_i is the energy content.

The embodied energy values were calculated in SimaPro using the CED method. This calculation was conducted for energy production and construction material productions. The initial embodied energy for water production (desalination) was calculated using the fuel consumption data in desalination plants obtained from the SWCC, and the Electricity and Cogeneration Regulatory Authority. Table 4-13 presents the initial embodied energy values and data sources and is followed by a description of each component studied to calculate the embodied energy.

Table 4-13 Main flows considered in the embodied energy calculation.

MFA component	Direct input flows	Direct input flows value	Data sources
Energy consumption	Energy stationary	211,568 TJ	Alyousef and Abu-ebid, 2012; Barau and Al Hosani, 2014
Water consumption	Desalination	383,021 kt	SWCC, the Electricity and Cogeneration Regulatory Authority
	Groundwater production	449,634 kt	SimaPro, Tap water {RoW}| tap water production, underground water with chemical treatment | APOS, U
Construction materials	Cement	4,004 kt	SimaPro, Portland {RoW}| production | APOS, U
	Steel	1,297 kt	SimaPro, Reinforcing steel {RoW}| production | APOS, U
	Aggregate	22,597 kt	ICE (V2.0)

Energy consumption

According to the British Petroleum (BP) Statistical Review of World Energy 2017, Saudi Arabia in one of the largest consumers of total primary energy. In fact, Saudi Arabia was the world's 10th largest consumer of total primary energy in 2016, with 266.5 million tons of oil equivalent (BP Statistical Review of World Energy, 2017). As previously indicated, the two most energy-intense sectors are electricity production and water desalination plants (Khondaker *et al.*, 2014). In terms of energy consumption, the embodied energy is defined as the total primary energy. In the MFA stage of this study, it was estimated that the primary energy factor is approximately 3.38, as reported by Alyousef and Abu-ebid (2012), and

Barau and Al Hosani (2014). In order to estimate the embodied energy, the primary energy factor is multiplied by the total energy stationery consumption.

Water consumption

Saudi Arabia is classified as possessing high water debts, which is defined as the amount of groundwater withdrawal being greater than the natural flow (Barau and Al Hosani, 2014). Moreover, the water consumption per capita in the country, and in Riyadh, is one of the highest in the world, as indicated in the results section. In order to meet the demand for water consumption, the country is heavily reliant on water obtained from desalination production, and the country is the largest producer of desalinated water in the world (Khondaker *et al.*, 2016). This reliance on desalinated water comes at a high cost, in terms of the energy consumption required to produce and operate the desalination plants (Barau and Al Hosani, 2014).

In 2016, the total energy consumed in the course of the country's desalination was 1,124 PJ. According to the annual statistical booklet for electricity and seawater, the fuels consumed in the desalination industry's plants were natural gas 81%, heavy fuel oil 18%, and diesel 1% (Electricity and Cogeneration Regulatory Authority, 2016). Meanwhile, the annual statistical booklet for electricity and seawater desalination industries showed that in 2016, the city of Riyadh consumed approximately 27% of the entire country's production, as illustrated in Figure 4-5. Therefore, it was essential to include the embodied energy for water flows in this study's analysis, as this industry is extremely energy intensive (Barau and Al Hosani, 2014).

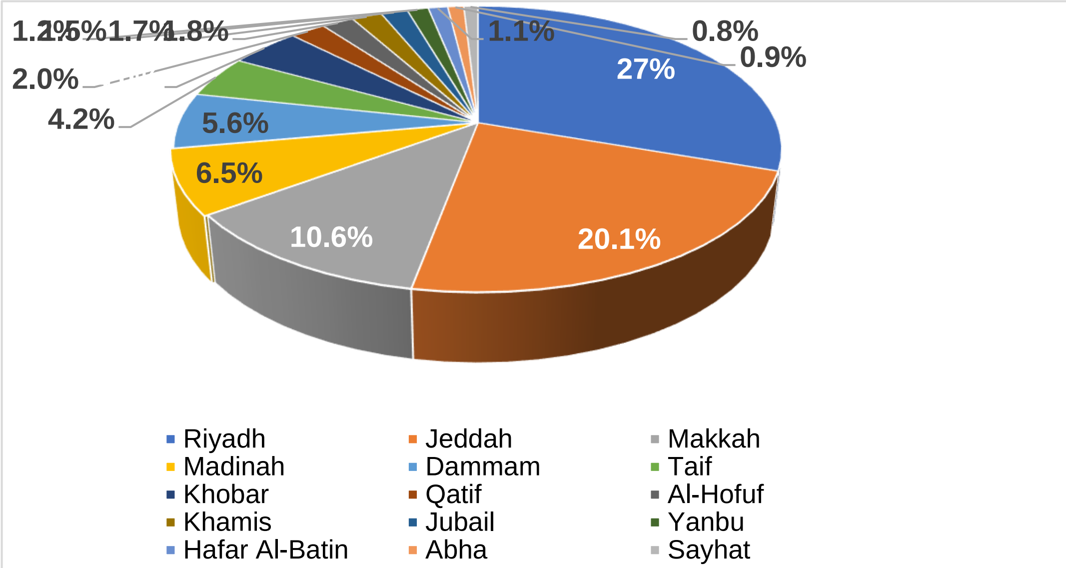


Figure 4-5 Riyadh's consumption of the total desalination production in Saudi Arabia.

Source: Saline Water Conversion Corporation, 2019

The city of Riyadh receives its share of desalinated water from the Jubail plant, 460km east of the city. The desalination technology employed in this plant is multi-stage flash (MSF). In order to estimate the total energy used to produce 1m^3 of water, the following equation was applied:

$$E_w = E_c - E_p \quad \textit{Equation 4.5}$$

Where E_w is the total energy used at the plants, E_c is the energy consumed at the plants, and E_p is the energy produced by the plants.

The annual report published by the SWCC for the year 2016 provided detailed information about the Jubail plant, in terms of its electrical energy production, fuel consumption, and the energy and water consumed at the plant. Using the information contained in this report, Table 4-14 presents the energy embodied values required to produce 1m^3 of water. It should be noted that the energy used for pumping the water and operating the 460km long water pipes is not included, due to the lack of data. To estimate such data requires applying Pumping theory which requires data about flow, pump efficiency, motor efficiency as well as gravity.

The energy intensity required to produce 1m^3 of desalinated water was validated using a number of previous studies. In specific terms, the energy consumed by 1m3 of desalted water produced at the Jubail plant was calculated to be 327 MJ/m^3, and in order to validate this result, a review of similar studies was conducted. In their study, Raluy, Serra and Uche

(2006) reported that the energy consumption of the MSF plant was 333 MJ/m^3, while Al-Qaraghuli and Kazmerski (2012) reported a value of 282 MJ/m^3. The desalination process, particularly at the MSF plant consumed not only electricity, but also fuels such as natural gas or oil to boil water, and this means that the desalination sector consumes 9% of the total primary energy consumed in Saudi Arabia (Jun, 2013).

Table 4-14 Embodied energy factor for water production.

Water component	Embodied energy factor	Sources
Desalination	327 MJ/m^3	Electricity and Cogeneration Regulatory Authority, 2016; SWCC, 2016
Ground production	13.4 MJ/m^3	SimaPro, Tap water {RoW}| tap water production, underground water with chemical treatment | APOS, U

Construction materials

In terms of construction materials, embodied energy is the energy used in the manufacturing phase of building materials, and encompasses the raw material extraction, manufacturing, and transport to the construction site. As stated previously, the system boundary considered in the analysis in this study was cradle-to-gate, and the materials selected for study were cement, steel, and aggregate. In order to estimate the embodied energy for each material, several sources were consulted. For cement and steel, SimaPro was used, and the CED method was selected. However, it should be noted that the processes selected for cement and steel were modified in terms of the energy mix in the production phase, to suit the local context in Saudi Arabia. Meanwhile, in order to estimate the embodied energy for aggregate, the ICE database (V2.0) was used. Table 4-15 presents the construction materials selected, and the associated embodied energy values.

Table 4-15 Construction materials and associated embodied energy values.

Material	Total input flows (2016)	Embodied energy (MJ/kg)	Source
Cement	4,004 kt	3.87	SimaPro, Portland {RoW}| production | APOS, U
Steel	1,297 kt	21.1	SimaPro, Reinforcing steel {RoW}| production | APOS, U
Aggregate	22,597 kt	0.083	ICE (V2.0)

4.5 Results and discussion

4.5.1 Description of the case study

Riyadh is the capital of the Kingdom of Saudi Arabia, and is the country's largest city. It is located in the centre of the Kingdom, and is one of the fastest-growing cities in the world, in terms of population growth and developed area demand Figure 4-6 (Riyadh Development Authority, 2016).

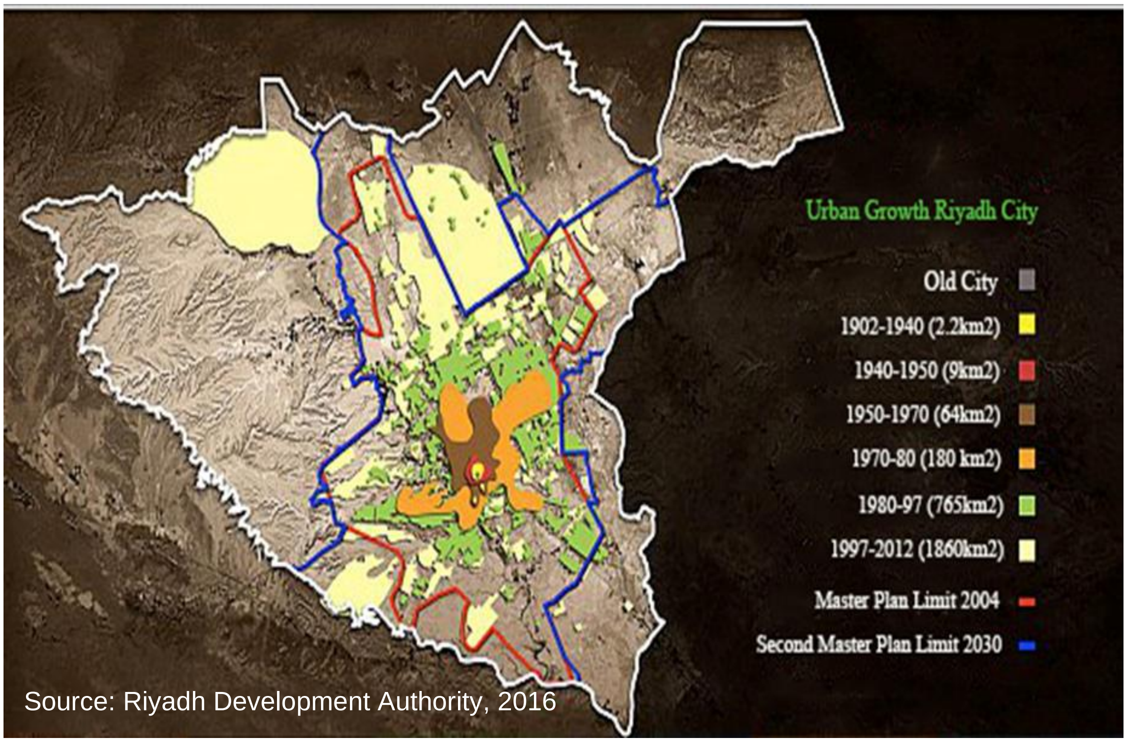
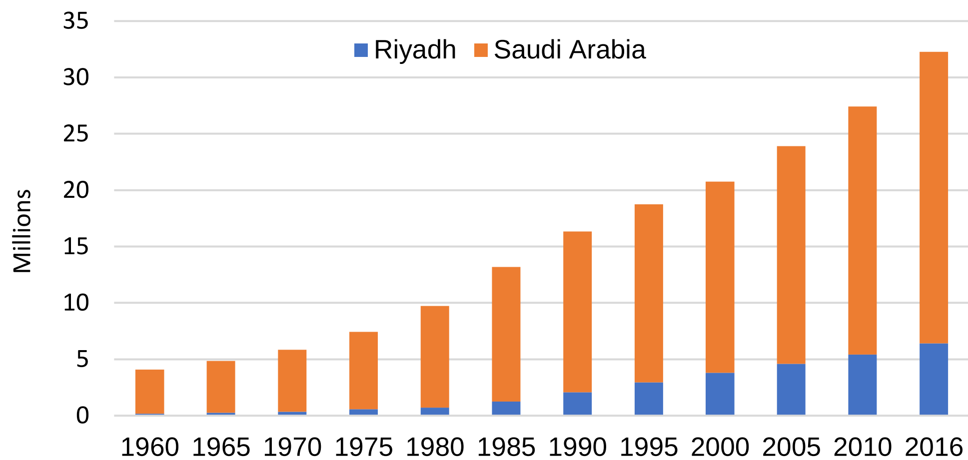


Figure 4-6 Urban growth in Riyadh.

The city was home to around 6.5 million people in 2016. Riyadh is the site of the headquarters of the central government bodies, and the majority of the major local and international companies and institutions. It is the largest population centre located on the Arabian Peninsula. The population of Riyadh has grown from almost one million in 1980 to more than six million today and is expected to reach 8.2 million by 2029 (Albelwi, Kwan and Rezgui, 2017a).

Between 2006 and 2016, the population of Riyadh grew at a rate of approximately 4%, annually. As illustrated in **Error! Reference source not found.**, the increase in population is the most noticeable feature of Riyadh, and has engendered the growth of other sectors. In 2016, the overall population of Riyadh reached 6,506,700, which constituted approximately 20% of the country's entire population (Riyadh Urban Indicators, 2017). The city’s population growth is characterized by qualitative improvements in its residents’ standard of living.



Source: Riyadh Development Authority, 2016

Figure 4-7 Riyadh’s share of Saudi Arabia’s population over time.

As the capital of the Kingdom, the city of Riyadh has witnessed growth rates higher than those of other cities. This strength in its economy can be explained by the increase in population and job opportunities that sustain the growth in demand for services and goods, as well as the city’s location at the centre of a large regional market, represented by Gulf Cooperation Council (GCC) states, and other neighbouring countries (Investment climate in Riyadh, 2016). Moreover, the population pyramid presented in Figure 4-8 demonstrates that around 35% of the population is under the age of 15 years

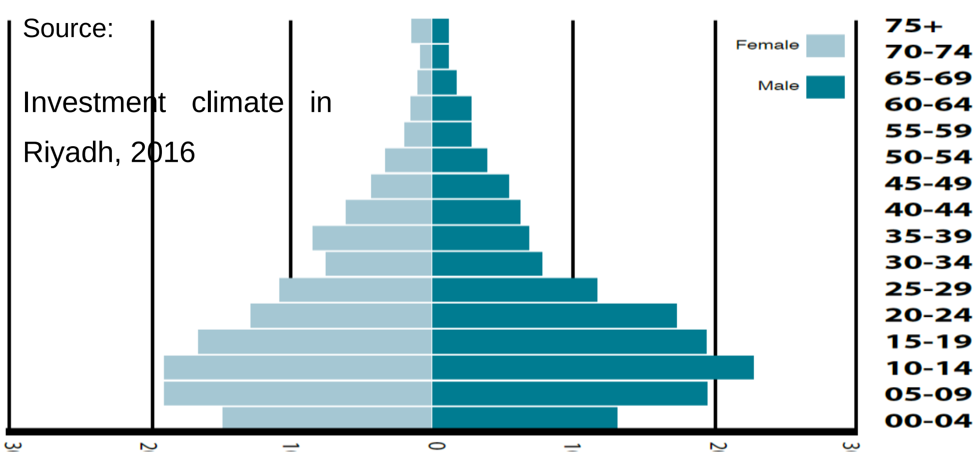


Figure 4-8 Riyadh population pyramid 2016.

This high percentage can be explained by the rapid population growth. Riyadh contributes 19% of the total GDP of Saudi Arabia; the GDP per capita in 2016 was 89,145 Saudi Riyal, which is approximately 23,770 USD (Riyadh Urbasn Indicators, 2017).

The total labour force of Riyadh in 2016 was 2.2 million, and the unemployment rate was 6.5% (ADA, 2016). Of this total labour force, approximately 35% were employed in the government sector, while the remainder worked in the private sector. According to the data obtained from the Gini index, which measures income inequality, the number for 2016 was 0.55. In addition, there were 319,217 commercial registration records, which represented 25% of the country's total, and there were three industrial cities with 2,395 plants that covered a total area of 22 km^2. These trends illustrate the need to study the urban MFA of the city, as it can assist the city officials to investigate the impacts of future development and to produce effective policies for sustainable urban development.

4.5.2 Socioeconomic indicators

The history of Riyadh, and its growth from a small town to a modern city, can be traced back to the year 1955, when it became the capital of Saudi Arabia. In this year, all of the ministries and government offices relocated to Riyadh. This caused an increased responsibility for the new capital, and more resources were allocated to cope with the growing population. As a result of the oil boom in the 1970s, the city experienced a considerable social and economic transformation. Table 3-16 summarizes the socioeconomic indicators for the years studied.

The table shows that the population of Riyadh was 3,004,600, 4,625,354, and 6,506,700 in 1996, 2006, and 2016, respectively, therefore in a matter of 20 years, the population doubled (116%). This steady increase in the population engendered an increasing demand for resources and services. Meanwhile, the average size of a household in Riyadh decreased from 6.3 individuals in 1996 to 5.7 in 2016, a decrease that can be attributed to the impact of economic and social factors. Another important indicator is the household formation rate, which is linked to the demand for new housing. The table shows that this increased from 2.7% in 2006, to 3.4% in 2016, which can be attributed to the increase in population age to between 15 and 59 years (Riyadh Urban Indicators, 2017).

Along with the population growth in Riyadh, the city has witnessed a pronounced transition in its economic sector, evidenced by the growth of the workforce, the average annual income, and the GDP per capita; these indicators increased by 120%, 19%, and 5%, respectively over the period studied.

In terms of the infrastructure-related indicators, Table 4-16 shows that there was an improvement regarding the connections to the public water network from 85% in 1996 to 98% in 2016. Meanwhile, the most significant improvement was evidenced by the two indicators regarding wastewater, demonstrated by the increased coverage of the public sewage network, the percentage of the wastewater treated, and the increased percentage of reused treated wastewater. In 1996, only 52% of households were connected to the public wastewater network, however, this number increased to 84% by 2016, which indicated the level of wastewater treatment. Until recently, the wastewater that was not collected through the wastewater treatment stations was deposited in sewage landfill. In conjunction with the improved network cover, a significant improvement was also witnessed in the treatment of wastewater, and the reuse of treated wastewater. The percentage of treated wastewater increased from 32% in 1996 to 61% in 2016, and more wastewater treatment stations are currently being built in Riyadh to increase the percentage further, and to manage the effects of urban growth. According to a report published in Arabic by the ADA (Water Crises in Riyadh, 2005), currently, the recycled water is distributed as follows: 42% for irrigation, and 3.7% to the Saudi Aramco refinery in Riyadh, as cooling water. The remaining 53% is discharged into the Wadi Hanifah, together with the running water in the valley.

In 2002, the ADA developed the so-called Wadi Hanifah Comprehensive Development Plan, in order to achieve two objectives:

- The restoration of the Wadi Hanifah as a natural balance for rainwater and surface water that flows from different sources of the city;
- The utilization of the valley as an open space, with walkways and entertainment services.

The Wadi Hanifah Rehabilitation Project received several awards and was recognized by a number of international organizations. In 2007, it was awarded gold status by the International Awards for Liveable Communities (livcom) Community Sustainability Award 'Natural Projects', and received a Highly Commended from the British Expertise Association in 2006.

Meanwhile, in another important sector of the city, namely transportation, the related socioeconomic indicators demonstrated that there was consistently a very low share of public transportation for the years studied, which can be associated with an over-dependence on private cars. Indeed, the figures revealed that automobile ownership per 1,00 people increased by 32% from 1996 to 2016. This, in turn, engendered many cars on the roads, causing traffic congestion, as evidenced by the trips per day, and the average travel time per trip. These daily trips increased from 3.5 million/day to 10 million/day, an increase of 185%. Meanwhile, the average travel time per trip was 11.8 minutes/trip in 1996 and increased to 31 minutes/trip in 2016.

Finally, the indicators related to solid waste showed an improving trend over the period studied, as the amount of solid waste, measured by kg/capita/day, was 2kg in 1996, but this figure dropped to 1.15 kg/capita/day by 2016, a decrease of 42%. Another positive trend was the increased recycling of municipal solid waste. At the beginning of the period concerned, there was no data reported regarding the recycling of municipal solid waste, as all of the municipal waste collected was simply buried in a specified location. However, due to the city officials' increasing concern about the low rate of recycling solid waste, a number of initiatives have been proposed, including the Riyadh Environment Initiative launched in 2017 by the ADA to monitor the environmental conditions in the city, and raise the level of coordination between the different agencies involved in the environmental sector.

In 2016, it was reported that 9% of the total municipal solid waste was recycled (Riyadh Urban Indicators, 2017), a positive indication of the improvements to the waste sector in Riyadh in recent years. The current recycling rate within the gulf region is less than 10%, while the recycling rates in the USA and the UK around 34% and 45%, respectively (Bhargava 2020).

Table 4-16 Socioeconomic indicators.

Indicators	**1996**	**2006**	**2016**	**Change (%) 1996-2016**
Population	3,116,773	4,448,010	6,506,700	116%
Density	1950	2167	2086	6%
Household size	6.4	6.3	5.7	-10%
Household formation rate	-	2.7	3.4	25%
Housing stock	454,476	786,343	1,217,996	180%
Households	433,598	727,070	1,116,339	157%
Housing units density	--	--	873	
Floor area per person	43	43	41	-0.05%
Workforce	1,034,697	1,546,812	2,283,073	120%
Employment-to-population ratio	49.5%	47%	49%	
Unemployment rate	7.2%	5.6%	6%	
Average annual income (USD 2015)	29,819	32,361	35,524	19%
GDP per capita (USD 2015)	17,700	15,530	18,598	5%
Household connections to public water network	85%	96%	98%	15%

Household connections to public wastewater network	52%	52%	84%	61%
Automobile ownership (per 1,000 people)	234	262	310	32%
Daily trips (million/day)	3.5	7.4	10	185%
Travel time (minutes/trip)	11.8	20	31	162%
Public transportation share of total trips	3%	3.2%	2.2%	--
% Wastewater treatment	32%	45%	89.7&	178%
Solid waste kg/person/day	2	2.49	1.15	-42%
Recycle solid waste	-	-	9%	

4.5.3 Biophysical indicators

This section presents the results of the biophysical aspects of the city of Riyadh. As for the socioeconomic indicators, the results are reported for years 1996, 2006, and 2016. The growth that was observed in some of the socioeconomic indicators, namely in population, household formation rate, automobile ownership, and daily automobile trips, is presented in the biophysical indicators, in terms of source demand.

The most noticeable feature among the biophysical indicators of Riyadh is the fact that the majority of the land within the city limits was specified as undeveloped. According to the ADA, 'developed land areas' refers to lands that contain buildings, or have been developed, whereas the undeveloped land area includes vacant lands, whether planned or unplanned. The category 'undeveloped land' also includes the valleys within city's urban limits. Table 4-17 summarizes the relevant characteristics of these biophysical indicators.

Table 4-17 Biophysical indicators.

Indicators	**1996**	**2006**	**2016**	**Change (%) 1996-2016**
Land area (km2)	1149	1373	3114	171%
Land area km2 (developed)	381	577	1119	193%
Land area km2 (undeveloped)	768	796	1995	160%
Heating degree days (18°C base) (average 5 years)	408	369	369	-
Cooling degree days (25°C base) (average 5 years)	1855	1855	1855	-
Average annual solar radiation (kWh/m2/year)	2318	2318	2318	-
Annual precipitation (mm)	61	97	89.202	46%
Residential building gross floor areas (m2)	129,197,800	198,890,250	266,774,700	106%

In 2016, the total land area was 3,114 km^2, an increase of 171% from 1996, while the developed land experienced a similar increase. Within the developed land, and excluding roads and infrastructure, residential use was the most prominent usage (61%) (Study of Riyadh's land use, 2013), as shown in Figure 4-9 Land use and urban growth limit.. In terms of the construction of new housing units, the period between 2006 and 2016 witnessed a significant increase in housing units from 727,070 in 2006, to 1.2 million in 2016, which can be attributed to the increased number of new households (610,731).

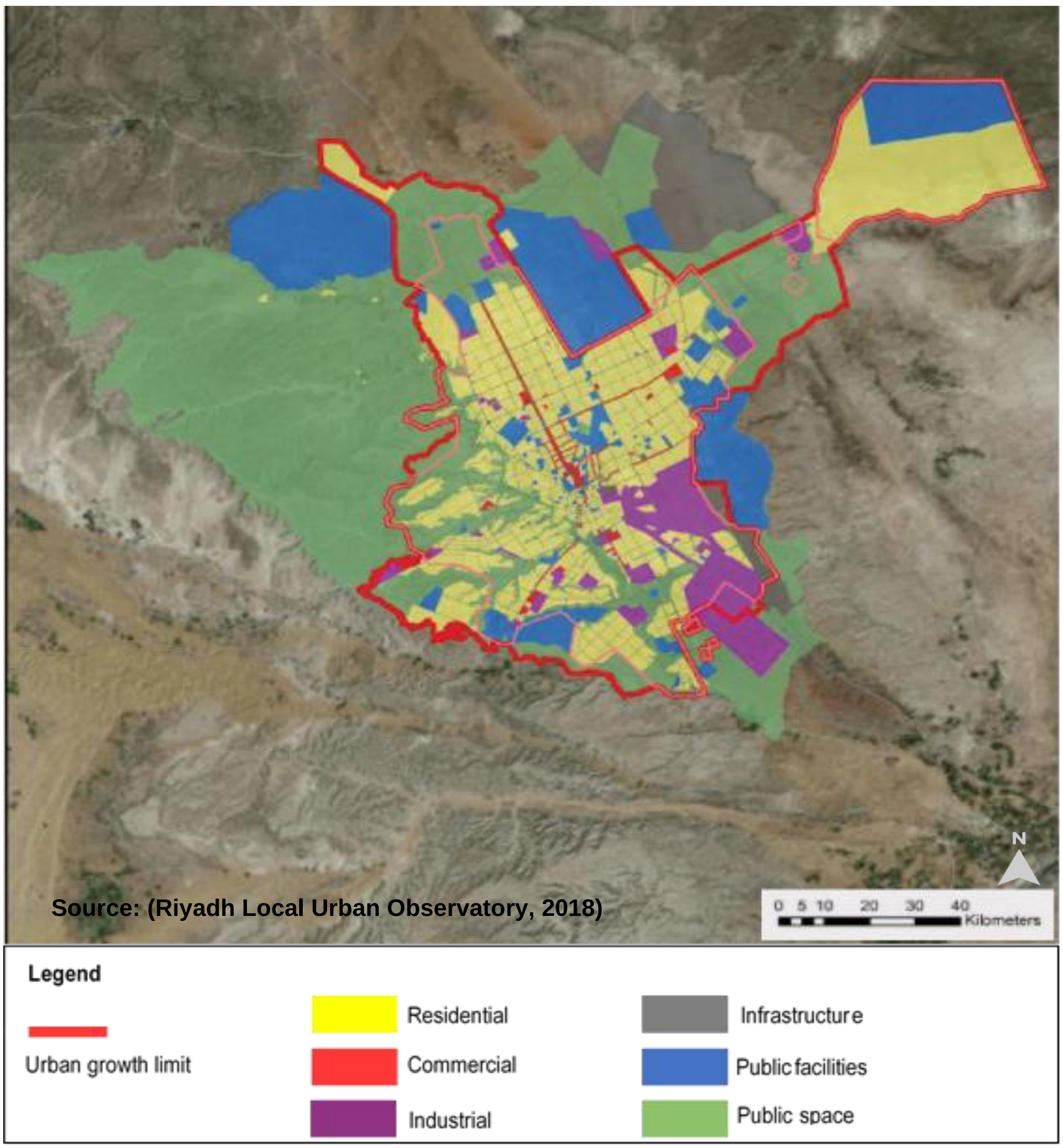


Figure 4-9 Land use and urban growth limit.

Housing production has kept pace with the increasing demand caused by the rapid population growth, as evidenced by the growth of total residential building gross floor area, which increased by 106% from 1996 to 2016.

Meanwhile, the indicators related to the weather and climate conditions showed that the annual precipitation in 2016 was 89.2mm, well below the global land-mean precipitation of 825mm reported by Skofronick-Jackson *et al.* (2018). In terms of the annual solar radiation data obtained from Myers *et al.* (2002), the average was 2,318 kWh/m^2/year, demonstrating the significance of this source for the country as a whole. Due to the abundant solar resources available, Riyadh can benefit by employing this resource to curb the use of fossil fuels in energy production. This point is explored further in Chapter 5, which concerns the integration of MFA with LCA to evaluate urban development policies.

The final data reported was that regarding cooling and heating degree days, which measures the need, or the demand, for heating and cooling spaces. The data obtained from https://www.degreedays.net/ showed that there were 369 heating degree days in 2016, which is the number of degrees that a given day's average temperature is below 18°C. Meanwhile, there were 1,855 cooling degree days when a given day's average temperature was above 25°C. It should be noted that the 18°C and 25°C were selected to represent the local conditions in Riyadh. It was therefore unsurprising that the need for cooling surpassed the need for heating in Riyadh, as its climate is characterized by extreme dryness and heat in the summer, and cold in the winter. During the summer months of April to September, the temperature can reach 45°C, while in the winter months of September to March, it can drop to as low as 15°C (Riyadh Local Urban Observatory, 2018), demonstrating a significant need for cooling that explains why this category was found by the MFA indicators to be responsible for 56% of the final energy end-use consumption in residential sectors.

4.5.4 Urban material flows of Riyadh

This section presents the results of the MFA for Riyadh in the years studied, 1996, 2006, and 2016. The results present every component as either input or output flows, and the interaction between these flows and the environment are indicated as follows: energy inputs (stationary and mobile) and emissions, water and wastewater, and construction materials and solid waste.

Table 4-18 provides a summary of the urban material flows of Riyadh in 1996, 2006, and 2016, with the results presented as gross and per equivalent inhabitant. Meanwhile, Table 4-19 illustrates the variation over the 20 years concerned, per equivalent inhabitant value. The main findings of the urban material flows are discussed below.

Table 4-18 Urban material flows of Riyadh: gross value and per capita.

MFA component	Source	Unit	Total 1996	per capita 1996	Total 2006	per capita 2006	Total 2016	per capita 2016
4.5.4.1 Energy (production)	Crude oil	TJ	60,597		118,191		304,633	
	Diesel	TJ	36,358		70,914		54,348	
	Natural gas	TJ	105,034		204,864		356,120	
	Total primary energy	TJ	201,989	64 GJ	393,969	85 GJ	715,101	110 GJ
	T&D loss	GWh	1,677	538 kWh	3270	707 kWh	4583	704 kWh
4.5.4.1 Energy (stationary)	Electricity consumption	GWh	16,600	5,326 kWh	32,377	7000 kWh	58,769	9,032 kWh
	Residential	GWh	9,462	3,035 kWh	18,455	3999 kWh	30,854	4,741 kWh
	Commercial	GWh	1,992	639 kWh	3,885	840 kWh	11,049	1,698 kWh
	Industrial	GWh	1,162	372 kWh	2,266	490 kWh	4,055	623 kWh
	Government and services	GWh	3,154	1,011 kWh	6,152	1330 kWh	9,873	1,517 kWh
	Others	GWh	830	266 kWh	1,619	350 kWh	2,938	451 kWh
Household fuel consumption	LPG	TJ	2,708	0.87 GJ	5,825	1.26 GJ	6,554	1.01 GJ
4.5.4.2 Energy (mobile)	Gasoline	TJ	80,108	26 GJ	142,881	31 GJ	259,131	39 GJ
	Diesel	TJ	76,081	24 GJ	119,170	26 GJ	157,055	24 GJ
	Jet fuel (kerosene)	TJ	--	--	22,047	5	39,764	6.11 GJ
4.5.4.3 Water flow	Total water consumption	kt	412,351	132 ton	519,527	117 ton	832,655	127 ton
	Ground production	kt	222,670		280,545		449,634	
	Desalination	kt	189,681		238,982		383,021	
	Distribution loss	kt	70,100	23.3 ton	105,827	23 ton	183,200	28 ton
4.5.4.4 Construction materials	Construction permits		5631		9579		16,915	
	Input floor area	m^2	4,040,231	1.34	12,230,524	2.64	17,619,661	2.71
	Cement-input	ton	918,158	306 kg	2,779,434	624 kg	4,004,136	615 kg
	Steel	Ton	297,457	99 kg	900,456	194 kg	1,297,224	199 kg
	Aggregate	ton	5,181,730	1,724 kg	15,686,053	3,391 kg	22,597,800	3,473 kg
4.5.4.5 Emission	GHG of energy use	kt-CO_{2e}	12,539	4.17 ton	24,457	5.28 ton	47,354	7.28 ton
	GHG of transport sector	kt-CO_{2e}	11,647	3.88 ton	20,730	4.48 ton	32,962	5.07 ton
	GHG materials production	kt-CO_{2e}	1,540	0.51 ton	4,664	1.01 ton	6,720	1.03 ton

	GHG water production	kt-CO_2e	4,634	1.49 ton	5,838	1.31 ton	9,357	1.44 ton
4.5.4.6 Wastewater	Total wastewater	kt	157,680	52 ton	266,893	57 ton	375,451	58 ton
	Untreated wastewater	kt	107,223	34 ton	146,792	33 ton	38,672	6 ton
	Treated wastewater	kt	50,457	16 ton	120,101	25 ton	336,779	51.7 ton
	Reused	kt	17,659	5.8 ton	45,638	9.8 ton	127,976	19.6 ton
4.5.4.7 Solid waste	Municipal waste	kt	2,193	0.73 ton	2,532	0.54 ton	2,731	0.42 ton
	Construction waste	kt	-	-	-	-	3,650	0.56 ton
	Recycled waste	%	-	-	-	-	9%	38 kg

For the purpose of this study, the energy inputs were divided into three sub-categories: energy production, energy stationery, and energy mobile. In terms of energy production, the data demonstrated the heavy reliance on fossil fuels for producing energy, together with the absence of a renewable energy share in the energy mix. The main fuels used in energy production were found to be crude oil, diesel, and natural gas, whose share of the final energy mix was 42.7%, 7.6%, and 49.7%, respectively. According to Alyousef and Varnham (2010), the primary energy factor is 3.38; this factor is used to estimate the total primary energy required to produce a unit of electricity. Therefore, in the year 2016, the city required 715,101 TJ of primary energy to produce 58,769 GWh, which is equivalent to 211,568 TJ.

Meanwhile, the energy stationary data demonstrated a significant trend in electricity and energy use. The electricity use in 2016 had increased, in terms of gross value, by 254% from the 1996 value, evidencing an average increase of 6.5% annually. In terms of energy use by sector, the commercial sector witnessed the greatest increase in electricity use (455%) from the value reported in 1996 to that in 2016. The other sectors, including residential, industrial, and government and services witnessed an increase of 226%, 249%, and 213% respectively.

In contrast, energy mobile, which is the energy consumption required for on-road transportation, witnessed less of an increase compared with that in the energy stationary sector. In 1996, the total energy mobile was 156,189 TJ, and in 2016, this increased by 166% to 416,186 TJ.

In terms of the water consumption component, the data demonstrated that there was an increase of 106% in the total input flows from 1996. However, when considering the change per capita, there was a decrease of 4%. This is discussed further in the next section.

Table 4-19 Changes in MFA values

MFA component	Source	Change (%) 1996- 2016 per capita	Change (%) 1996- 2016 gross value
Energy production	Total primary energy	72%	254%
	T&D loss	31%	173%
Energy (stationary)	Electricity consumption	70%	254%
	Residential	56%	226%
	Commercial	166%	455%
	Industrial	67%	249%
	Government and services	50%	213%
Household fuel consumption	LPG	16%	254%
Energy (mobile)	Gasoline	50%	142%
	Diesel	0%	223%
Water flow	Water consumption	-4%	106%
	Distribution loss	20%	709%
Construction materials	Construction permits	200%	161%
	Input built floor area	102 %	77%
	Cement (input)	101%	336%
	Steel	101%	336%
	Aggregate	101%	336%
Emissions	GHG of energy use	75%	278%
	GHG of transport sector	31%	183%
	GHG materials production	101%	336%
Solid waste	Total municipal waste	-42%	278%
	Recycled waste	100%	100%
Wastewater	Total wastewater	12%	138%
	Untreated wastewater	-82%	-64%
	Treated wastewater	223%	157%
	Reused	238%	625%

As indicated by a number of previous studies, construction materials are a critical input component to a city's urban system, as buildings are constructed to meet the socio-economic development demands of cities and nations. However, meeting this demand causes an intensive use of resources and energy, and produces a considerable amount of waste and emissions (Cuéllar-Franca and Azapagic, 2012). In terms of floor input, which is a measurement of housing demand, the data revealed an increase of 77% from 1996 to 2016, in order to meet the demands of population growth. In terms of the specific construction materials studied, namely cement, steel, and aggregate, the data showed that there was 244% increase in the gross value from 1996 to 2016, an increase of 60% per equivalent inhabitant. While the associated figure was 8.5 million tons in 1996, it increased to 29.2 million tons in 2016. In terms of the per equivalent inhabitant figure, in 1996 the construction material input was 2.8 ton/eq.inhab, which increased to 4.4 ton/eq.inhab in 2016.

Meanwhile, regarding the output flows, the total emissions generated by the city's activities increased by 216% from 28,279 kt $CO_{2\,e}$ to 89,623 kt $CO_{2\,e}$ from 1996 to 2016, respectively, and for per capita, it increased by 52% during the same period. In the year 2016, energy production and consumption was responsible for 53% of these emissions, whereas the transportation sector was responsible for 37%. The GHG emissions resulting from the production of the materials cement, steel, and aggregate, was responsible for 10% of this figure evidencing a decrease in its share from 14% in 1996. In contrast, the emissions per capita was 13.8 ton $CO_{2\,e}$ in 2016, an increase of 52% from 1996 (9.07 ton $CO_{2\,e}$).

In 2016, Riyadh generated 375 million tonnes of wastewater in 2016, an increase of 138% from 1996, although the per equivalent inhabitant values showed an increase of only 11.5%. The wastewater component was, therefore, the sector in which the greatest improvement over the period was apparent, which is discussed further in the next section.

Moreover, Riyadh generated 2,731,187 tonnes of solid waste in 2016. While this number indicated an increase of 278% from 1996 in terms of gross value, there was a decrease in the per equivalent inhabitant values by 42%. This is discussed further in the next section.

The following sub-sections provide further details of the findings, per component.

4.5.4.1 Energy stationary

This component differentiates between energy production and energy consumption. The latter concerns the amount and type of fuels used at power plants, and is significant as it is related to two important factors. First, the amount of fuel used in energy production is important for determining the efficiency of the power plant; a recent publication reported that the efficiency of a typical Saudi power planet was 29.5% (Alyousef and Varnham, 2010). The second factor concerns the type of fuel used at power plants. For the purpose of the present study, this information was obtained from the annual statistical booklet for electricity and seawater desalination industries (Electricity and Cogeneration Regulatory Authority, 2016).

From 1980 to 2012, the primary energy consumption increased by an average of 5% annually, decreasing to 4% after 2012, as shown in Figure 4-10. This increase in primary energy was mainly due to the increased demand over the period concerned. For example, the per capita consumption of electricity in Riyadh in 2016 was 9,032 kWh, an increase of 70% from the 1996 value.

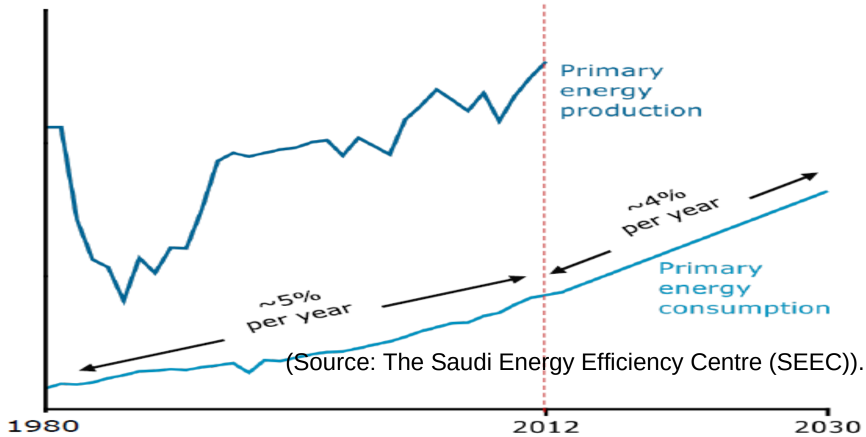


Figure 4-10 Primary energy production and consumption in Saudi Arabia.

As shown in Figure 4-11 , the rapid increase in energy consumption is a prominent feature of the energy sector in Saudi Arabia. This unsustainably high rate growth in energy demand presents a major challenge for a large city like Riyadh, and for the country as a whole, a fact recognized by a number of recent studies, including those conducted by Taher and Hajjar (2013; 2014), Alrashed and Asif (2014), Nachet and Aoun (20s15), Albelwi, Kwan and Rezgui (2017a), and Wada (2017)

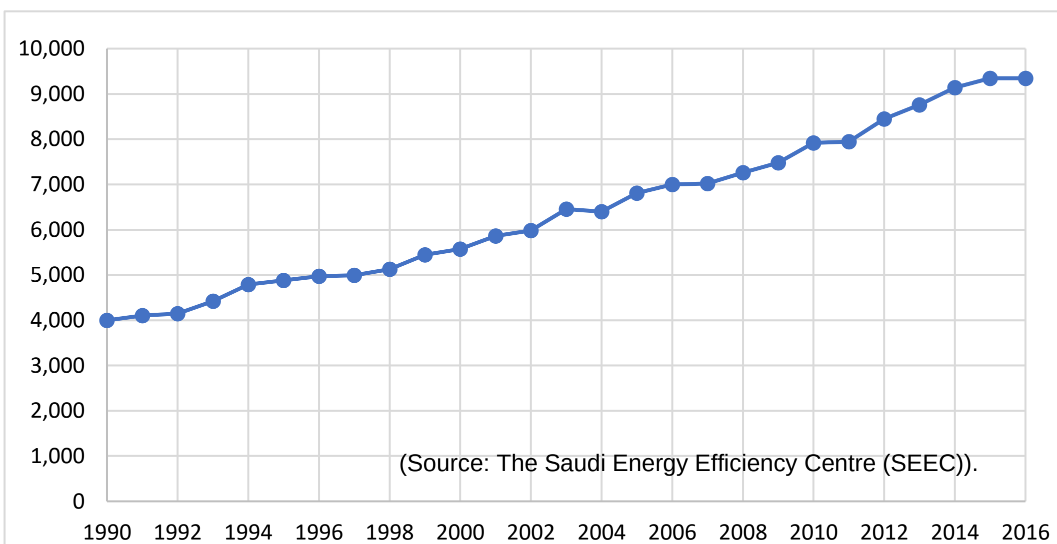


Figure 4-11 Trends in electricity consumption per capita in Saudi Arabia (kWh/capita).

Figure 4-12 depicts the energy flows in Riyadh in 2016. This year was chosen as it has the most related data available. The main feature of the energy flows in the city is the low efficiency in energy production. In 2016, Riyadh required 715,102 TJ (3.38*211,568) of primary energy to produce an equivalent of 211,568 TJ (1 GWh equals 3.6 TJ). This figure also shows that there was a 7% loss in electricity, due to the transmission and distribution processes involved.

In terms of the main users in the city, the residential sector was responsible for 53% of the energy used, while more importantly, 58% of electricity consumption in Riyadh was used for cooling systems, due to the harsh weather during the long summer, as well as to the relatively large size of the city's households (5.7); the average household size in Europe was 2.3, and 2.6 in the US, in 2016. Meanwhile, lighting and food preservation was responsible for 12% and 10% of the energy consumption, respectively.

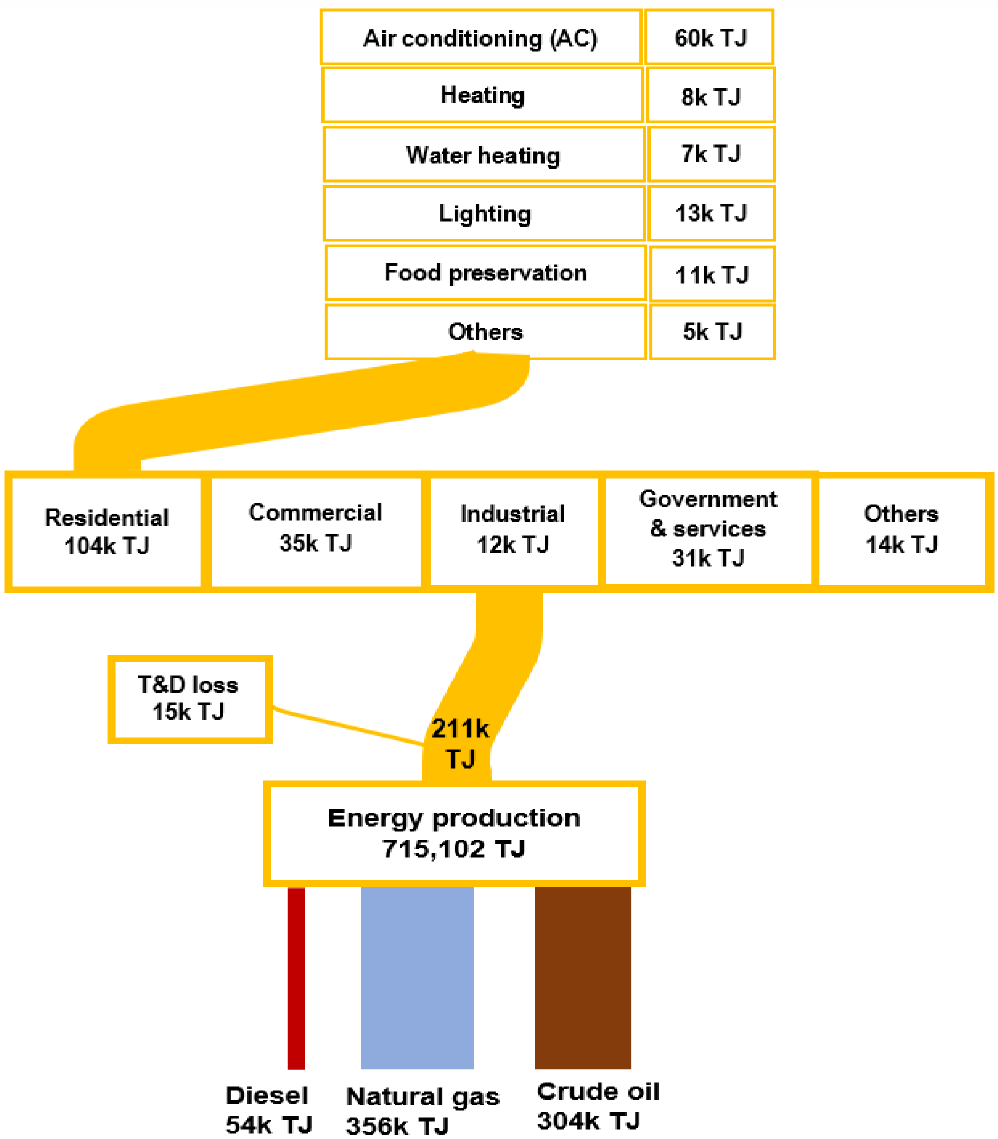


Figure 4-12 Energy flows and end users in Riyadh, 2016.

4.5.4.2 Energy mobile

Due to the improvement in socio-economic indicators over time, the road network now plays a significant role in contributing to the development of different economic sectors (Aldagheiri, 2009). Figure 4-13 presents the total energy consumption associated with the transportation sector in Riyadh, as well as per capita. The overall trends observed in the socioeconomic indicators are well represented in energy mobile consumption.

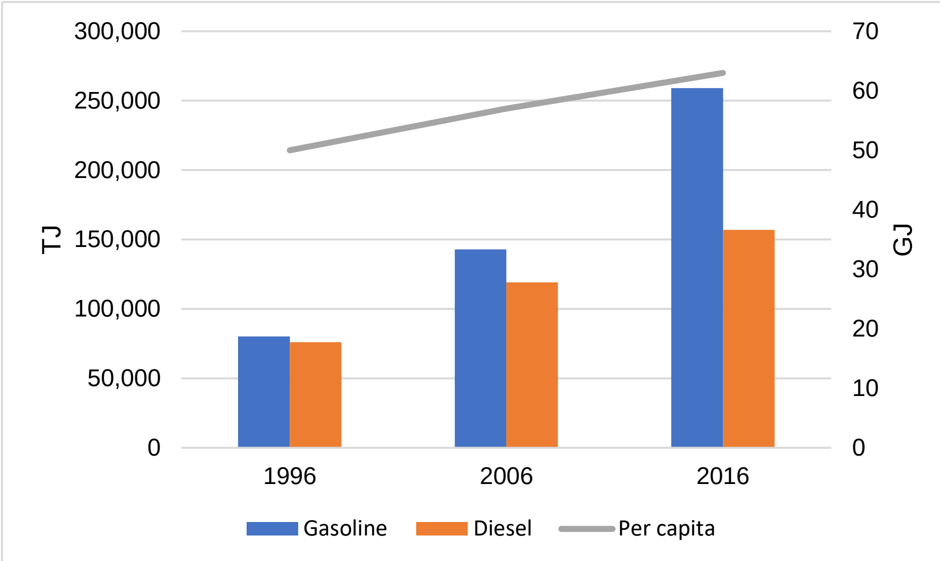


Figure 4-13 Total and per capita energy mobile consumption.

The indicators associated with the transportation sector are presented in Table 4-20, which demonstrates the temporal increase in all of the indicators. The most noticeable feature of Riyadh's transport sector in the years studied was the low share of public transportation. However, it is hoped that the on-going Riyadh metro project will increase this share, and curb the energy consumption. This is discussed further in Chapter 6.

Table 4-20 Indicators associated with transportation. Source: The Royal Commission for Riyadh

Indicators	1996	2006	2016
Automobile ownership (per 1,000 people)	234	262	310
Travel time (minutes/trip)	11.8	20	31
Average annual income (USD, 2015)	29,819	32,361	35,524
Daily trips (million/day)	3.5	7.4	10

4.5.4.3 Water flows

In Riyadh, the total water input flows was 832,655 kt in 2016, representing an increase of 106% from 1996. However, the per capita data showed a decrease of 4% in the same period. This may be attributed to the increase in water price due to changes in water tariff that was introduced in 2016. Figure 4-14 presents a Sankey diagram of water flows in Riyadh.

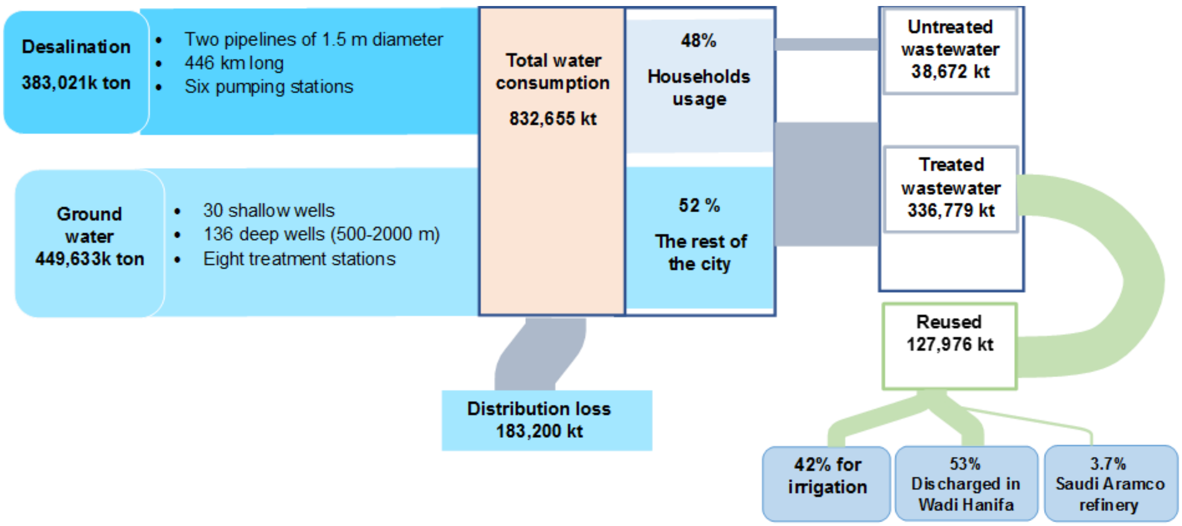


Figure 4-14 Water flows in Riyadh, 2016.

The input water flows demonstrate that 832,655 kt of water entered the city in 2016, but that only 45% was collected as wastewater. The low percentage can be explained by the fact that approximately 22% of the water flow was lost during the distribution process, and only 84% of the city was covered by public sewer networks. While these two points indicate a low-efficiency performance in the system, several positives trends were also captured by the integrated framework. For example, in 1996, only 52% of the city's buildings were covered by the public sewer network, but by 2016, this had improved significantly to 84%. Another positive trend was the increasing percentage of wastewater treated; in 1996 and 2006, only 44% was treated, but by 2016, this had increased to 89%. About 42% of the recycled wastewater was used for irrigation, and 3.7% was used by the Saudi Aramco refinery in Riyadh as cooling water, while the remaining 53% was discharged into Wadi Hanifa, in addition to the running water in the valley.

4.5.4.4 Construction materials

Most previous studies regarding construction material flows focussed on the temporal and spatial trends of materials or energy flows, and the related environmental impacts (Müller, 2005; Piña and Martínez, 2014; Niza *et al.*, 2015). Meanwhile, an MFA applied at an urban scale revealed that the construction material component contributes significantly to the environmental impacts of cities (García-Guaita *et al.*, 2018).

As indicated by the socioeconomic indicators in the present study, the city of Riyadh has witnessed rapid growth in its population. In order to meet the demands of this increase, a significant amount of construction materials have been required; such materials are one of the most critical input flows in cities (Piña and Martínez, 2014), because they constitute the largest flows and stocks of materials in cities (Kennedy, Baker and Brattebø, 2014b).

The results of the present study demonstrated that the input flows of construction materials increased in gross value by 336% from 1996 to 2016, and by 106% per capita. This is mainly due to the increased demand for housing, as evidenced by the increase in the number of construction permits issued over the years concerned, as illustrated in Figure 3-18.

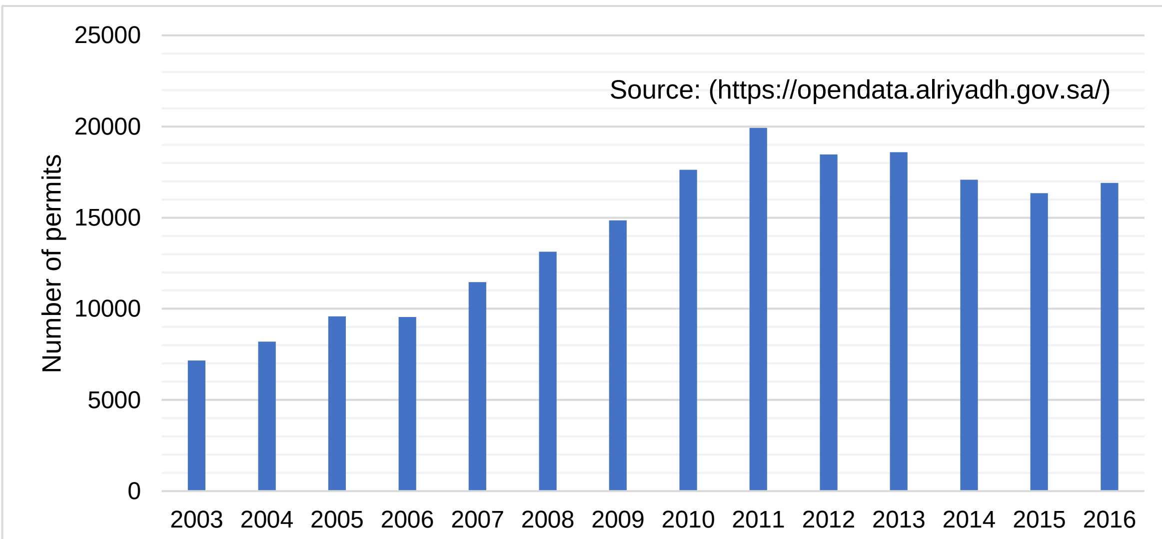


Figure 4-15 Construction permits issued over time.

The input flows of construction material corresponds to the annual input floor area. As discussed previously, the focus of this study was residential buildings. In 1996, four million square metres were added to the housing stock, and the total construction materials was 6.3 million tonnes. Meanwhile, in 2016, 17.6 million square metres of floor area were added to the housing stock, and approximately 27.8 million tonnes of construction materials. This can be explained by the increase in the number of housing units in Riyadh over the years concerned, as shown in Table 4-21, which presents the growth rate from the previous year.

Table 4-21 Development of housing units in Riyadh. Source: The Royal Commission for Riyadh

Year	Housing units
1987	307,212
1991	351,266
1996	454,476
2005	704,754
2016	1,217,996

In terms of the materials with which this study was concerned, aggregate constituted the large share, in terms of weight (81%), while cement and steel constituted 14% and 5%, respectively as shown in **Error! Reference source not found.**. While these percentages are based on representative buildings, they concurred with the findings of Hu et al. (2010), who reported that aggregate constituted the largest share in their study, in terms of weight (84%). However, cement and steel have the highest environmental impact, in terms of embodied energy and emissions.

Between 1996 and 2016 there was about 101% increase in material flows (cement, steel, aggregate) in terms of per capita. This increase is corresponding to the increase in population and its demand for housing (floor area input). Modelling the input flows assumes that there is a linear relationship between population growth and material demands. This assumption was validated using reported data by Riyadh Municipality which will be discussed further in Chapter 5, section 5-4-4. The increased demand for construction materials has negative environmental impacts. Given that these materials are produced locally, understanding these impacts is crucial in developing climate change mitigation policies. This will be explored further in the following section.

4.5.4.5 GHG emissions

This section reports the emissions associated with input flows. The focus of this study was GHG emissions, because, as recent reports indicated, GHG emissions are the factor that contributes the most to climate change, especially CO_2 (Cheng *et al.*, 2019). Since the oil boom of the 1970s, Saudi Arabia has experienced economic prosperity and socio-economic development that has resulted in an improvement to the standard of living in the country. However, for an oil-based economy, this comes at the price of increasing the level of emissions, especially CO_2. According to the recent national GHG inventory (Ministry of Energy Industry and Mineral Resources, 2016), the total estimated CO_2 emissions in Saudi Arabia in 2010 was 472 million tonnes. The major sources of these emissions are energy production (31%), on-road transportation (21%), and desalination (12%). Meanwhile, cement and steel production were responsible for 5% and 4%, respectively, and the petroleum refining and petrochemical industry was responsible for 15%. The average GHG per capita, according to the same report, was 19.8 tonnes $CO_{2\,e}$/capita. This average is considered to be among the highest, globally (Khondaker *et al.*, 2016).

Cities are responsible for approximately 75% of the world's GHG emissions (National Academies of Sciences and Medicine, 2016). Table 4-22 presents the total GHG emissions of Riyadh, corresponding to the input flows studied, showing that in 2016, the GHG emissions of the city were 14.64t$CO_{2\,e}$. For that year, the per capita GHG in Saudi Arabia was 16.01 t$CO_{2\,e}$[2].

Table 4-22 GHG emissions of Riyadh, 2016.

MFA component	GHG (t$CO_{2\,e}$)	Percentage (%)
Energy consumption (stationary)	48,323,457	50.7%
Energy mobile	26,862,449	28.2%
Construction materials production	6,802,638	7.1%
Water (ground production)	390,415	0.4%
Water (desalination)	8,966,522	9.4%
Solid waste	3,809,851	4%
Wastewater treatment	107,189	0.1%
Total	95,262,521	100%
Per capita	14.64 t$CO_{2\,e}$	

As shown in **Error! Reference source not found.**, energy production contributed the most to the overall city emissions, which was to be expected, since this sector consumes more primary energy by far than the other. Moreover, energy production in Saudi Arabia is characterized by low efficiency (Khondaker *et al.*, 2014; Albelwi, Kwan and Rezgui, 2017a; Wada, 2017). The second greatest contributor to the city's GHG emissions was found to be the transport sector; with more than 1 million cars, and 10 million trips per day, the transportation sector was found to be the second highest consumer of primary energy.

Moreover, the temporal trends per capitavalue showed that the overall results suggested an increase in the pattern, as illustrated in Table 4-23. However, GHG emissions related to water production showed a decrease of 3.4%, which can be attributed to a lower water consumption, per capita.

[2] https://knoema.com/atlas/Saudi-Arabia/ CO_2-emissions-per-capita

Table 4-23 Temporal trends in GHG emissions in Riyadh.

MFA component	(1996-2016) changes in per capita value (%)
Energy consumption (stationary)	74%
Energy mobile	31%
Construction materials production	101%
Water production	-3.4%

Another important component of GHG emissions is water production, as the GHG emissions associated with the production phase highlight the importance of understanding the energy-water nexus. This concerns the fact that energy is required to extract groundwater, in desalination plants, and to deliver the water to the end-users. This study did not include energy, and the related emissions corresponding to water delivery, due to the lack of data available. However, when employing secondary sources, the GHG emissions associated with water production were estimated, and are shown in Table 4-24. It should be noted that the emissions associated with water production from desalination are estimated according to the type of technologies employed in desalination plants in Saudi Arabia, as reported by the SWCC (2016) in their annual statistical booklet for the operation and maintenance sector.

Table 4-24 Relative emissions associated with water production.

Water production component	Emissions $CO_{2\ e}$	Source
Ground production	0.868 kg/$CO_{2\ e}$/ m^3	SimaPro, Tap water {RoW}| tap water production, underground water with chemical treatment | APOS, U
Desalination	5.23 kg/$CO_{2\ e}$/ m^3	(Life cycle assessment of MSF, MED and RO desalination technologies), (Raluy, Serra and Uche, 2006)

4.5.4.6 Wastewater

In Riyadh, while the total water input flow was 832,655 kt in 2016, 48% or 399,675 kt of this was for household usage. Additional usages included agriculture, industry, commercial, government operations and services. However, insufficient data is available concerning how much water each sector within the city consumes. The total volume of wastewater collected overall was 375,451. Thus, the amount of water lost at the distribution stage was 183,200 kt. The total wastewater discharged increased 138% by gross value, but per capita this represents a 12% increase. The amount of wastewater treated rose by 223% from 1996 by volume and by 157% per capita. Moreover, the amount of recycled wastewater used increased significantly in volume from 625% and 238% per capita. This is mainly attributable to significant improvements over the last 20-year period increasing both the amount of wastewater being treated and the level of use of recycled wastewater. For example, the sewer network covered only 52% of the city in 1996, whereas by 2016 it provided for 84%.

A further improvement in this sector has been a significant reduction in untreated wastewater. The amount of untreated wastewater fell by 64% in volume and 82% per capita from 1996 to 2016. Most of the untreated wastewater was disposed to landfill. It was difficult to obtain detailed information on the fate of the untreated wastewater, as there were several types of disposal. However, up to 2010, there was a specified location used to dispose of untreated wastewater. This location was closed that year due to environmental concerns.

4.5.4.7 Solid waste

Solid waste data, as mentioned previously, was available through publications from Riyadh Development Authority (ADA), and Riyadh General Authority for Cleanliness. The results showed an increase in gross value of 278% from 1996 to 2016. Despite this increase, there was a noticeable reduction in per capita value. The results showed a 42% decrease from 1996 to 2016 in terms of per capita value. However, in 2016, municipal solid waste per capita was 1.15 kg/day, whereas in 1996 it was 2kg/day. These two values are still well above the global average (0.74kg/day)[3].

Solid waste recycling continues to fall behind despite improvements to this sector. The results showed that 9% of the solid waste collected was recycled in 2016. This percentage is predicted to increase over the coming years, as there are several initiatives in place to address the issue of waste management. For example, in early 2019, the National Waste Management Center, the Riyadh Municipality and the Saudi Investment Recycling Company signed an agreement to start integrated waste management and waste recycling activities in Riyadh[4]. According to this agreement, the first phase will be the recycling of construction and demolition waste into building materials for road construction and housing projects. The plan aims to recycle 80% of municipal solid waste and 47% of construction and demolition waste annually by 2035 [5].

[3] https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management
[4] https://www.mewa.gov.sa/en/MediaCenter/News/Pages/News793.aspx
[5] https://www.argaam.com/en/article/articledetail/id/1303850

4.5.4.8 Sankey diagram

Given the substantial amount of information contained in urban MFA, a diagram is beneficial to present the results in a useful way. A Sankey diagram is typically used in similar studies, as it is useful for presenting and displaying material and energy flows by fuel types and according to end-use (Kennedy, Baker and Brattebø, 2014b). In this type of diagram, the most important information is displayed, which makes the results easy to read and understand. Other ways to present MFA results include flow diagram and input-output tables. Both flow and Sankey diagram enable a visual translation of MFA findings that could be useful for different decision-makers, while input-output tables are less effective in showing MFA results in a meaningful and easy to understand. The urban material flow diagram for Riyadh in 2016 is presented in Figure 4-16.

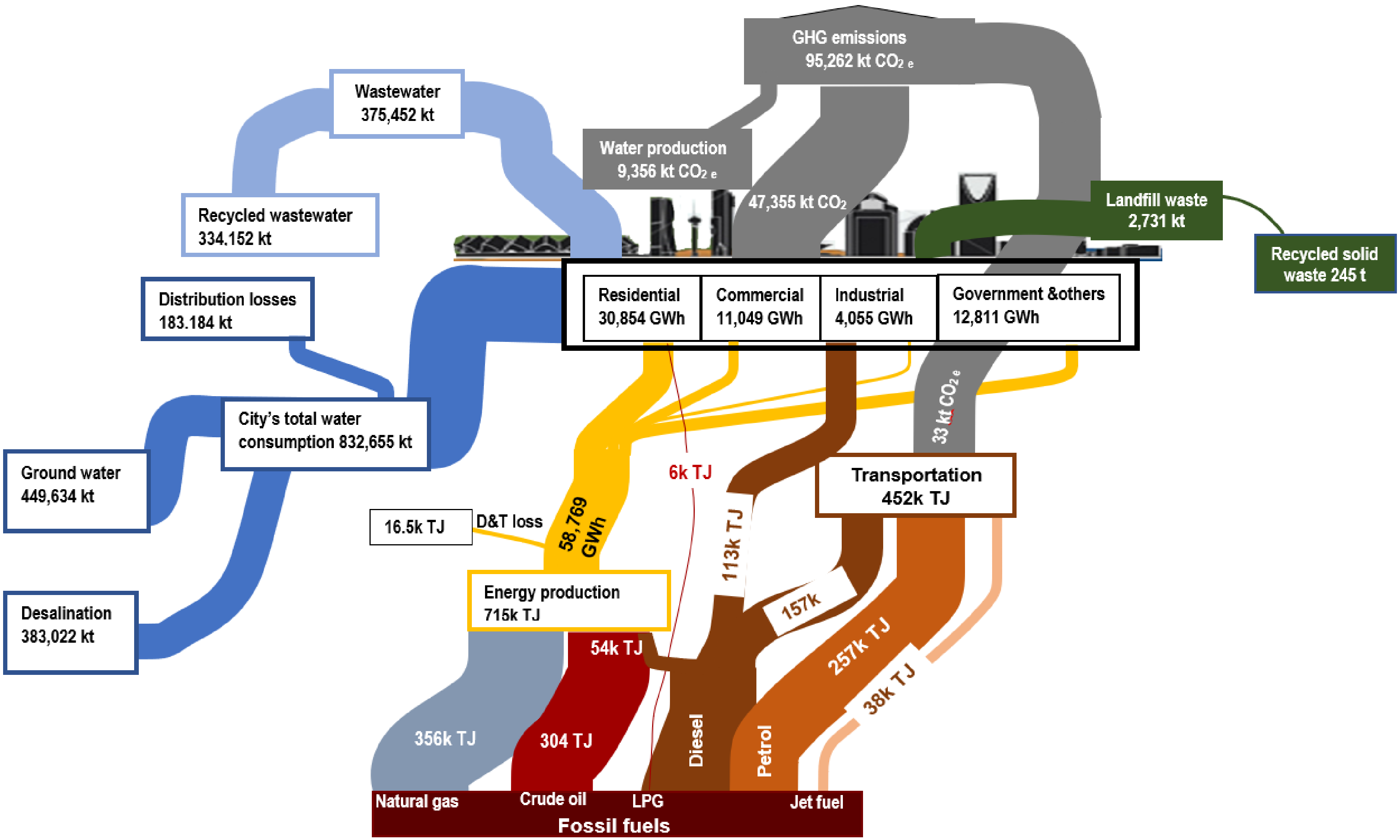


Figure 4-16 Sankey diagram of urban material flows of Riyadh, 2016.

4.5.5 Life cycle assessment indicators

Thus far, MFA has provided physical information on the consumption of resources by the city. This includes energy, water, materials, wastes and emissions. Applying LCA has proven to be a powerful tool for assessing additional information on resource consumption within society. In this study, LCA was applied to develop an environmentally friendly profile for the city, by assessing the impact of the studied flows in terms of emissions and embodied energy. In this section, the results are reported regarding two aspects of LCA; the environmental impact of the main input flows and outflows, and the embodied energy associated with these main input flows.

4.5.5.1 Environmental impacts of Riyadh's urban material flows

Table 4-25 presents the environmental impact of Riyadh reported as a per capita. It reveals that the total for GHG emissions in 2016 was 16 tonne $CO_{2\ e}$ per capita. Other impact categories are reported for comparison with similar studies. Additional details for each impact category are given in the following paragraphs.

Table 4-25 LCA results per capita for 2016.

Impact category	Unit	Riyadh
Climate change	tCO2 eq	15.10
Fine particulate matter formation	kg PM2.5 eq	21.27
Freshwater ecotoxicity	kg 1,4-DCB	293
Fossil resource scarcity	kg oil eq	5649.68
Water use	m^3	171.77

Climate Change

Studies considering the impact of cities on climate change have been popular among researchers worldwide. Studies, such as that by Goldstein *et al.* (2013), have estimated the GWP per capita for several cities, and have found that GWP ranges between 11.2 tons $CO_{2\ e}$ in Cape Town, and 18 tons $CO_{2\ e}$ in Toronto. This study estimates the GWP for Riyadh to be 15.10 $tCO_{2\ e}$. As shown in Figure 4-17, around 50% of this is amount is a consequence of energy production. The transport sector was responsible for 28%.

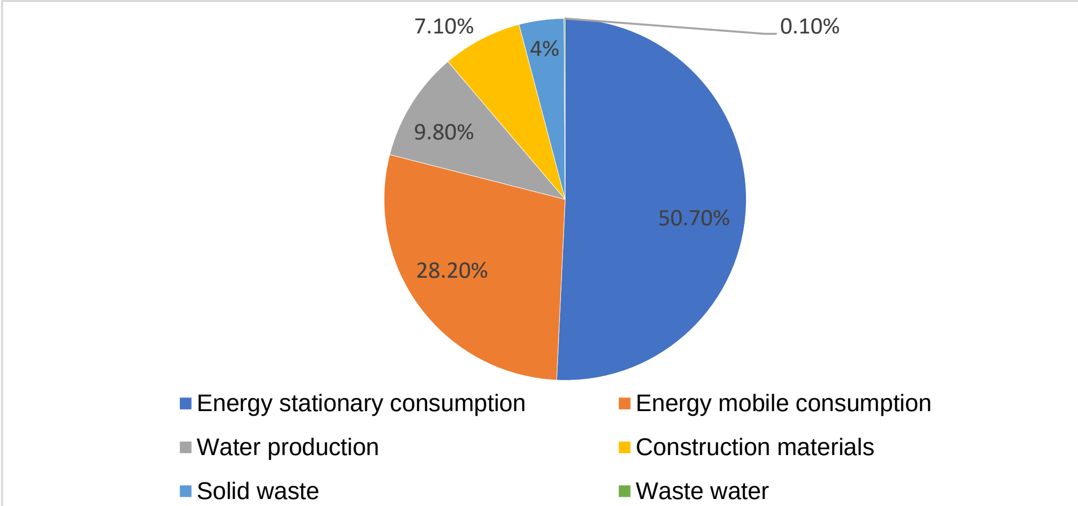


Figure 4-17 GWP per main flows.

Other sectors, such as water production, and the production of construction materials contribute 9.80% and 7.10%, respectively to the city's total GWP. These findings correlate with recent publications on climate change in Saudi Arabia (Ministry of Energy Industry and Mineral Resources, 2016). In terms of impact related to energy production, oil-based fuels are the most significant, even though oil constitutes about half the energy mix in Riyadh (see Figure 4-18). In terms of other contributors, natural gas is responsible for the lowest share of environmental impact across all the selected categories. This is due to its lower carbon content of natural gas relative to oil-based fuels such as diesel and heavy fuel oil. This can be considered an important consideration when implementing climate change mitigation policies.

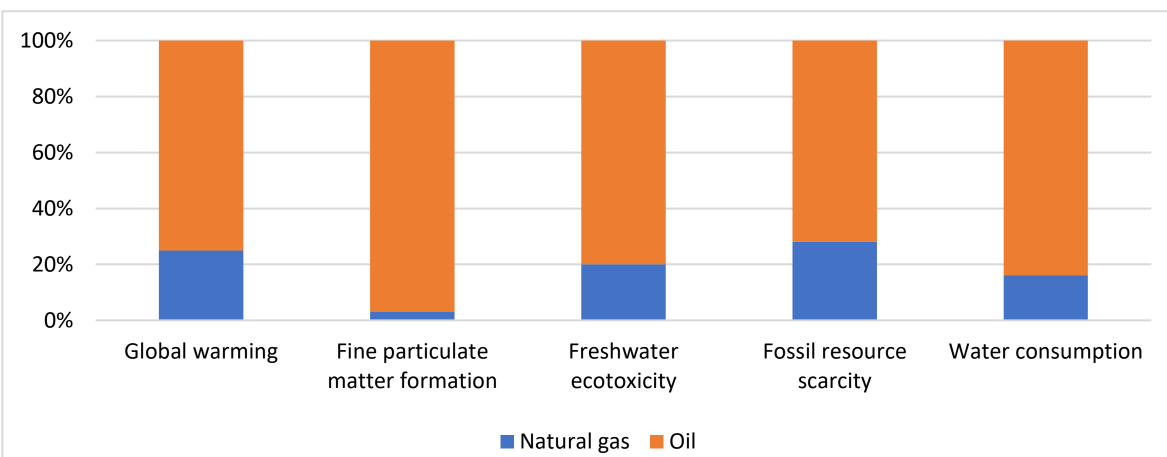


Figure 4-18 Distribution of environmental impacts from energy production.

Fine particulate matter formation (PMF)

The results showed emissions related to PMF totalled 21.27 kg PM_{10} per capita in 2016. These emissions are related to the consumption of fossil fuels for energy production and transportation-related emissions. As shown in Figure 4-19, energy production and energy mobile consumption were responsible for 89% of PMF. The production of construction materials was responsible for 7%. Studies assessing PM_{10} in cities reported values ranging between 1.9 and 6.0 kg PM_{10} per capita, as reported in Gonzalez-Garcia *et al.* (2018). The difference here is mainly related to higher energy intensity between Riyadh and these cities. However, this provides city officials with a clear picture about where to focus any policies intended to curb PM_{10} emissions.

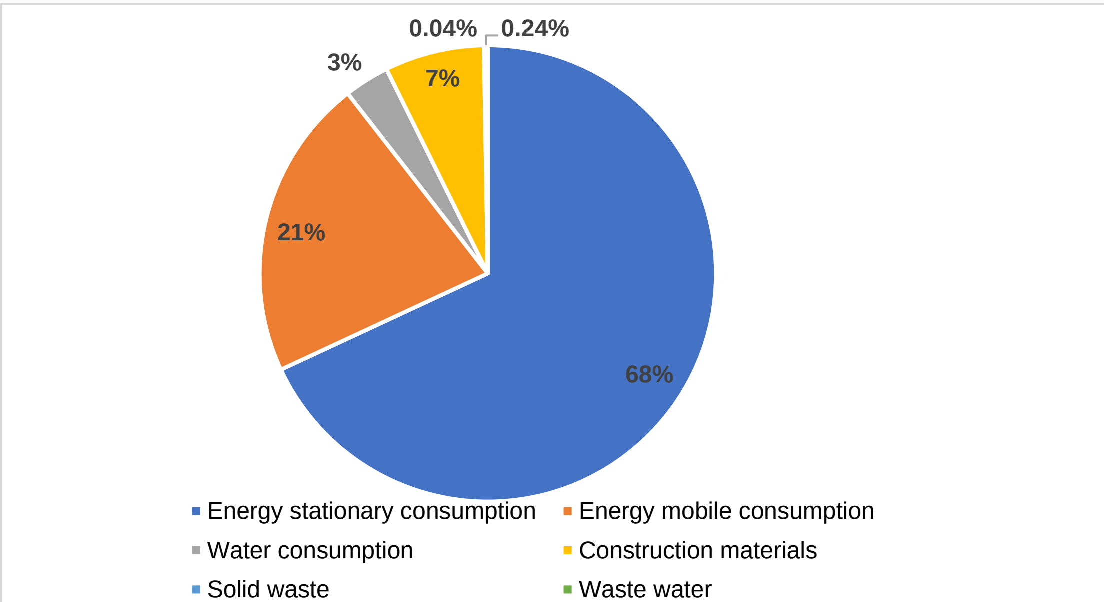


Figure 4-19 Fine particulate formation impacts per main flows.

Freshwater ecotoxicity

Studies have demonstrated that the fossil fuel-based energy production is a major reason for freshwater ecotoxicity (Shi *et al.*, 2014). In Riyadh, energy production remained the main cause at 44%, as shown in Figure 4-20. Moreover, water production was responsible for 21%, due to fossil fuels usage at desalination plants. In terms of per capita value, the results showed that in 2016 the level was 293 kg 1,4-DCB. In Goldstein *et al.* (2013), the reported values were 169.8 kg 1,4-DCB in Beijing, China and 55 kg 1,4-DCB in Toronto, Canada. In the case of Beijing, the presence of solid waste was responsible for about 50% of the total freshwater excitotoxicity. However, in Toronto, it was energy production (stationary and mobile) that accounted for 50%. The difference between the two cases relates to differences in volume consumed by each activity group per capita (Goldstein *et al.*, 2013).

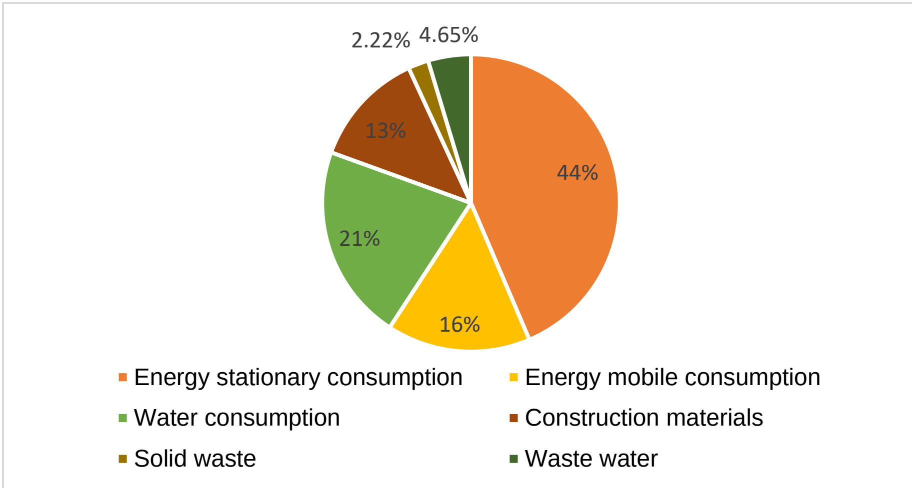


Figure 4-20 Freshwater ecotoxicity impacts per main flows.

Fossil resource scarcity

Fossil fuel potential (FFP) is based on the higher heating value (HHV) of each fossil resource, including crude oil, natural gas, and coal (Huijbregts *et al.*, 2017). It is important because the majority of services (i.e., electricity, desalination) are heavily dependent on fossil fuel products. The results showed a per capita value of 5649 kg oil eq. This high number indicated a very oil intense economy, as suggested by Alnatheer (2005). As presented in Figure 4-21 , 95% of the effects associated with energy consumption are linked to the electricity sector and transportation.

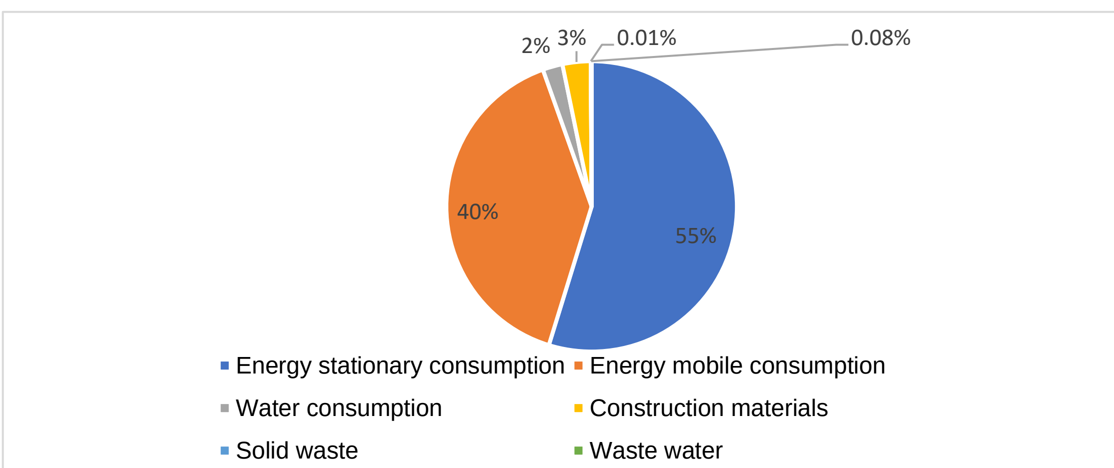


Figure 4-21 Fossil fuel resource scarcity impacts per main flows.

Water use

Considered from a global perspective, Saudi Arabia is a relatively water-scarce nation. It is the largest country in the world with no access to lakes or rivers serving as renewable water sources (Kajenthira, Siddiqi and Anadon, 2012). Therefore, this category is an essential one to assess, particularly in relation to water consumed for industry, energy and fresh water production (Huijbregts *et al.*, 2017). In the case of Riyadh, results demonstrated that in 2016, the per capita value was 171.7 m^3. This can be compared with other studies, such as Gonzalez-Garcia *et al.* (2018) in which the average value for 26 Spanish cities was 64 m^3. In terms of per capita water use, Saudi Arabia is the third-largest country in the world (Kajenthira, Siddiqi and Anadon, 2012). As shown in Table 4-26, water production contributes the most to this category.

Table 4-26 Distribution of water use impacts per MFA component.

MFA component	Water use impact (m^3/inhabitant)
Energy mobile consumption	17%
Water production	107%
Construction materials	13%
Solid waste	6%
Wastewater	0.002%

To develop the analysis further, Figure 4-22 identified impacts according to water source. From this figure, it is apparent that desalination production has the greatest impact across all categories with the exception of the water use category. This is a result if there is a high share of groundwater production (54%). As indicated in the literature, Saudi Arabia experienced water withdrawal in excess of about 20 billion m^3 in 2010 (Kajenthira, Siddiqi and Anadon, 2012), although the country has annual renewable water resources comprising only 2.4 billion m^3 (Frenken, 2009).

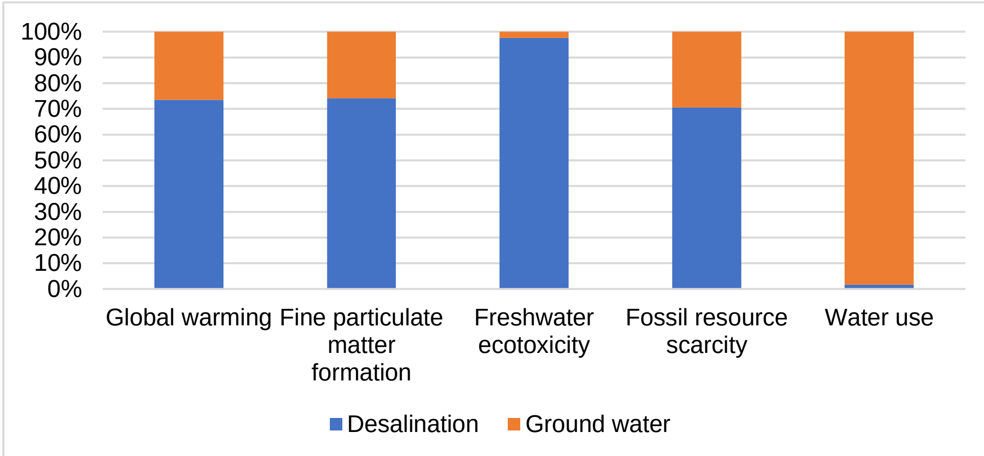


Figure 4-22 Distribution of water use impacts per source of water.

4.5.5.2 Embodied energy associated with Riyadh urban material flows

Embodied energy as discussed in this study is based on a cradle to gate approach, as mentioned previously. The embodied energy intensity for the main flows are given in Table 4-27. The focus when studying energy flows in cities is driven by the fact that energy is a crucial component in service provision for city inhabitants who are involved in manufacturing materials and goods, as well as in energy production for households and transportation (Mpakati-Gama, Brown and Sloan, 2016). Extending the MFA framework to capture embodied energy is a key advantage when combining LCA with MFA. In the case of Riyadh, the results showed that embodied energy contributes to about 59% of the city's total life cycle energy requirements. When contrasting these findings with similar studies, comparable trends are apparent. For example, as shown inFigure 4-23, embodied energy accounts for 48% in Toronto, 76% in Hong Kong, 67% in London (Goldstein *et al.*, 2013). In Goldstein *et al.* (2013) the data for embodied energy was assessed from upstream and downstream flows (cradle to grave), whereas in this study, it was calculated for upstream flows only (cradle to gate). However, in the case of embodied energy, the downstream implications contribute to only 5% to the total life cycle energy, as also found by Moncaster and Symons (2013).

Table 4-27 Embodied energy intensity.

MFA component	Direct input flows value	Direct input flows	Embodied energy	Data sources
Energy consumption	Energy stationery	211,568 TJ	12.44 MJ/kWh	SimaPro using Cumulative Energy Demand V1.11. Process (Electricity, high voltage {SA}| production mix | APOS, U)
Water consumption	Desalination	383,021 kt	327 MJ/m^3	Saline Water Conversion Corporation, the Electricity and Cogeneration Regulatory Authority
	Groundwater production	449,634 kt	13.4MJ/m^3	SimaPro, Tap water {RoW}| tap water production, underground water with chemical treatment | APOS, U
Construction materials	Cement	4,004 kt	3.87 MJ/kg	SimaPro, Portland {RoW}| production | APOS, U
	Steel	1,297 kt	21.1 MJ/kg	SimaPro, Reinforcing steel {RoW}| production | APOS, U
	Aggregate	22,597 kt	0.083 MJ/kg	ICE (Inventory of Carbon & Energy) (V2.0)

The annual share of embodied energy to total life cycle energy reveals the advantages of using LCA to calculate embodied energy. In the case of an oil-based economy, understanding the relationship between direct and embodied energy is critical for determining the path forward to develop more sustainable practices.

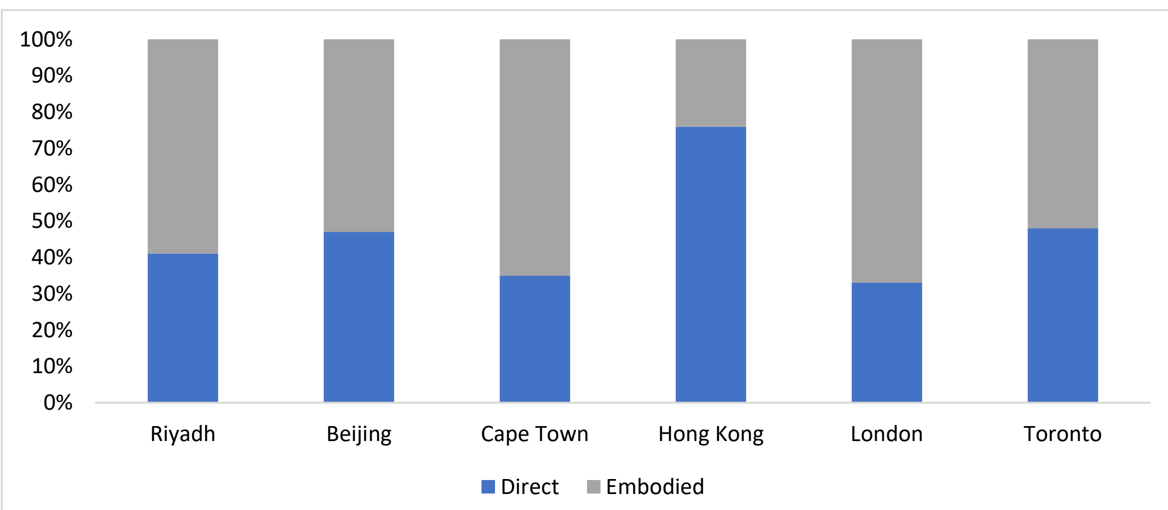


Figure 4-23 Embodied and direct energy flows for Riyadh compared with other cities.

Source: (Goldstein et al., 2013)

Moreover, the results for embodied energy related to the main flows in Riyadh, Table 4-28 demonstrate an urgent need for a comprehensive polices to manage the hidden impacts arising from the built environment. These hidden flows, which can represent up to 74% of life cycle energy demand are typically overlooked (Stephan and Crawford, 2014). To illustrate what flows contribute most markedly to the city's total embodied energy, details the embodied energy according to the input flows. Energy consumption and water production comprise the most at 81% and 15%, respectively. As stated previously, these two sectors are the most energy-intense in the country, as well as being heavily dependent on oil products and natural gas.

Table 4-28 Breakdown of embodied energy according to the input flows.

Input flows	Contribution to total embodied energy
Energy consumption	81%
Water production (desalination)	14%
Water production (groundwater)	1%
Construction materials	5%

4.6 Appraisal of Riyadh's sustainability through an integrative framework

The principal argument throughout this thesis involves introducing a life cycle perspective into an MFA framework when accounting for urban material and energy flows, making it vital to assessing the sustainability of urban systems. The impetus for such integration was the need to effectively assess the impact associated with urban flows. To date, there have been multiple calls from different scholars to consider such integration when developing policies to achieve more sustainable practices (Finnveden *et al.*, 2009; Kennedy, Baker and Brattebø, 2014a; Pincetl *et al.*, 2014b; Janet L. Reyna and Chester, 2015; Facchini *et al.*, 2017). This realization of the importance of MFA-LCA integration is associated with significant indicators that can be provided through a process of integration. One such benefit mentioned by Goldstein *et al.* (2013) is that cities' performance can be quantified and compared relative to different environmental impact categories (e.g., GHG emissions, water use, land use, etc.).

The inclusion of biophysical and socioeconomic indicators helps to provide a holistic understanding of cities' urban flows. These indicators provide information pertaining to variables such as land use, urban density, housing stock, accessibility to essential infrastructure and services (e.g., public transportation, water network, wastewater treatment, etc.), household formation rates, and annual income. The selection of these indicators was based on an extensive review of related literature pertaining to the topic of urban material flows, and recent sustainable development goals (SDGs), published by the UN Department of Economic and Social Affairs. However, these indicators were also subject to significant selection criteria. Table 4-29 summarizes these criteria and provides a short description for each criterion.

Table 4-29 Criteria for selecting biophysical and socioeconomic indicators.

	Criteria		
	Geographical Correlation	Independence of Data Supplier	Data availability
Description	Data from area under study	Verified data, information from public or other independent source	Data available for the area under study

The urban flows selected for MFA-LCA based assessment were associated with significant roles in terms of sustaining life in cities (e.g., energy, water, materials). These flows are essential to a city's growth and for maintaining its built environment. As with biophysical and socioeconomic indicators, the indicators selected for MFA-LCA analysis were based on a literature review and a recently published report about sustainable development goals (SDGs). Previous sections provided the method and results for each of the indicators. This section attempts to shed light on these results from an integrative perspective.

The concept of sustainability in this study relates to assessing changes in Riyadh's ecosystem according to a set of indicators that cover social, economic, and environmental areas. The use of such indicators is proposed throughout the literature, as they can provide an effective measurement of change within the urban ecosystem (Shen *et al.*, 2011). Based on these indicators, a sustainability assessment matrix was developed. The main purpose of this matrix is to collate the results obtained in this chapter into a more meaningful and easier to understand format. Table 4-30 summarizes this matrix as it pertains to biophysical, socioeconomic and MFA indicators. It reveals temporal trends in resource consumption combined with changes affecting the biophysical and socioeconomic characteristics of the city. The overall observation made here is that there has been a rapid increase in the majority of indicators related to urban resource consumption, which reveals the Riyadh ecosystem to be highly inefficient.

The socioeconomic indicators showed an overall increase across all the indicators, with the exception of household size and solid waste per capita. These two indicators fell by 10% and 42%, respectively per capita. The most noticeable feature linked to these indicators relates to the transportation sector; namely, the average travel time per trip, which increased by 162%. It shows the impact of urban sprawl, as evidenced by the increase in land area, as well as the lack of alternative transport options. Two positive improvements were observed in relation to wastewater treatment and solid waste recycling. These two indicators improved by 162% and 9%, respectively.

Table 4-30 Overall changes in studied indicators from 1996 to 2016.

	Indicators	Changes in per capita value
Socioeconomic indicators	Population (total change)	116%
	Density	6%
	Household size	-10%
	Household formation rate	25%
	Housing stock	180%
	Input built floor area	101 %
	Households	157%
	Floor of housing area per person	-0.05%
	Average annual income (USD)	19%
	GDP per capita	5%
	Household connections to public water network	15%
	Household connections to public wastewater network	61%
	Travel time (minutes/trip)	162%
	% Wastewater Treatment	180%
	Solid Waste per Person/Day	-42%
	Recycle solid waste	9%
Biophysical indicators	Land area	171%
	Land area (developed)	193%
	Land area (undeveloped)	160%
	Residential building gross floor areas	106%
Urban MFA indicators	Total primary energy	72%
	T&D loss	173%
	Total electricity consumption	70%
	Residential electricity consumption	56%
	Commercial electricity consumption	166%
	Industrial electricity consumption	67%
	Government and services electricity consumption	50%
	LPG household consumption	16%
	Transportation (petrol)	50%
	Transportation (diesel)	1%
	Total water consumption	-4%
	Water distribution loss	20%
	Cement	101%
	Steel	101%
	Aggregate	101%
	GHG emissions of energy use	75%
	GHG emissions of transport sector	31%
	GHG emissions of materials production	101%

	Total municipal waste	-42%
	Recycled waste	9%
	Total wastewater	12%
	Untreated wastewater	-82%
	Reused wastewater	238%

On the basis of estimated MFA, the values suggest inefficient system performance. This is apparent from energy and water flows. In terms of energy flows, the T&D losses increased by 173% relative to the per capita value. Another significant indicator pertained to the increase in primary energy of 72% evaluated on the same basis. This is significant because the share of renewable energy in Riyadh energy mix is 0% and the city continued to rely on fossil fuels for energy production. This explains the increase of GHG emissions associated with energy production by 75%.

Urban sprawl influences resource consumption, particularly for transportation. The per capita values show an increase of 50% for petrol consumption, while diesel has remained about the same. This impacts the environment as GHG emissions associated with transportation increased by 31% according to the per capita value.

Furthermore, as the population increases, the demand for new house rises, and construction materials become a consideration. Two significant factors arise from the socioeconomic indicators in relation to constructing new housing: household formation rate and the population pyramid. Household formation data showed an increase of about 35% as the population is under 15 years of age in 2016. As stated earlier, the evidence of this impact is apparent from the rapid increase in the number of construction permits annually since 1996.

In another significant study finding, the water input flows fell on a per capita basis by 4%. From an outflow perspective, the percentage of recycling also increased significantly. The same patterns were observed with solid waste, although the recycling of solid waste only started recently.

While these trends capture the physical impact of the city, the environmental impacts of these flows were assessed using an LCA approach. In Figure 4-24 the associated impacts are presented for all impact categories according to ReCiPe2016 method. For most of these impacts, energy consumption is the most significant point. More importantly, the water consumption potential (WCP) category revealed that groundwater production has the greatest effect while it shows that wastewater treatment has a negative score. This is because water consumption is characterised with a positive factor (has a damaging effect) while wastewater treatment is characterised with a negative factor. This means recycling wastewater is beneficial to the environment.

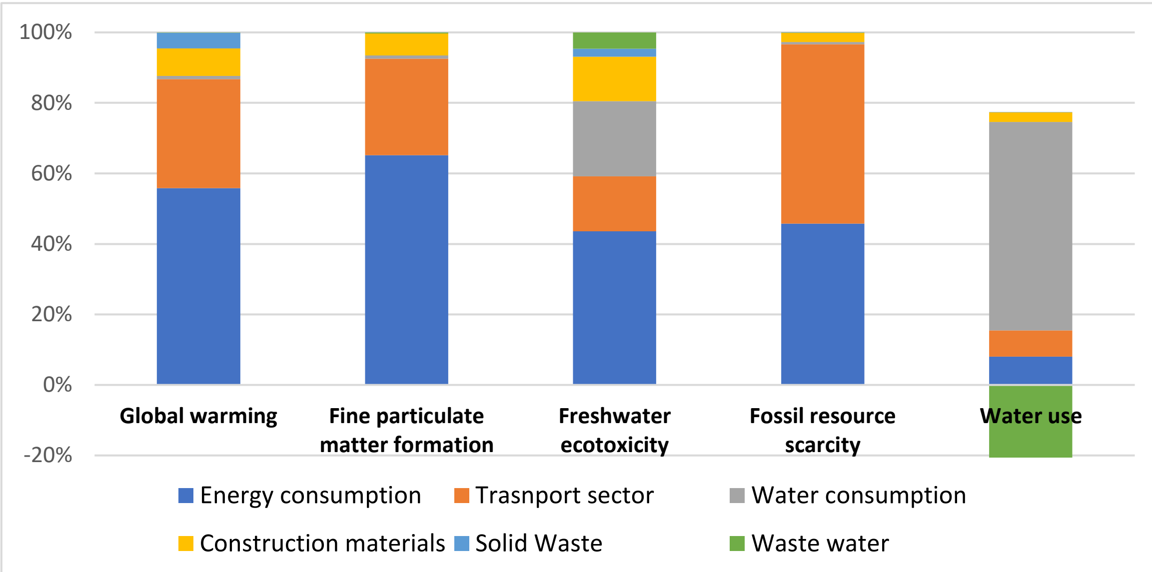


Figure 4-24 Distribution of environmental impacts across main flows for 2016.

These findings point to three important components that together are significant across all impact categories. As the country takes steps towards developing a more sustainable built environment in the future, a clearer understanding of the impact associated with these three components would be expected to greatly assist in the development of meaningful and effective policies. A short description is given below for each component.

The energy production sector has witnessed a rapid increase in the consumption of fossil fuels over recent years, to meet the growing demand for electricity (6% annually). Current trends show demand is creating a great burden on the national economy, as more oil and gas are allocated for domestic energy production rather than to export. In terms of embodied energy, GWP and fine particulate matter formation energy production have contributed 81%, 65% and 56% respectively. From an MFA and LCA perspective, policies for a sustainable built environment should priorities energy production.

Another significant element is the transportation sector, which is the second greatest contributor in terms of environmental impact. GWP results show mobile energy accounts for a 31% share of this impact. However, socioeconomic indicators related to the transport sector resulted in a significant increase in the number of cars, trips per day, and average travel time per trip over the years studied. With the low share of public transportation affecting these daily trips, energy consumed in the transportation sector has historically increased rapidly.

More positively, water has seen an improvement in terms of decreasing the input flows and increasing the recycling percentage from wastewater treatment. However, from an LCA perspective, two impact categories showed this component cannot be ignored in terms of policies to curb energy consumption or GHG emissions. The embodied energy associated with water production contributes about 15% of the total embodied energy associated with urban material flows in Riyadh.

In conclusion, the proposed hybrid MFA-LCA based indicators have the potential to describe and assess the performance of the city over time, and to shed light on which urban flows have the greatest impact from a life cycle perspective. Evidence of this potential is presented in the case study of Riyadh. The findings are also important, in that they have assessed the success of former sustainability initiatives, clarifying a possible direction for new initiatives. Although the proposed framework is based on a set of indicators assessing urban development in the city, due to the scope of the study it does not provide a comprehensive analysis of the relationship between these indicators. Recent studies have acknowledged that doing so is a challenge because of the many dynamic factors within urban systems (Hu, 2010; Klein Goldewijk, Beusen and Janssen, 2010; Kennedy *et al.*, 2011; Mostafavi, Farzinmoghadam and Hoque, 2014; Reyna and Chester, 2015; Kalmykova, Rosado and Patrício, 2015a).

4.7 Conclusion

The 21st century is an urban century, and it is anticipated that there is a move towards 66% of the world's population living in cities. The majority of this increased urbanization will occur in developing countries. This growth in cities population demands additional investment in infrastructure to cope with population growth. It is, therefore, imperative that growing cities model the evolution of the built environment with the expectation of ongoing expansion, and assess the associated environmental impacts accordingly, to achieve sustainable development goals. Methods such as MFA and LCA have proven valuable as tools to meet this objective. MFA provides a framework for characterizing the magnitude of the resources required by cities but lacks the capacity to provide practical guidance to decision-makers because it primarily focuses on accounting annual direct mass and energy flows. This means the data it presents does not serve as a proper basis for assessing the environmental sustainability of a city. Contrary to the MFA methodology, the LCA methodology does not stop at the mass, direct material and energy exchanges with the environment. It provides a cradle-to-grave accounting of potential resource use and a wide range of associated environmental impacts from extraction to disposal. Although the defining of boundaries must be made explicit, how far upstream to take the analysis remains a problematic question in LCA.

First, the MFA framework was enhanced by synthesizing critical factors, including biophysical and socio-economic indicators, with the goal of moving MFA beyond an accounting framework, towards a strategic planning one. This framework was applied over a different period of times to investigate how such indicators change over time. Second, results from the MFA stage were utilized as an inventory of input and output, which can then be supplied at the LCA stage to assess the environmental impacts of these flows. Results obtained from conducting LCA on these flows enables an assessment of the direct and indirect impacts associated with urban material flows within the city. Thus, those MFA components with the highest impacts could then be effectively determined.

Biophysical and socioeconomic indicators provided the MFA study with sufficient strength to examine how the city interacts with the surrounding environment in the context of resource consumption. The inclusion of both sets of indicators helped further our understanding of temporal trends associated with resource consumption. This integrated approach facilitates the identification of factors triggering a high demand for services, which further assists decision-makers in achieving sustainability.

On a per capita basis, the city demonstrated an increase in most MFA components. Throughout the literature, many definitions of sustainable systems were afforded. However, in this research, this was defined from the point of view of efficiency in urban flows over the studied period. The results indicate that a proposed integrative approach can be used to quantify and assess these flows while shedding light on the social and economic characteristics of the city. The outcome of this study comes aligns with previous studies, in which MFA and LCA were combined and applied to different aspects of the built environment to assess efficiency level and provide potential improvements to benchmarks.

Sustainability in Riyadh’s ecosystem was analysed and evaluated according to indicators based on an integrative approach. The results indicate that rapid population growth resulted in increased changes in land use, showing signs of urban sprawl problems. The application of a proposed framework to Riyadh’s urban development shows it was unsustainable over the period reviewed. The environmental pressures caused by main flows can be reported in five impact categories representing impacts critical to the case study. The results indicate that the energy consumption component is the main contributor to all effects, with the exception of freshwater ecotoxicity; with energy mobile contributing the most. Groundwater production contributes the most extensively to the water potential use impact category. Therefore, policies for improving the city's performance should be directed toward energy production.

The proposed MFA-LCA has revealed its usefulness for assessing the impact of urban development, although some uncertainty exists regarding the availability of data. This drawback in data availability was accepted in MFA and LCA studies. The results are intended to serve as guidelines for decision-makers wishing to identify and modify flows that require further attention.

Chapter 5 Dynamic material flow analysis based environmental framework to assess urban development: the case of housing stock in Riyadh

This chapter provides an overview of the potential use of dynamic material flow analysis (DMFA) as a means of assessing the dynamic of built environment. It aims to introduce DMFA as a tool to evaluate the development of flows and stocks of floor area and materials, using the residential sector in Riyadh as a case study. First, it provides a description of the development of this stock's dynamic approach, extending the current framework to include energy parameters that are energy related and associated with household and transportation use by households. Additionally, an integrated approach, based on combining DMFA and LCA is introduced to the model to assess environmental impacts and estimate embodied energy related to housing stock input flows. The chapter concludes with a discussion of the model's implications and its limitations.

5.1 Introduction

In recent years, the built environment in cities has been discussed in relation to curbing resource consumption and reducing environmental impacts. These discussions are critical because today 55.3% of the world's population lives in cities, and cities are expected to house 60% of the world's population by 2030 (United Nations, 2018). This is creating demand for the built environment to expand to fulfil the needs of the growing urban population, which in turn is resulting in the consumption of massive amount of energy and materials (Göswein *et al.*, 2019).

From an input flows perspective, building materials comprise the largest material flows, globally, that enter urban areas after water flows (Augiseau and Barles, 2017). In terms of energy use and CO_2 emissions, buildings and building construction consume 36% of final global energy consumption and around 40% of total CO_2 emissions[6]. The housing stock itself represents 27% of global energy consumption, and 17% of CO_2 (Nejat *et al.*, 2015). From an output flows perspective, construction waste accounts for about 50% of all urban solid waste (Castro *et al.*, 2019). Moreover, the environmental problems associated with housing stock and the corresponding flows are of great concern to global society at the present time and will be for future generations. These impacts extend from a local scale (e.g., terrestrial ecotoxicity) to a global scale (e.g., climate change) (Huang *et al.*, 2018).

[6] https://www.iea.org/topics/energyefficiency/buildings/

In the context of developing countries, the increase in building stock and associated flows (e.g., materials, energy, emissions, etc.) has been acknowledged as a vital environmental issue within the local and global context (Hu *et al.*, 2010; Huang *et al.*, 2013a; Zurbrügg, Caniato and Vaccari, 2014; Lin, Liu and Müller, 2017; Stephan and Athanassiadis, 2018). The reasons for this concern are informed by two main factors. First, as mentioned above, the majority of the increase in urban population is expected to occur in developing countries (United Nations, 2014). Second, these countries are relatively less equipped than developed ones to handle the challenges associated with sustainable development.

In the context for Riyadh and its use of materials, the city has experienced a significant increase in material and energy consumption over the last three decades. As was shown in Chapter 4, building materials demand increased from about 6 million tonnes in 1996 to almost 27 million tonnes in 2016. In terms of energy use and CO_2 emissions, housing stock consumes 54% of the total energy consumption and around 50.7% of the total direct CO_2 emissions. From an output flows perspective, construction waste accounts for about 57% of all urban solid waste in Riyadh in 2016. Moreover, the recent trends in floor area demand suggest that the environmental problems associated with housing stock and the corresponding flows are of great concern at present and will be for future generations.

Although current trends suggest urbanization is continuing worldwide; in view of the limited resources available, any unsustainable growth of in-use stock will mean more environmental pressure with potentially severe consequences (Krausmann *et al.*, 2018).

This chapter aims to introduce DMFA as a tool to evaluate the development of flows and stocks of floor area and materials, using the residential sector in Riyadh as a case study. To define the scope of the analysis the following three questions are posed:

1. How will the demand for housing floor area, and the related construction materials in Riyadh, develop over the coming decades, considering the ongoing urbanization?
2. How can dynamic stock models be extended to include both direct and indirect energy consumption and carbon emissions, and what are the critical assumptions and variables concerned?
3. What will the environmental impacts related to housing stock development be?

The following section describes how a DMFA approach to the problems related to housing stock and its related flows.

5.2 DMFA approaches employed to study the built environment

Dynamic models are used to shed light on how systems perform over time. An understanding of present and former trends is crucial for establishing future development along a sustainable pathway. In addition, such an understanding is vital for achieving future sustainability goals (Wittmer and Lichtensteiger, 2007). The long term perspective afforded by using DMFA can support sustainability strategies in the built environment (Pauliuk, Wang and Müller, 2012). DMFA differs from static MFA, in that it includes an investigation of stocks in society, making it possible to explore future flows of emissions and waste, based on historic and future inflows and stock characteristics (Elshkaki *et al.*, 2005).

DMFA approaches to urban building stock can be categorized according to two main methodological approaches, namely, flow-based and a stock-based model (Hu, Bergsdal, *et al.*, 2010). The former was applied by Kohler and Hassler (2002), Elshkaki and colleagues (2005), Bradley and Kohler (2007), and Roja and Müller (2012). In this approach, the input flows are determined by extrapolating their recent yearly average (Augiseau and Barles, 2017). The building stock in this approach is driven by input and output flows, whereas inflow is estimated using socioeconomic factors, and outflow is determined through a leaching or delay process (Hu, van der Voet and Huppes, 2010). As for the in-use stock, this is determined according to differences between annual inflows and outflows.

The second consideration was the stock dynamic based approach, in which the stock of service units drives input flows (Hu, Bergsdal, *et al.*, 2010). This is based on the assumption that by assigning certain factors one can estimate in-use stock and associated flows. These factors include referencing the expansion rate, as done by Wiedenhofer and colleagues (2015). In addition, stock can be estimated as a function of population, and associated lifestyles, as proposed by Müller (2006). The outflow in this approach is estimated according to a delay process that involves applying lifetime distribution (Bergsdal, 2009; Sandberg, Bergsdal and Brattebø, 2011; Pauliuk, Wang and Müller, 2012; Pauliuk, Sjöstrand and Müller, 2013; Gallardo, Sandberg and Brattebo, 2014b; Pauliuk and Müller, 2014b; Vásquez, Amund N. Løvik, *et al.*, 2016a; Albelwi, Kwan and Rezgui, 2017b; Sandberg, Sartori, Magnus I. Vestrum, *et al.*, 2017). Between these two approaches, recent studies have indicated using a stock-based approach reflects a better understanding of the evolution of the built environment from a resources consumption perspective (Huang *et al.*, 2013a; Augiseau and Barles, 2017).

Although it could be argued that these two approaches are obvious even in the absence of stock dynamic modelling; however, stock dynamic modelling provides a better tool to analyse the development of the stocks taking into consideration important factors such as building lifetime and demolition rate. Also, it allows for the assessment of different development scenarios to guide sustainable development.

Stock dynamic model can be either retrospective evaluating past flows and stocks based on historical data, or prospective, assessing the future using data extrapolation (Hilty *et al.*, 2014). However, the built environment is constantly and rapidly evolving and it is most likely that the built environment in the future will be very different from the present (Hunt and Rogers, 2016). For this reason, stock dynamic model may not be the best tool that captures the details of the future of the built environment. In their study, Hunt and Roders (2016) listed four foresighting approaches that include Trend Analysis, horizon Scanning, Side-Swipes or Black Swans, and Scenarios Analysis. The latter approach includes 'Aspirational' scenarios, 'Extreme yet Plausible' scenarios, and scenarios predicated on one or more dominant drivers (Hunt and Rogers, 2016). These approaches differ from stock dynamic model in that these approaches call for determining what is constant, what changes, and what constantly changes and explore unexpected issues, persistent problems and trends, including matters that challenge past assumptions (Dixon, Connaughton and Green, 2018).

The primary aim of this chapter is to investigate the potential use of DMFA as presented in Müller (2006) when analysing the past and future trends in housing stock and its flows, and determining the pathways complementing DMFA with LCA to assess the environmental impacts associated with housing stock. After which, a proposed extended DMFA is outlined and applied to the housing stock in Riyadh, Saudi Arabia.

5.2.1 Recent studies on DMFA and housing stock

DMFA is vital when analysing change and long term effects in a system. The built environment has a number of unique features including its extremely long lifespans and a vast selection of materials (Almulhim, Hunt and Rogers, 2020). Therefore, a long-term perspective helps advance understanding of the dynamics of the system, and its critical variables, and can also provide valuable information to support the implementation of sustainable strategies (Brattebø *et al.*, 2009).

Müller (2006) presented a generic dynamic material flow analysis (DMFA) model to establish resource demand and waste generation. In his study, Müller applied parameters related to population, lifestyle, material intensity, and lifetime, to create the designed DMFA model. This approach has also been used to examine floor area and materials in dwelling stocks (Bergsdal *et al.*, 2007), and for predicting construction wastes (Bergsdal, Bohne and Bratteb, 2007). Several other studies on building stock modelling have followed the same approach as that proposed by Müller.

Estimating material flows associated with housing stock has been the focus of several studies. Sartori and colleagues (2008) applied this method to model construction, renovation and demolition activities in Norwegian residential stock (Sartori *et al.*, 2008). In another study, Brattebø and colleagues (2009) applied it to the study of the material and energy metabolism of built environment stocks. Combined with archetype-specific energy intensities, the model was extended and applied to estimate total energy demand for dwelling stocks in Norway (Sandberg, Sartori, Magnus I. Vestrum, *et al.*, 2016). Moreover, the future energy demand of dwelling stock was estimated with this approach (Sandberg, Sartori, Vestrum, *et al.*, 2017). In this study, Sandberg and colleagues (2017) developed various scenarios to evaluate the potential for further reduction in energy demand in dwelling stock.

In a developing countries context, the same approach has been applied in several studies. For instance, Hu and colleagues (2010) investigated the relationship between the urbanization progress and resulting material use, by analysing urban and rural housing (Hu *et al*., 2010). The dynamic model was applied for future development, assuming different development pathways in the population, demand per capita, and the building's lifetime. In another study, Hu and colleagues (2010) applied the model to a study of the urban housing system in Beijing, with a focus on understanding the mechanism of future construction and demolition waste generation (Hu, van der Voet and Huppes, 2010).

In another study, Gallardo and colleagues (2014) used the stock dynamic model to evaluate long term changes in stock and flows of residential floor area, including changes resulting from earthquake damage (Gallardo, Sandberg and Brattebo, 2014b). This study adapted a demolition rate approach to estimate outflows due to earthquake. In their study, Albelwi and colleagues (2017) used this approach to estimate future energy demand, and assessed scenarios for future energy mixes with changing GHG emission factors (Albelwi, Kwan and Rezgui, 2017b).

However, there are several issues with stock dynamic modelling studies. First, there is an issue regarding the model choice, is the model stock dynamics driven or flow-based model. That is, whether the projected behaviour of the stock or the flows is the driving force of model behaviour. The second issue is related to the estimation of outflows. The outflows could be calculated based on the stock size or by a delayed factor for a given period of time (leaching model and the delay model). Moreover, these studies do not distinguish between different buildings features and ages nor technology dynamic that includes all life cycle stages of products and services.

5.2.2 Stock dynamic model in the context of sustainable development

The intense use of resources from in-use stock has led city officials to introduce a broad spectrum of initiatives. For the most part, these initiatives have focused on maximizing efficiency in energy end-use and final consumption in the housing stock. These initiatives, however, fail to consider socioeconomic factors, which are the main driver of these flows. As Pauliuk and Müller (2014) stated, the climate change mitigation policies proposed by cities need to place more weight on the economic, social, cultural, and other environmental aspects of sustainability (Pauliuk and Müller, 2014).

The path supporting the transition of current housing stock to sustainable stock can be evaluated and assessed by applying a stock dynamic approach; especially when coupled with socioeconomic factors and LCA. Moreover, recent studies have called for different approaches when studying in-use stock. The flows of energy and materials associated with in-use stock can be better assessed by coupling between the stock dynamic, socioeconomic indicators, and LCA, as has been suggested in recent publications (Weisz, Suh and Graedel, 2015; Södersten, Wood and Hertwich, 2018; Göswein *et al.*, 2019; Lanau *et al.*, 2019). The argument, in this case, moves towards increasing recycling rates to reduce the drain on resources, and shift to renewable sources of energy.

In their study, Pauliuk and Müller (2014) stated that the built environment is characterized by infrastructure anticipated to have a long lifetime (e.g., dwellings), and this can play an important role in shaping cities' efforts when developing sustainability (Pauliuk and Müller, 2014b). This places emphasis on the importance of applying a stock dynamic to allow guidelines to be drawn to reduce input flows and the associated environmental impact.

From the point of view of urban sustainable development, a system-based understanding of the embedded impacts of building stock growth should be studied (Reyna and Chester, 2015). Moreover, built environment stock plays a critical role in urban material and energy flows, and a better understanding of this would assist decision-makers in developing sustainability policies. The recently published 2030 Sustainable Development Goals (from the United Nations) has become the foundation of urban sustainability agendas that cities worldwide are seeking to implement. In this context, a stock dynamic approach has the potential to assess cities as they transition through sustainability (Lanau *et al.*, 2019). This role is further explained and outlined in Table 5-1

Table 5-1 Stock dynamic modelling and sustainable development strategies.

Sustainability strategies drawn from UN SDGs 2030	Stock dynamic applications	Examples
Sustainable materials consumption	Analyse trends in stock accumulation, inflows, outflows of studied materials	(Bergsdal, Brattebø, Rolf A. Bohne, *et al.*, 2007; Bergsdal, 2009; Hu, van der Voet and Huppes, 2010; Wiedenhofer *et al.*, 2015; Stephan and Athanassiadis, 2018)
Efficient use of energy and materials	Examine efficiency measures in energy use, recycling, fuel switching	(Pauliuk, Wang and Daniel B. Müller, 2012; Milford *et al.*, 2013; Pauliuk and Daniel B. Müller, 2014a; Vásquez, *et al.*, 2016; Sandberg, *et al.*, 2017)
Reduce the adverse per capita environmental impact of cities	Estimate future floor demand and related environmental impacts	(Sandberg and Brattebø, 2012; Sandberg, Sartori and Brattebø, 2014; Vásquez, *et al.*, 2016)
Reduce waste generation through recycling and reuse	Investigate construction and demolition waste	(Hu, van der Voet and Huppes, 2010; Wang *et al.*, 2015b)
mitigation and adaptation to climate change	Assess policies for climate change mitigation related to building stock	(Sandberg and Brattebø, 2012; Pauliuk, Sjöstrand and Müller, 2013; Pauliuk and Daniel B. Müller, 2014b; Vásquez *et al.*, 2016b)

Dynamic MFA is an important factor when analysing change and its long term effects on the system. In particular, the built environment is characterized by a long service lifetime, so a long-term perspective fosters an understanding of the dynamics of the system and critical related variables, and also could provide valuable information for those responsible for the implementation of sustainable strategies (Brattebø et al., 2009).

In this chapter, an extended stock dynamic framework is proposed to provide a comprehensive assessment of the current stock, with the goal of providing guidelines and recommendations to assist in sustainable development transitions. The factors included to extend the framework can be summarized as follows.

(1) End-use services (energy: electricity and transportation, water).

(2) Environmental impact assessment of flows associated with stock demand for services.

To include these factors, intensity per capita is introduced for each service. This builds upon data and results obtained in Chapter 4. To assess the environmental impact, the LCA method is used, and the ReCiPe2016 impact assessment method chosen. While the same method applied in Chapter 4, its scope was limited to assessing the current flows associated with the city’s overall flows. This chapter, though, will extend the scope of analysis to capture the potential impacts of future development. However, the environmental impact assessment will be limited to GHGs and the climate change category. This is because the target of this assessment is the impact of future development and there are several initiatives that aim to reduce GHGs by 2050. Therefore, this assessment would help shed lights on the impacts of future development focusing on housing stock since this stock contributes to about 20% of global GHG emissions in 2016 (Song *et al.*, 2019).

5.3 Methodology and data

The developed stock dynamic model proposed in this study draws on work carried out by Müller (2006). The model has been employed in recent studies, and it has been proven that it has the potential to contribute to the evaluation and assessment of sustainability within the built environment. The following sections offer a system definition, a stock dynamic model calibration of the model and simulation results, including sensitivity analysis. It concludes with scenario-based calculations and model validation.

5.3.1 Data and assumptions

As stated above, the parameters studied in this model are population, floor area per capita, material intensity and energy intensity. The following subsections offer brief descriptions of these parameters.

5.3.1.1 Population and floor area per capita

Population (P) and its lifestyle as represented by floor area per capita (A_p) are the main driving forces when determining the demand for new housing stock. In this study, population data was obtained from several sources. The main data sources were reports from the Riyadh Development Authority (ADA) including the Metropolitan Development Strategy for Arriyadh (MEDSTAR) and the Investment Plan for Riyadh reports. Other sources included the statistical yearbook published by the General Authority for Statistics in Saudi Arabia. In some cases, secondary sources are consulted when there is no official data available for that year.

The floor area per capita (PCFA) is the most critical parameter in the model, as it shapes the demand for floor area of housing stock. This parameter is widely used as a social indicator in sustainable development studies, as a way to evaluate the housing quality (Müller, 2006). Increases in PCFA values indicate better living standards in terms of quantity, and also represents the major driving forces required to shape stock growth (Hu, van der Voet and Huppes, 2010). In the case of Riyadh, this value was only available for several years, as indicated in Figure 5-1. These missing values were estimated using a simple linear regression technique. The findings were then justified according to established linear trends in available data. This method has been applied in similar studies (Thyholt *et al.*, 2009; Sandberg, Sartori and Brattebø, 2014a).

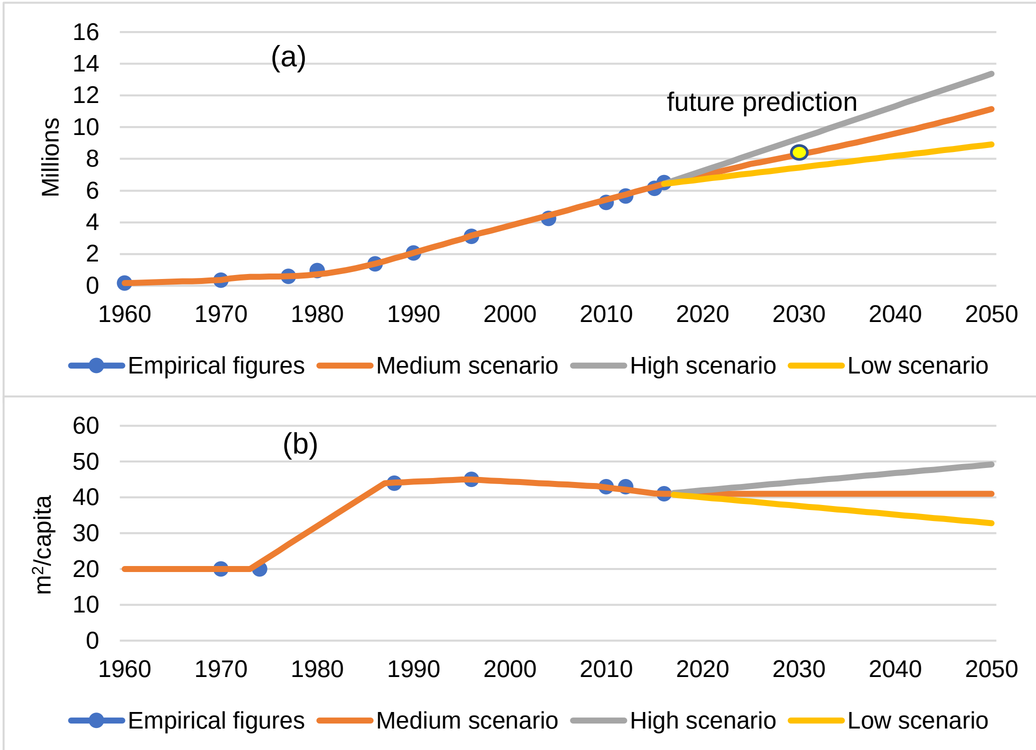


Figure 5-1 Calibration of population (a) and floor area per capita (b) parameters.

5.3.1.2 Material intensity

Introducing this parameter to the model is critical, as a way to analyse material stocks and flows within the system. It links the stock model to floor areas and materials. The scope of this study is limited to concrete, as it constitutes more than 98% of the building structure type in Riyadh. In addition, it is the most widely analysed material in stock dynamic studies. Its intensity is expressed by weight per square metre of floor built area. Since there is no data available defining material intensity in buildings in Saudi Arabia, a bottom-up approach has been developed. This approach involves classifying building stock into representative groups according to their types and material characteristics. Riyadh's housing stock typically comprises two types of building: villas and apartments (Albelwi, Kwan and Rezgui, 2017b). With the aid of local construction firms, and using bills of the materials, representative quantities of the material were established for each group.

However, there was no historical data available on material intensity, meaning it had to be assumed the intensity is a valid measure for historical dwelling stock. Since the time frame for the stock analysis starts from 1970 there was no reported change noted in the main building structure. However, it could be argued that material intensity tends to be higher in older buildings, as stated by Gallardo and colleagues (2014). Data on material intensity is shown in Table 5-2 for all three houses. The drawings of these houses can be found in Appendix (1). It should be noted that material intensity shown in Table 5-2 does not include data related to the traditional house which represent less than 3% of the housing stock. This is mainly due to lack of data. Also, these houses are in decline in terms of their percentage share of the total housing stock (Middleton, 2012).

To estimate the material demand for future stock, two assumptions have been made. First, that there will be no major changes regarding building structure. Second, material intensity would follow the current value. However, these assumptions can be justified for several reasons. The main argument in stock dynamic modelling, in general, relates to assessing how current practices, if continued, would impact on urban development in terms of consumption of resources and environmental impacts. Second, current trends in construction practices suggest that concrete will be the main construction material going forward. Although, it is possible that improvements to reduce embodied carbon and energy associated with concrete might be developed.

Table 5-2 Material intensity for three housing types.

Dwelling type	Total floor area (m^2)	Concrete intensity (ton/m^2)
Villa	381 m^2	1.8
Apartment building (18 apartments)	1839 m^2	2.4
Villa (precast)	307 m^2	2.8
Average (ton/m^2)		2.3

5.3.1.3 Electricity, transportation energy use and water intensity

To determine the demand for services created by housing stock, per capita intensity factors are included in the model. These factors relate to electricity, transportation and water consumption. While other studies have provided data for intensity per square metre, this information was not available in detail for Riyadh. In the case of Riyadh, the most frequently used indicator to report energy consumption is (kWh/capita) (as seen in Hepbasli and Alsuhaibani, 2011; *Urban indicators of Riyadh*, 2012; *Riyadh Urban Indicators*, 2017; Riyadh Chamber, 2016; Riyadh Development Authority, 2016 as well as the statistical yearbook published by General Authority for Statistics (GASTAT) and the Electricity & Cogeneration Regulatory Authority (ECRA) website (https://www.ecra.gov.sa)). Adopting energy use per capita as a factor to estimate energy flow preferred in cases where data is lacking on energy use per dwelling type, with regard to age and other physical characteristics (Sandberg and Brattebø, 2012b; Pauliuk and Müller, 2014b). However, this study distinguishes between consumption per capita as a total and consumption per capita for residential use. Since the study is concerned with housing stock, it uses data pertaining to the residential sector.

After collecting the required data, a linear regression analysis was performed to find the values for the missing data and to estimate future values. This was done in Excel, after establishing the trendline for the collected data, as shown in Figure 5-2.

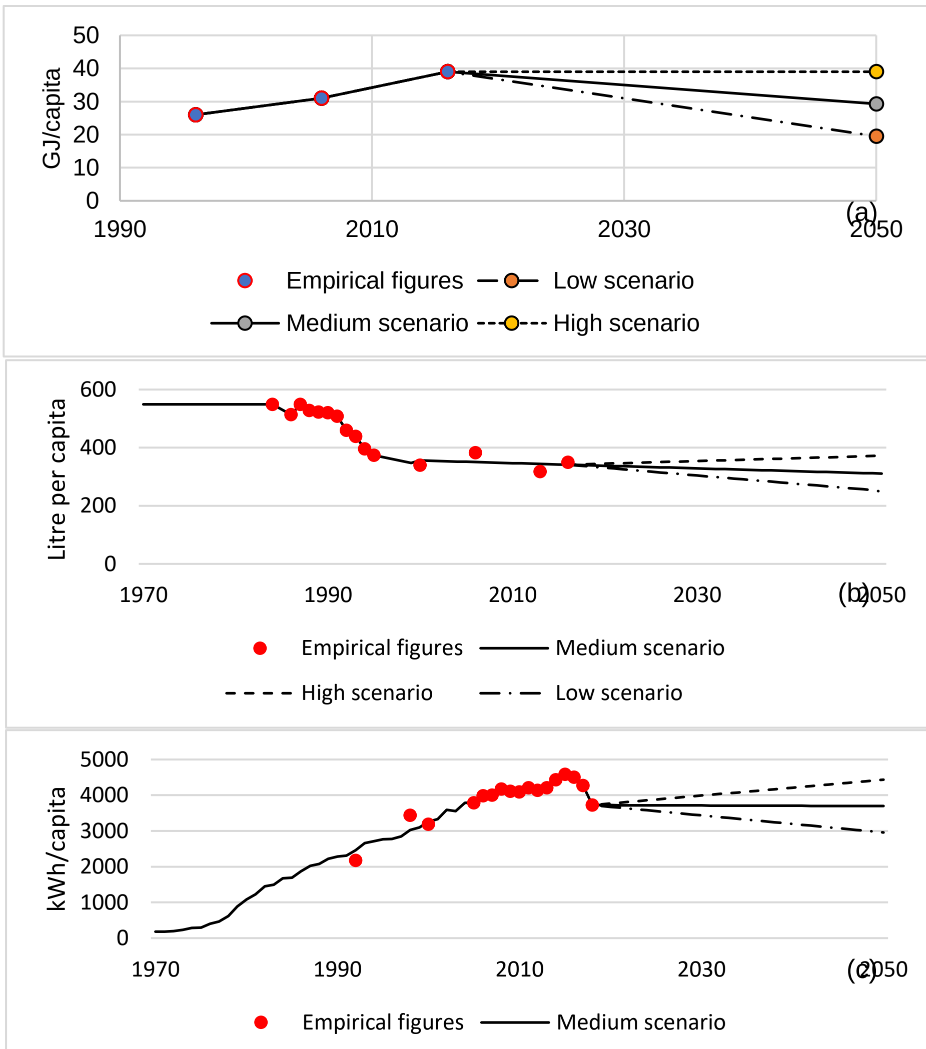


Figure 5-2 Intensity factors for transportation (a), water (b) and electricity consumption (c).

The electricity intensity factor was introduced to the model for its important role not only to provide an estimate for future demand but also to enable assessing the impacts associated with this demand. Also, the current electricity mix is 100% based on non-renewable sources

(Nachet and Aoun, 2015). To estimate residential electricity consumption per capita several sources were used. First, the annual Statistical Booklet from Electricity & Cogeneration Regulatory Authority (ECRA) was consulted. Also, several publications from the Royal Commission for Riyadh, the Statistical Yearbook published by General Authority for Statistics (GASTAT), and published reports from Riyadh Urban Observatory including Riyadh Urban Indicators for years 2012 and 2016.

A water intensity factor was included, due to its significance to a city that depends heavily on non-renewable resources to meet the demand from its population in a region classified by the United Nations as water-scarce (DeNicola *et al.*, 2015). Several sources were consulted to obtain the data related to water consumption per capita. These sources include the Riyadh Development Authority, National Water Company (NWC), Riyadh Urban Observatory. However, the majority of the data reported for water consumption per capita for Riyadh was based on the city's total water consumption. The only data reported for residential use was located in a recently published report (*Riyadh Urban Indicators*, 2017). This shows that the residential sector consumes about 48% of the total water consumed in the city. Due to the lack of data, this study uses this percentage to estimate residential water use over the course of a year, when consumption per capita data is available.

The transportation energy use associated with households' movement is too critical to ignore when assessing the impact of future development. This becomes more critical in the case of Riyadh, as the data shows a growing trend in all aspects related to the transportation sector, as evidenced by two main factors. First, car ownership was 234 per 1000 in 1996 and had increased to 310 per 1000 by 2016. A further important factor relates to the number of trips per day within the city's boundary. Data showed that in 1996 the city generated about 3.5 million trips per day, which later increased to about 10 million trips per day.

Finally, by using three different scenarios representing low, medium and high consumption patterns, the results were extended to capture different possible trends for future stock demand for sources and the related impact from a life cycle assessment perspective, as this would be the next step in the analysis. The high and low values were estimated for each service according to different factors.

For electricity intensity, three scenarios were analysed. The low scenario assumes that the current decrease in consumption per capita will continue as the government has recently implemented a broad energy price reform programs that aim to raise electricity prices for households and other sectors. This assumption was supported by the recent decrease in Electricity consumption per capita as shown in Figure 5-2. The medium scenario is based on the assumption that the value reported in the reference year (2016) will continue the same. This will allow higher and lower values to be analysed and assessed. For the high scenario, the model assumes there will 20% gradual increase from the reference year by 2050. This will allow a better understanding of the environmental impact of increasing demand for electricity.

For water intensity, although per capita values had shown a dramatic decrease over time, since the 1990s there has been no major fluctuation in the data. For the future scenarios, the medium-term scenario follows a linear trend for the reported data after 2000. Low and high rate scenarios represent ±20% relative to the medium scenario.

To establish energy use for transportation, this chapter relied on data reported in Chapter 3 related to Riyadh's urban material flow analysis. However, for a high flow scenario, this study assumed the current value would stay constant over the study period (2016-2050). Additionally, this value (39 GJ/capita) is considerably higher than the average for the world's highest ten megacities (28 GJ/capita) as reported in (Kennedy *et al.*, 2015). The low rate scenario is based on the assumption that there will a reduction in both energy intensity and emissions of (50%). The medium scenario assumes there will be a decrease of (25%). These two assumptions take into consideration changes increasing the share of public transportation and technology advancement influencing vehicles' energy efficiency.

5.3.1.4 Lifetime parameter

Introducing this parameter to the model is critical when analysing the demolition flow, which in return affects new demands. This study employs a normal distribution with a default mean lifetime and a standard deviation equal to 40 years and 8 years, respectively. A normal distribution has been widely used to estimate the delay in the service lifetime of buildings in stock dynamic studies (Huang *et al.*, 2013b; Stephan and Athanassiadis, 2018). This is because parameters are straightforward and understandable, and can easily be derived from the available data (Müller *et al.*, 2014). Including lifetime distribution is also a key parameter in the projection of future flows of demolition waste (Miatto, Schandl and Tanikawa, 2017), even though having limited empirical data might result in greater uncertainty over the lifetime parameter (Chen and Graedel, 2015). However, in cases where the lifetime of buildings is very poorly understood, it is essential to use a lifetime distribution approach (Lanau *et al.*, 2019).

5.3.2 Calibration of input parameters and scenario analysis

For each of the studied parameters, a calibration process is conducted to ensure inputs are within the range of the available historical data. Figure 5-3 depicts the input parameters for population and the floor area per capita following a medium scenario. For the model inputs to represent the real condition of the system being studied, it is crucial to calibrate the inputs with historical data (Müller, Bader and Baccini, 2004; Wittmer and Lichtensteiger, 2007; Sandberg *et al.*, 2016). Despite some of the historical data not being available on a yearly basis, it can still provide sufficient information to allow a trend on historical development to be drawn. As acknowledged by Sandberg and colleagues (2016), historical data can be used in the calibration process to evaluate the reliability, as well as the applicability of the model, if a pattern of historical development pattern can be identified (Sandberg *et al.*, 2016). Moreover, Buchner and colleagues (2015) stated that the calibration of model parameters is beneficial to improve model reliability (Buchner *et al.*, 2015).

Scenarios are mental explorations used to evaluate the consequences of possible future development paths for complex systems. Scenarios are not predictions but can be used to explore possible future outcomes resulting from different options. For example, "In industrial ecology, scenarios provide the inspiration for the development of corporate and governmental policy involving technology, society and the environment" (Graedel et al., 2015).

Scenario analysis is highly beneficial, as it can reveal the demand for sources and areas where improvements are taking place (Harvey *et al.*, 2014). In this chapter, scenario analyses are used to examine various development paths according to different sets of assumptions associated with input parameters. High and low scenarios represented a final value in 2050 of +/- 20% compared to the medium scenario. These include scenarios for future stock development, moving towards 2050. The choice of this year is governed by two factors. The first factor aims to avoid greater uncertainty in the analysis of future development. Second, the housing stock in Riyadh is relatively new compared to that investigated in other case studies; therefore, a full understanding of the stock and the related parameters is challenging.

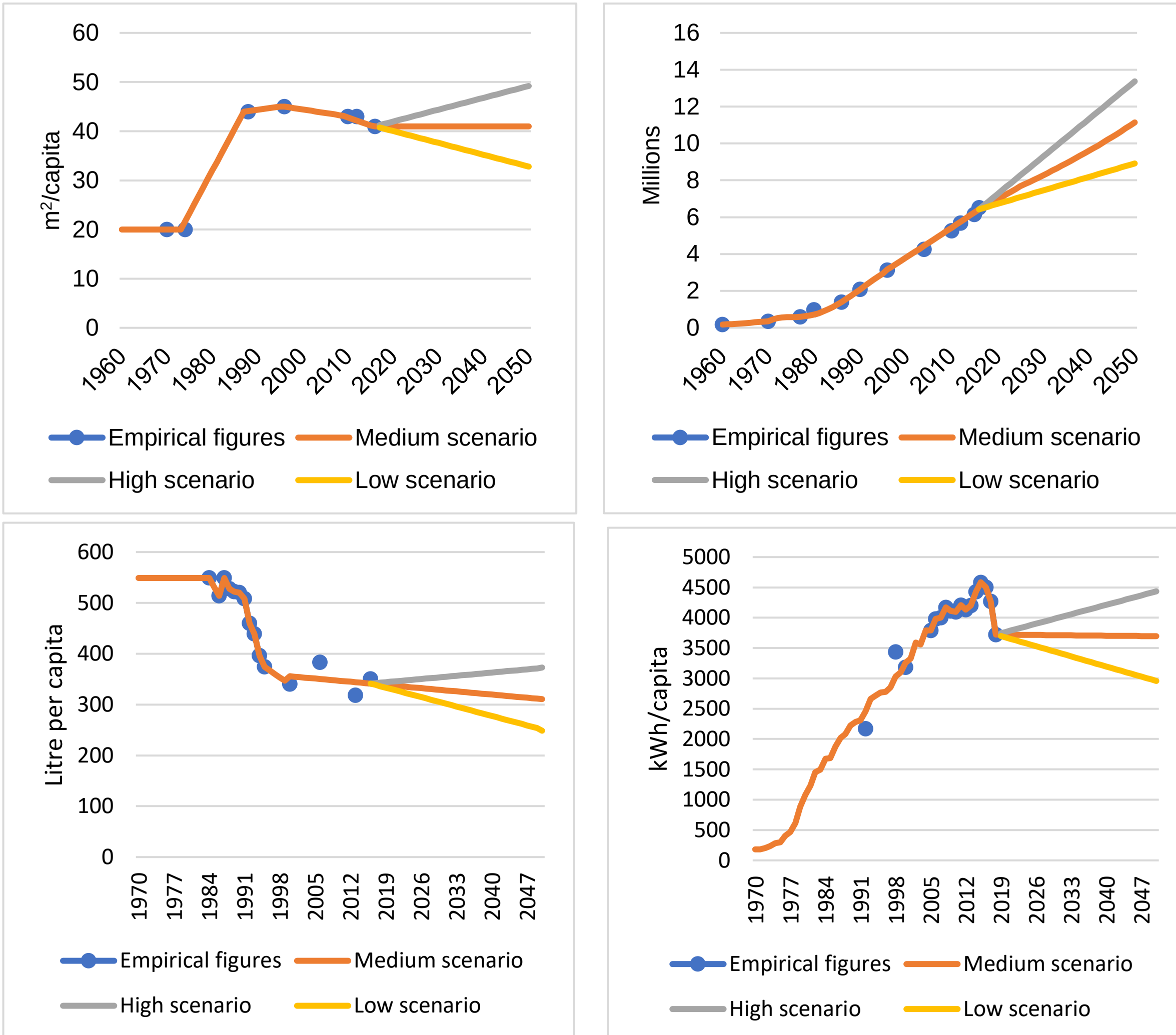


Figure 5-3 Input data to the model with three different scenarios.

5.4 Results and Discussion

In this section, the results for stock modelling will be presented. Then, results obtained by extending stock dynamic framework will be introduced. Following that, there is a summary investigating different scenarios for future stock development. Finally, results obtained from stock-dynamic based LCA are presented and discussed.

5.4.1 Housing stocks and flows in Riyadh

This section details the results obtained by stock modelling, depicting the evolution of both stock and flows from 1970 to 2050.

The stocks and flows based on a medium scenario are presented in Figure 5-4. In the medium scenario, all inputs are set at medium scenario values. The population growth and impacts associated with the oil booming in the 1970s (e.g., increasing floor area per capita) resulted in rapid and almost linear growth in housing demand during the late 1970s and into the 1980s. As mentioned in section 4.3, after 1975 the city experienced a high rate of population growth caused largely by internal migration flows, as well as the external migration flow. According to the model, demand for housing was controlled by two main factors; population growth, adaptations in lifestyle, and replacement of demolished housing that had reached the end of life stage. The historical figures suggest the two factors led to a rapid increase in demand until the 1990s at which point demand reduced.

The evolution of Riyadh's dwelling stock, as occurred and is predicted from 1970 to 2050, as shown in Figure 4-5 (a), indicates that total stock in m^2 of floor area increased from 7 million m^2 in 1970 to 259 million m^2 in 2016 and that stock is expected to increase further to 450 million m^2 by 2050.

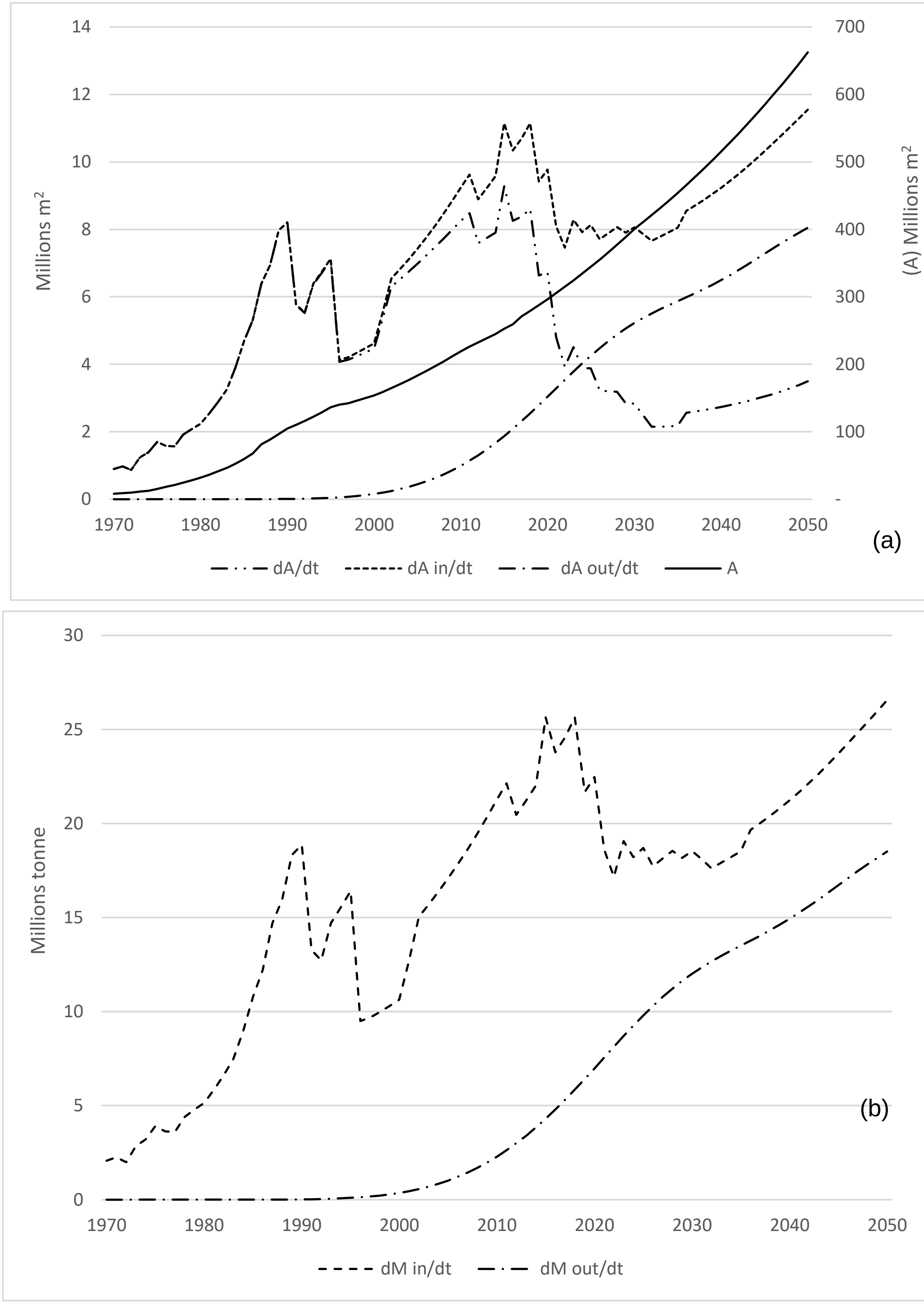


Figure 5-4 (a) Floor area flows and stocks, (b) Concrete flows and socks.

The stock witnessed two periods of high demand. The first between 1978 and 1991, and the second was between 2005 and 2018. This increase in demand at this time contributed to an increase in GDP per capita, as seen in Figure 5-5. The correlation coefficient for measuring the statistical relationship between the two variables (GDP per capita, floor demand) was estimated in Excel as 0.67. This indicates a moderate positive relationship between the two variables.

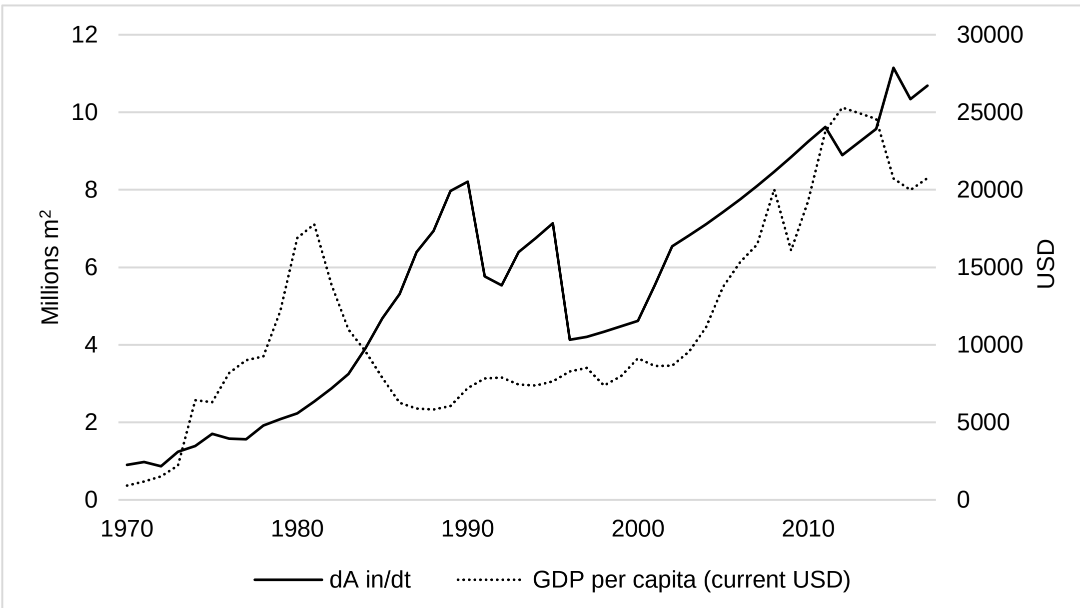


Figure 5-5 The relationship between floor demand and GDP per capita.

From a historical perspective, the rapid expansion is due to two principal reasons. First, the rapid growth in population the city faced after 1975, and second the increase in floor area per capita. The growth of future stock is driven mainly by the expected population increase and by new housing replacing old after demolition. However, as mentioned above, future increases in stock will be lower paced than it was between 1975 and 1990. This slowing down of stock growth has been witnessed since 2000. Although population growth is still a common feature in Riyadh, the population's lifestyle has changed, as indicated in floor area demand per capita. Current indicators declined from 45 m^2/capita in the 1990s to 41 m^2/capita in 2016. However, around 2035 stock is expected to increase at a higher rate, due to more buildings being demolished, as in a medium scenario the lifetime of dwellings is set at 80 years, and the peak of construction in the 70s and 80s will produce a peak of demolition in the 2030s and early 2040s. As indicated by the figures, the first peak in housing construction was prompted by a growing urban population. However, during the 2030s and 2040s, most of the demand will be caused by the need to replace old and retired housings.

5.4.2 Material input and output flows

As stated previously, the model was applied to concrete only. The material intensity was expressed as amount of concrete per square metre of built floor area. Although the model could include other construction materials if pursuing the same approach, this study was limited to concrete, as it constitutes the greatest fraction of construction materials in Riyadh's buildings. The simulation results regarding concrete flows are shown in Figure 4-5 (b). As illustrated in this figure, the behaviour of concrete flows is similar to floor area inputs. It must be noted that the simulation of concrete flows is based on the assumption that there will no major change in the concrete intensity over the time targeted by the model (2050). However, the increasing use of concrete correlates with the construction boom that the city experienced in the late 1970s.

Moreover, the stock change (input-output) for concrete can be considered as an indicator describing the consumption of resources. As seen in Figure 5-6, the peak in concrete stock was around 1992. After a short decline in the 1990s, the stock level is expected to remain steady until the late 2020s, when it will increase mainly due to replacing retired housings. The results of stock change indicate an expected small increase of the stock immediately before 2050.

The results may serve as a basis from which to create policies to benefit from the output flows (concrete waste) as a secondary resource. The studied material (concrete), could be crushed and used as aggregate; which in turn could help minimize the use of natural resources.

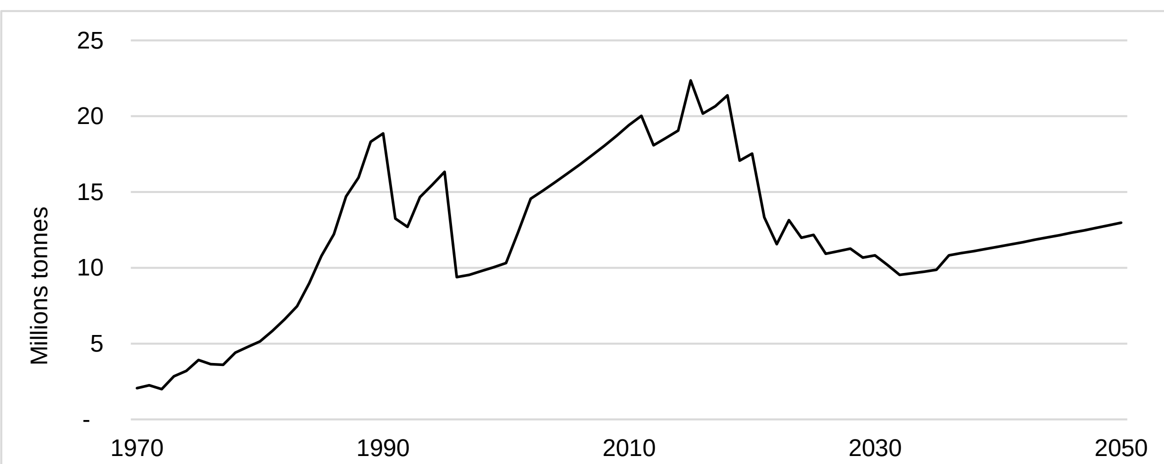


Figure 5-6 Stock change (concrete).

5.4.3 Electricity, transportation energy and water flows

As stated before, one of the most noticeable features in the stock dynamic approach to studying the built environment is that it can be combined with other tools and approaches to include factors other than housing demand. While the stock dynamic has proven to be a valuable tool to estimate future housing demand, services provided for future housing stock are crucial to assess and analyse (Müller, Bader and Baccini, 2004; Pauliuk and Müller, 2014b). The most vital services are energy and water. In this section, energy and water flows are estimated by coupling stock dynamics with service intensity factors. As shown in Figure 5-7, the trends of water and energy flows suggest an increase in the near future, due to rapid population growth.

Although the per capita measure for water consumption has fallen over time, overall demand is increasing due to large population growth. The same pattern has been observed for energy flows. Results relating to energy flows showed total energy consumption fell for the first time in 2018. This may have contributed to new tariffs introduced recently. In 2018, the tariffs imposed on electricity in the Kingdom increased by 250% compared to the 2015 price (Harbi and Csala, 2019).

For future demand, all three scenarios for both energy and water suggest an increase in demand. However, for the low scenario, the trend seems to suggest a levelling off around 2050, as per capita value decreases. The findings highlight the significant efforts needed to curb consumption per capita from its current values. A final note regarding water consumption suggests the per capita value was reported for total consumption by the city and that residential use was estimated based in years where data was made available.

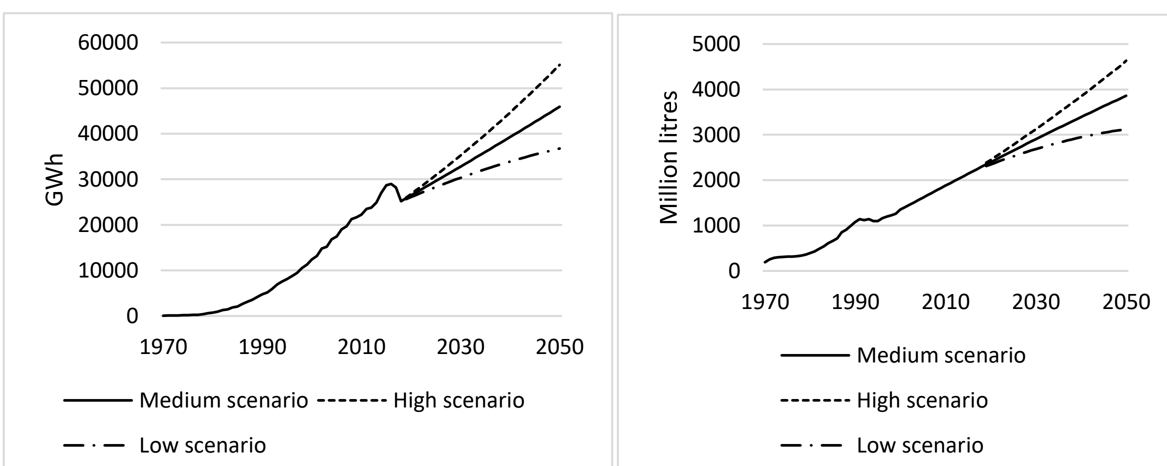


Figure 5-7 Water (right) and energy (left) past and future flows.

5.4.4 Stock dynamic model validation

The results of applying a stock dynamic were validated using available data on the current stock as well as historical data. Validation was done using two main sets of data, namely, validating the inputted floor area and the vintage housing factor. Selection of these two factors is governed by the availability of the data. For the input floor area, data related to construction permits and built floor area was obtained from the Ministry of Municipal and Rural Affairs, which publishes online construction permit data, as well as information about floor area for each type of construction (i.e., residential, commercial, etc.). This data was only made available between 1987 and 2017.

The vintage housing data used was published recently by the General Authority for Statistics (General Authority for Statistics, 2017). This data was for the year 2016, and was compared to model results for the same year. Figure 5-8 validates the model's results. According to the figure, the model results capture trends in housing demand; although the simulated results do not report exact numbers. Similar studies that tried to validate stock dynamic model with actual data have shown the same outcome from the validation process (Sartori *et al.*, 2008; Hu *et al.*, 2010). The model results were within the range of that allowed by statistics. However, for vintage housing stock between (2013-2016), the model reports a higher volume, which could influence the replacement of old houses after passing the designated lifetime considered in the model.

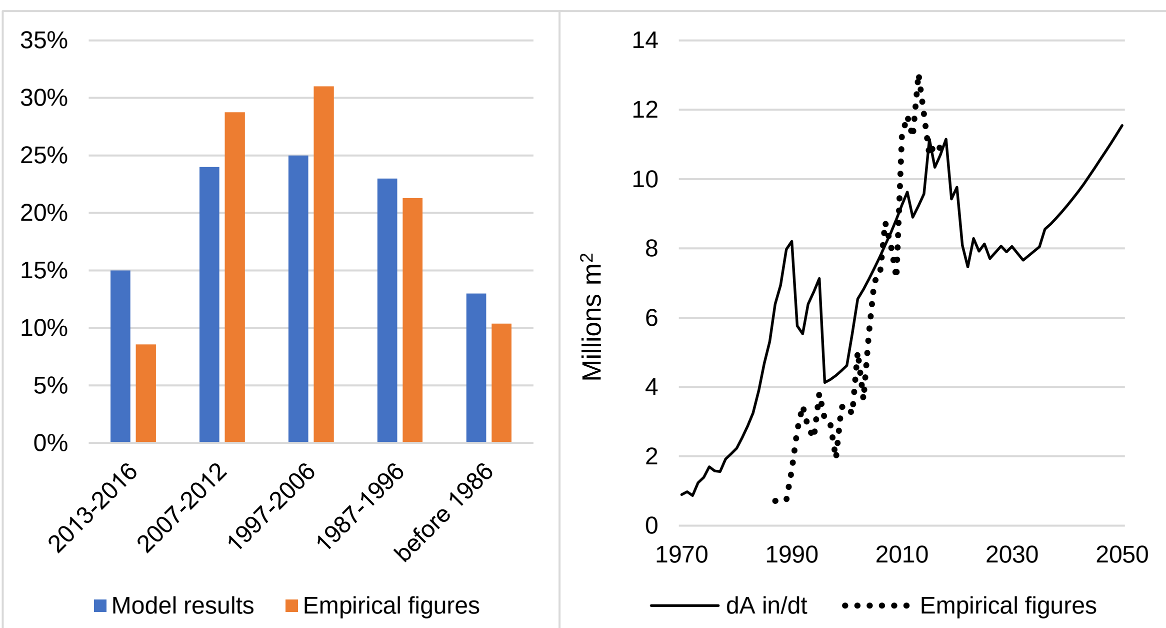


Figure 5-8 Model results and empirical figures (a) construction activity, (b) housing vintage.

5.4.5 Sensitivity analysis

The application of stock dynamics to assess future development has been seen as especially useful (Sandberg, Sartori and Brattebø, 2014b). However, since the model is based on different parameters, there might be significant uncertainties regarding these parameters. Therefore, this study conducts a sensitivity analysis and has performed different simulations, varying the input data from low value to high value. This is done to evaluate the model, which results in uncertainties. As indicated previously, the three factors that influence housing demand are population growth, floor area per capita, and the dwelling's lifetime. The population and per capita floor area are the two values investigated (high, low). The variation between these two values, and the medium scenario value, are set at 20% above and below for high and low scenarios respectively. For lifetime factors, two additional estimations of the dwellings' lifetime are investigated using a normal distribution function, with two different means and standard deviations. The high scenario considers a higher lifetime, assuming a 50 year mean and a 10-year standard deviation, while the low scenario considered a 25 year mean and a 5-year standard deviation. The results from the conducted sensitivity analysis are presented in Figure 5-9. The following paragraphs describe the main findings from the sensitivity analysis.

In terms of the housing stock demand parameters (i.e., population growth, floor area per capita), the results of the sensitivity analysis showed that oscillations in the housing stock over the period analysed will not be affected. However, the evidence also showed stock demand is sensitive to population demand and lifestyle in terms of floor area per capita. Changing these two variables above the medium scenario (± 20%) led to a change in total floor area in 2050 of +51% and -61% from the medium scenario respectively. This is due to the fact that the future stock is only determined by these two factors. Moreover, in the low scenario, the results showed that by 2050 stock will show signs of decreasing, due to the lower floor area per capita and smaller population growth. Similar studies conducting a sensitivity analysis for stock modelling reported the same findings, as future stock demand is affected by changes in population growth and floor area per capita. For example, Hu and colleagues conducted a sensitivity analysis for their stock dynamic model for urban housing stocks in China. The sensitivity analysis results showed changing the input parameters by ±20% resulted in changes in future floor demand of +180% and -40%. In the same study demolition activities was less sensitive to changes in the input parameters at +68% and -25% (Hu *et al.*, 2010).

For the stock outflows, the results of the sensitivity analysis showed less response to changes in input parameters compared to stock demand. The results also showed that changes in input parameters ±20% lead to changes in outflow of +4% -8%. This can be explained by the delay in the model using a mean for lifetime with normal distribution.

Sensitivity analysis related to changes in the lifetime of buildings showed that demand for new housing is dependent on a building's lifetime. Using the three different means for lifetime (25 year (low value), 40 year (medium value), 50 year (high value)), the results in terms of stock demand showed changes in lifetime to a lower value (25 years) resulted in higher stock demand, of 35% from the medium scenario. The Saudi Council of Engineers (SCE) stated that the average life span of buildings in Saudi Arabia is between 25 and 50 years [7].

Changing the building's lifetime to 50 years resulted in -15% for floor demand in the year 2050. However, for stock outflows, applying 25 year as the mean for building lifetime would result in higher stock outflows of 58% from the medium scenario, while applying 50 year as a mean would result in -14% for the medium scenario in year 2050. This signifies the importance of developing a better understanding of the lifetime of buildings.

In conclusion, it is important to conduct a sensitivity analysis for models, to illustrate the level of sensitivity for each parameter. The results showed that for stock demand, the medium scenario is better aligned with empirical figures, as shown in Figure 5-9. In addition, the results showed that housing demand is greatly influenced by population growth and demand is determined by floor area per capita. On the other hand, a building's lifetime seemed to influence housing demand more than its outflows, because of the life span of the analysis.

[7] https://www.arabnews.com/news/519231

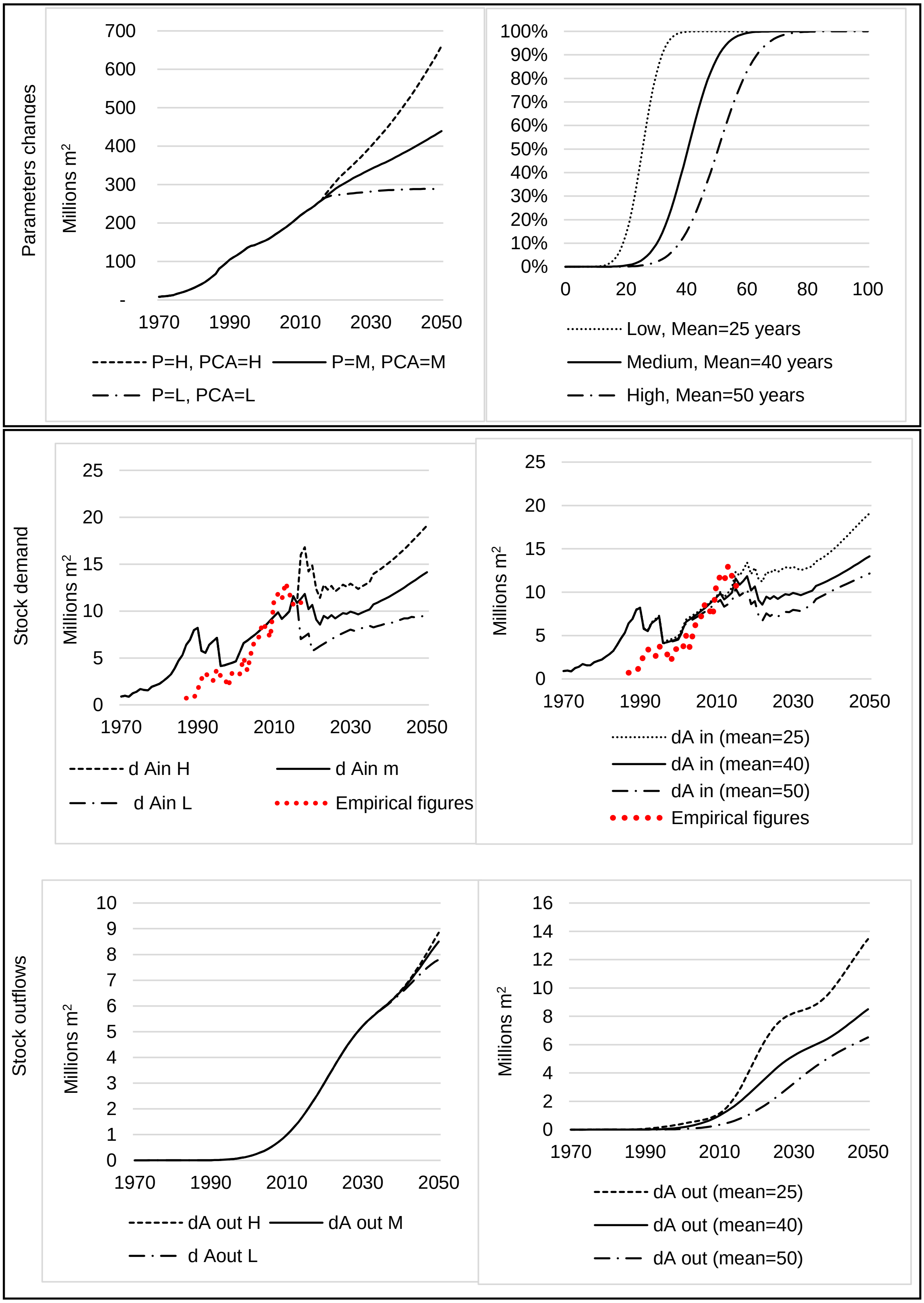


Figure 5-9 Sensitivity analysis for the Riyadh stock model.

5.5 Environmental assessment of stock dynamic results

As indicated above, LCA is used to assess GHG emissions associated with energy and water consumption as related to housing stock demand over the studied period (2016-2050). The results obtained from the stock dynamic model serve as an inventory for the LCA. The model reports demand for energy and water for Riyadh's housing stock until 2050, based on three different scenarios. These scenarios relate to electricity, transportation energy and water consumption per capita, and range from a low, medium, and high scenario to capture different development patterns in terms of resource consumption. Figure 5-10 shows the results for energy and water consumption by housing stock until 2050 according to three different scenarios. These scenarios are relevant to consumption patterns associated with housing stock.

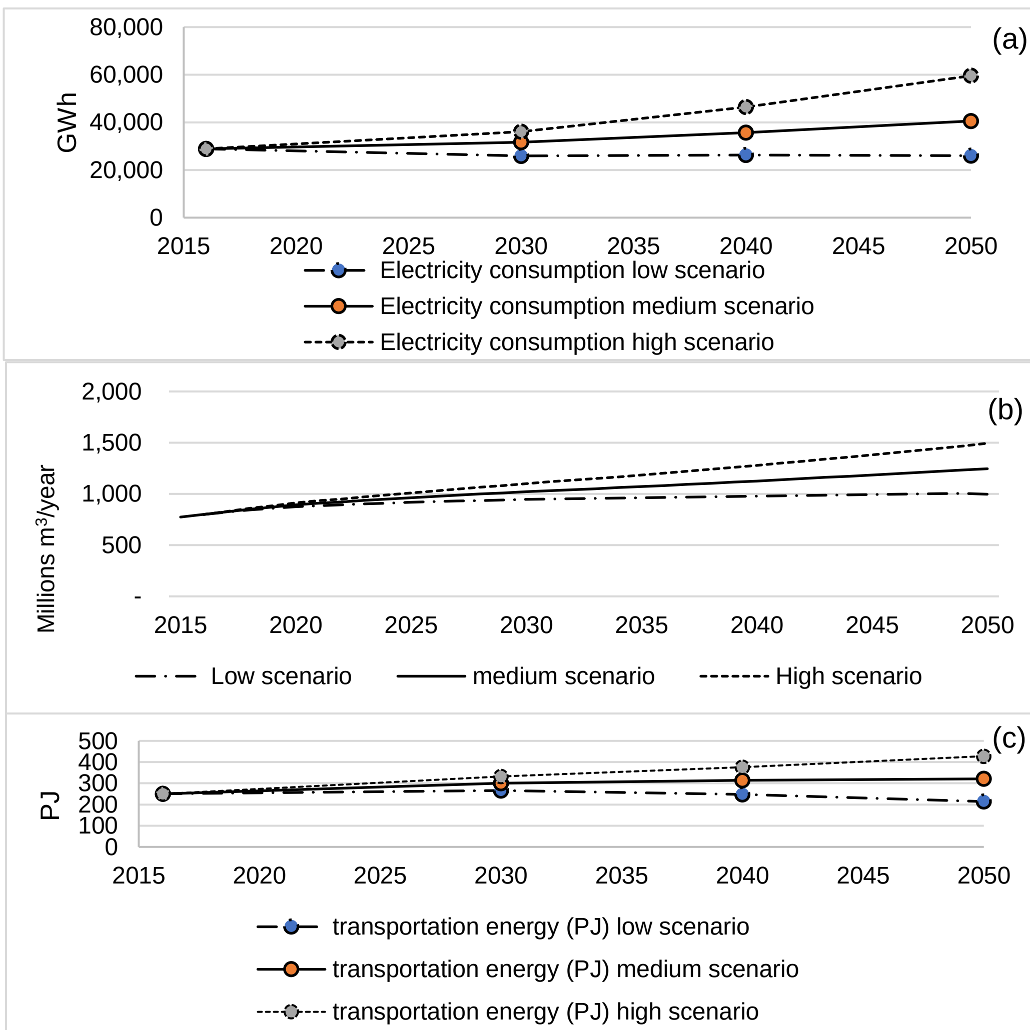


Figure 5-10 Electricity (a), water (b) and transportation energy (c) demand of housing stock (2016-2050).

The results from Figure 5-10 were used and entered into SimaPro to estimate the GHG emissions for all three scenarios. The goal is to assess the environmental impacts associated with stock development. The impacts are then reported as $CO_{2\ e}$. It noteworthy that for all the scenarios it was assumed there would be no change in terms of the technology or energy mix. However, the outcomes of the assessment would be used in Chapter 5, as policies to mitigate GHGs are developed and assessed. Table 5-3 details the GWP factors for electricity and water. For electricity, emissions are based on Saudi Arabia's energy mix, as reported by the Electricity & Cogeneration Regulatory Authority (ECRA) in their annual statistical booklet on the electricity industry. Emissions related to water production were estimated according to known water sources in Riyadh (groundwater, desalination).

Table 5-3 GWP factors for electricity, water and transportation.

Component	Unit	GWP impact/unit
Electricity	kg CO_{2e}/kWh	0.805
Water (ground water production)	kg CO_{2e}/m^3	0.868 (54%)
Water (desalination)	kg CO_{2e}/m^3	26.4 (46%)
Water (total)	kg CO_{2e}/m^3	12.61
Transportation (low scenario)	kg CO_{2e}/GJ	37.69
Transportation (medium scenario)	kg CO_{2e}/GJ	56.53
Transportation (high scenario)	kg CO_{2e}/GJ	75.38

A note must be made regarding the process of water desalination. The emissions associated with water production (desalination) are estimated based on the *Third National Communication of The Kingdom of Saudi Arabia* report (Ministry of Energy Industry and Mineral Resources, 2016). This report set out the GHGs inventory for the Kingdom for 2010. The inventory is reported in relation to different sources (e.g., electricity generation, road transport, desalination, etc.). Using the ReCiPe2016 method, GWP was calculated and reported in CO_{2e}. This led to an estimation of 26.4 kg CO_{2e} per m^3 produced. Although this number is based on aggregate data, it can; however, be accepted as within the range of values reported in the literature regarding LCA of water desalination industry (Raluy, Serra and Uche, 2006; Gude, Nirmalakhandan and Deng, 2010). Figure 5-11 shows the LCA results obtained for all developed scenarios.

One main conclusion from this figure is that only one scenario showed a decrease in GHG emissions from the reference year 2016. High and medium scenarios showed an increase in GHG emissions of 90% and 28% respectively. On the other hand, the low scenario showed a decrease of 20% from 2016 values. Even though the studied component was only limited to electricity, water consumption and transportation energy of the city, these sectors are considered major contributors to GHG emissions in cities around the world (Kennedy *et* *al.*, 2011; Zhou *et al.*, 2015; Facchini *et al.*, 2017) and in Saudi Arabia (Wogan, Carey and Cooke, 2019). These key findings illustrate the importance of developing meaningful measures to curb GHG emissions. This will be discussed and analysed further in Chapter 6.

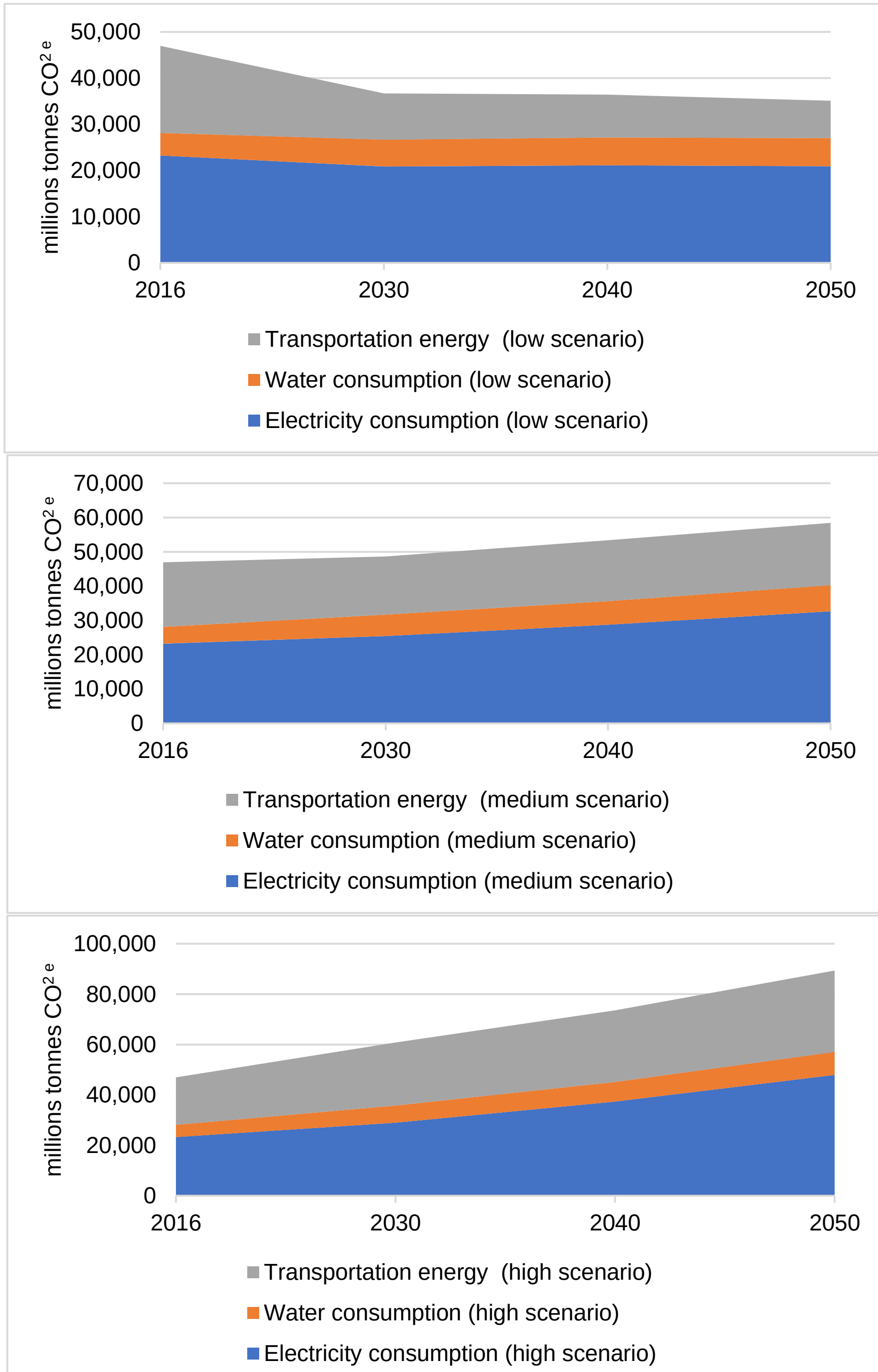


Figure 5-11 GHG emissions for all scenarios.

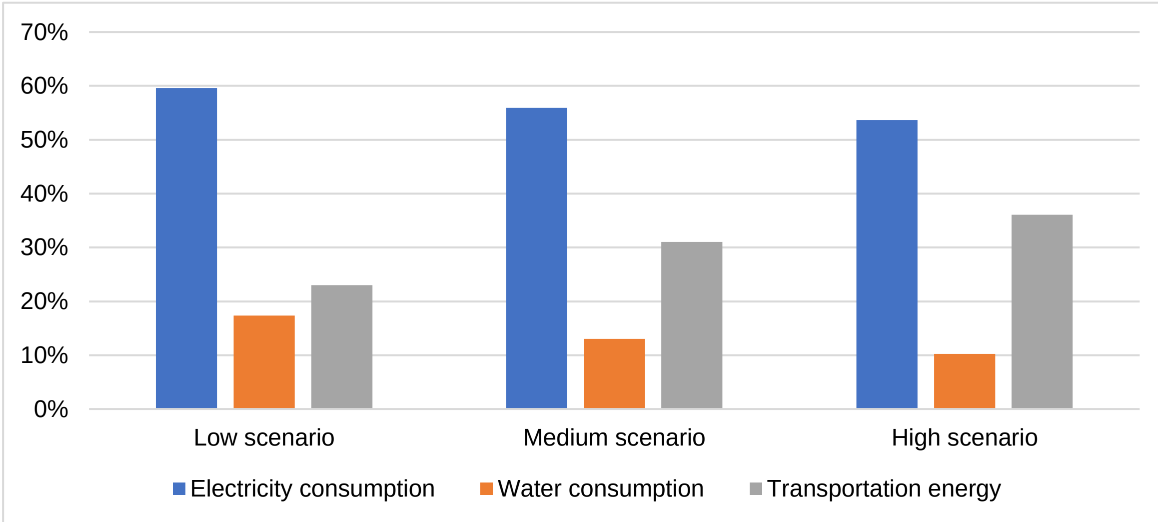


Figure 5-12 Sectors share of GHG emissions across all scenarios.

With regard to the sector that contributes the most to GHG emissions, the results showed that across the three scenarios, electricity consumption is responsible for 60%, 56% and 54% in low, medium and high scenarios respectively. Moreover, as shown in Figure 5-12, in the low scenario, GHG emissions from water production and transportation are close (6% difference). This relates to how significant each sector is when considering all possible scenarios.

Extending stock dynamic model to include service in-use parameters provided better knowledge and understanding of those impacts associated with the future development of stock. Generating such knowledge from the stock dynamic model is crucial for the application of the model, as it provides information that is useful to the decision-makers in the cities, as they develop policies to mitigate GHG emissions and move towards a more sustainable built environment.

It was shown in this chapter that combining MFA and LCA provided a better assessment for environmental aspects of sustainability in the built environment. Also, integrating MFA-LCA can be used to provide information about the resilience in the built environment. While environmental sustainability in this thesis was defined as a set of socially derived goals that aim to reduce the ecological footprint of the built environment, resilience can be defined as a modelling framework that indicates the phenomena that facilitate achieving the sustainability goals (Pickett et al., 2014). Within housing stock, resilience means that the function of the housing stock is sustained under changing circumstances (Lombardi *et al.*, 2012; Almulhim, Hunt and Rogers, 2020). MFA-LCA approach can be used to assess the impact of these changing circumstances on the built environment in general and housing stock in particular. For example, the environmental threats of future housing stock such as climate change can be estimated using MFA-LCA approach which allows for measures and policies to be proposed at present time to absorb any related threats. This scope is recommended for future work.

5.6 Limitations of the proposed Model

The main assumption throughout the model is that stock demand is determined by two major factors; namely, population and lifestyle, as determined by floor area per capita. When validating the model outcome with empirical results, it was found to provide reasonable results concerning the evolution of the stock to date. However, using the same factors to predict future stock demand is challenging, and this study attempted to overcome this challenge by developing deferent development scenario. Although stock dynamics have been applied in several cases with different objectives, it is not intended to provide rigid predictions; rather, it provides possible development scenarios, usually based on understanding the historical development of the stock and related parameters. However, these parameters are not available for each year historically, and so some values had to be estimated using regression analysis. Therefore, the process of quantifying the model's variables involves some uncertainty. Another parameter used in the model that involves uncertainty is the lifetime assigned to stock. The results from the sensitivity analysis indicated that the model estimation of outflows in the future is influenced by the lifetime assumed in the study. However, three different lifetimes were analysed, and the results indicated the robustness of the model's results.

Including service in-use intensity factors improved the analysis of the model for future stock. However, the included factors (electricity, water, transportation energy) are also based on the per capita consumption data. The estimation of these factors for future stock relates to simple linear assumptions. To capture changes in consumption patterns, this study developed three scenarios ranging from low, medium and high. However, the changes noted were limited to changes in the populations' consumption behaviours.

Integrating a stock dynamic with LCA improved and expanded the scope of the stock dynamic model. LCA was applied to assess environmental impact, focusing on global warm potential. The assessment based on a static system, assuming no changes in the system's behaviour in the future.

5.7 Conclusion

This chapter provides a stock-dynamic based model to evaluate the dynamics involved in Riyadh's housing stock. The housing stock is estimated using a function combining population and lifestyle, defined as floor area per capita. The results of the stock model and associated uncertainty were also presented and discussed. The two most important variables in the stock model are population and floor area per capita, as these determine stock evolvement in the future, in terms of its inflows and outflows. Although there is some uncertainty present in the input parameters used in the model; the results and scenarios developed help to provide useful information on Riyadh's housing dynamic. Moreover, when adding parameters for electricity, water and transportation, the model can be used to analyse future stock demand applying a systematic approach. However, these parameters need not consider the characteristics of individual houses. This may be interesting for future work, as there is lack of data in this area.

To further understanding of stock dynamic model results related to future stock, LCA is integrated with a stock dynamic model to assess the environmental impacts associated with stock development. Although the LCA in the integrated model is based on a static approach that assumes no change to background processes, the results can still provide sufficient robustness to assist decision-makers in finding pathways to mitigate environmental impacts.

Chapter 6 **Hybrid Stock dynamic LCA model to evaluate climate change mitigation**

This chapter provides an assessment of policies aimed at mitigating climate change. It shows the potential contribution of the stock dynamic model combined with LCA when evaluating these policies, illustrating a systemic understanding of the impacts and benefits associated with the implications of these policies when seeking to achieve required emissions reduction by 2050.

6.1 Introduction

In most countries worldwide, the pursuit of material items such as cars and the expansion of housing developments is the predominant feature of urban development (Reusswig, Lotze-Campen and Gerlinger, 2003). Moreover, changes to the lifestyle of urban populations have resulted in a rapid increase in material demand, energy consumption and waste generation (Kalmykova, Rosado and Patrício, 2015b). As cities become more populated over the coming decades, as predicted in recent reports published by the U.N. (United Nations, 2018), it is essential to understand the associated future impact of the urban population so that city planners can device suitable policies to mitigate these effects.

The housing stock is responsible for 25% of global final energy consumption (Pauliuk, Sjöstrand and Müller, 2013). In Saudi Arabia, building stock accounts for 29% of the total energy consumed in the country. It also accounts for 80% of total electricity consumption, with an average annual growth about 7%[8]. The residential sector accounts for about 53% of Riyadh's total electricity consumption (Electricity and Cogeneration Regulatory Authority, 2016). Moreover, building stock contributes to nearly 20% of the GHG emissions worldwide (Dean *et al.*, 2016). This percentage covers building related energy use and construction. In Saudi Arabia, according to the latest GHG Inventory, GHG emissions related to electricity consumption only contributed 30% of the country's total GHG emissions. Nevertheless, with the urban population expected to reach 66% by 2050 (United Nations Population Division, 2014), it is incumbent on cities to assess the potential influences of urban population growth.

The 2015 Paris Agreement put forward a new plan for better the global cooperation to address climate change and its impacts. Many nations and cities have outlined longer-term decarbonization goals and objectives to ensure a more sustainable future. When assessing the sustainability of urban development, building stock can be treated as a major potential

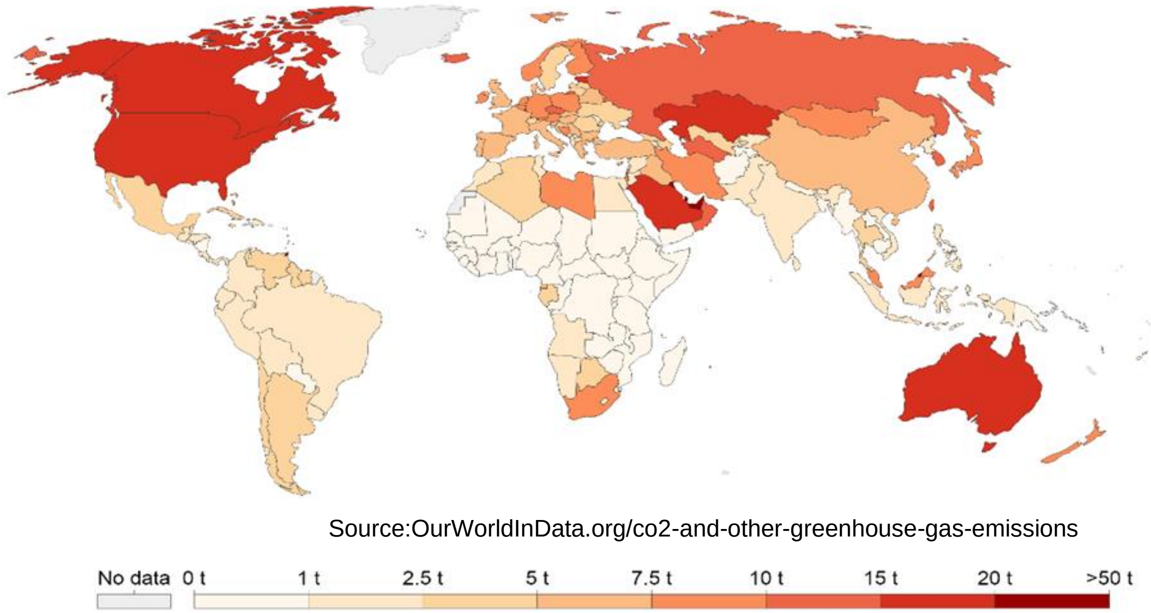
[8] https://www.seec.gov.sa/en/blog/buildings

contributor to reducing the environmental burdens associated with urban development (National Academies of Sciences and Medicine, 2016).

Several studies have employed a stock dynamic model to investigate this potential. For example, Pauliuk and colleagues combined a stock dynamic model with life cycle assessment (LCA) to evaluate potential reductions in carbon emissions from housing stock by 2050. Different scenarios were evaluated and assessed to find the best scenario to achieve an emissions reduction of 50%, requiring an average limit on global warming of up to 2 degrees Celsius. Other studies have used the same approach to estimate energy consumption for future stock and related emissions (Sandberg, *et al.*, 2017). By applying a stock dynamic approach, Vásquez and colleagues evaluated the impacts of stock renovations and policies related to NZEB (Nearly zero energy buildings), finding that for the two studied cases, 50% energy reductions could be attainable by 2050 (Vásquez *et al.*, 2016b). Another study by Sandberg and Brattebø (2012) used a stock dynamic method to analyse future energy and carbon flows (2000-2050). This same model was applied to 11 European countries to analyse the energy saving potential within building stock (Sandberg *et al.*, 2016). The aforementioned studies demonstrated the applicability of the model to different scales of the built environment. However, as the majority of urbanization is estimated to occur in developing countries, an understanding of housing stock and its associated impact into the future is critical to sustainable development goals.

In Saudi Arabia, the Kingdom is seeking to achieve GHG mitigation of co-benefits, avoiding up to 130 million tonnes of CO_{2e} by 2030 or 21% from 2016 values. As shown in Figure 6-1, the country has one of the highest CO_2 emissions per capita. However, GHG emissions need to be reduced by 50% before 2050, to limit global temperature rises to within 2°C of pre-industrial levels (Masson-Delmotte *et al.*, 2019).

This chapter is motivated by the potential contribution of the housing stock model when developing insights along different paths to reduce GHG emissions by 2050. To achieve this goal, this study used a stock model developed in Chapter 5, extending its scope to capture the impact of changes to the background system. This includes changes in the energy mix, fuels used in desalination plants, as well as changes in transportation patterns (e.g., share of public transportation, fuel efficiency). These scenarios are meant to shed light on different GHG mitigation pathways to achieve the required reduction to GHG emissions by 2050.



Source:OurWorldInData.org/co2-and-other-greenhouse-gas-emissions

Figure 6-1 CO_2 emissions per capita, 2017.

This chapter aims to evaluate the reduction in GHG emissions in three sectors: power generation, transportation, and water production industry. To define the scope of the analysis the following two questions are posed:

1. How can a stock dynamic model be applied to assess climate change mitigation policies?
2. What is the role of in-use stock in reducing associated emissions when tackling climate change?

6.2 Methodology

As stated above, the stock dynamic model developed in Chapter 5 served as the basis for assessing and analysing future energy and GHG emissions. Meanwhile, the model in Chapter 5 was applied to estimate future flows, and assess associated environmental impacts. However, in Chapter 5 future flows were assessed assuming there was no change to the background system. In this chapter, different assumptions were developed based on current goals and initiatives as proposed by the Kingdom of Saudi Arabia, to move towards a low-carbon economy. To develop these scenarios, firstly, a review of the country's initiatives to tackle climate change is conducted. The aim being to locate the developed GHG mitigation scenarios within the context of the country's efforts to date. In Table 6-1 a summary is provided of chief recent initiatives.

Following the initial review of the country's recent initiatives towards reducing GHG emissions, the study developed a number of scenarios to assess the contribution of each scenario as a means to achieve the required reduction. These scenarios were applied to the stock model developed in Chapter 5. Meanwhile, LCA was used to assess GHG emissions relative to each scenario. As mentioned previously, the proposed scenarios were justified by recent policies and initiatives, which were developed to tackle climate change. However, some of these scenarios use extreme values, in terms of share of renewable energy. This is deliberate, as a way to evaluate the impact of such scenarios on future GHG emissions.

Table 6-1 A summary of the main initiatives proposed by the Kingdom.

The initiative scope	Implications and examples	Goals and objectives
Energy efficiency	• Tariff restructuring • Energy efficiency labels and standards for new equipment • Energy efficiency information and awareness • Saudi Arabian Standards Organizational Initiatives • Green Building Initiatives • Saudi Energy Efficiency Centre	• Proposed scheme for energy intensity certification of existing and new buildings • Increase fuel efficiency at energy power plants • Develop and update standard specifications for small and large capacity air conditioners
Renewable energy	• The Renewable Energy Project Development Office (REPDO) • King Abdullah City for Atomic and Renewable Energy • Sakaka wind energy project • National Committee for clean energy development mechanism • King Abdullah Initiative for Solar Powered Desalination	• Increase the share of renewable energy to the national energy mix by 10% in year 2030. • Desalinate seawater using solar energy
Transportation sector	• The National Transport Strategy	• Development of a multimodal transport system • Formulate regulations to enhance the transport sector performance and reduce its emissions

The percentages shown in Table 6-2 represent the changes associated with each scenario relative to the values reported in the medium scenario. These values can be justified in reference to the recent government report, which estimates the future energy mix (*Towards Saudi Arabia's sustainable tomorrow*, 2018). Although some values might represent an extreme scenario, it serves the aim of this chapter, as it provides insights into the possible contribution when introducing renewable energy as part of the economic development of the Kingdom.

In conclusion, the scenarios developed in this chapter are intended to capture the impact of changes in energy consumption patterns arising from higher energy efficiency, because of technological improvements and the impact of changes in the future energy supply mix.

Table 6-2 Scenario overview and input values for the reference year 2016.

Scenario	Alternative Energy mix	GHG emissions coefficient for water production to reference year (2016)	GHG emissions coefficient for transportation to year (2016)	Justifications and assumptions
(1)	Oil (50.2%) Natural gas (49.8%)	Base scenario (medium scenario developed in Chapter 4)	Base scenario (medium scenario developed in Chapter 4	This scenario presents the business as usual scenario against which other scenarios are compared.
(2)	30% natural gas 20% oil 20% wind 30% solar	30% reduction in GHG emissions coefficient from medium scenario developed in Chapter 4	30% reduction in GHG emissions coefficient from medium scenario developed in Chapter 4	• Energy mix assumes that the current plans of building solar and wind power plants will contribute to 50% of the current national energy mix. • Emissions related to water production assume a decrease of 30% due to using more advance and efficient systems at desalination plants (e.g., reverse osmosis (RO) membrane systems) • Emissions related to on-road vehicles assume an increase in fuel efficiency and a higher proportion of public transportation
(3)	50% wind 50% solar	40% reduction in GHG emissions coefficient from medium scenario developed in Chapter 4	40% reduction in GHG emissions coefficient from medium scenario developed in Chapter 4	• Energy mix assumes that the current plans for building solar and wind power plants will contribute to 100% of the current national energy mix. • Emissions related to water production assumes a decrease of 40%, due to using more advance and efficient systems at desalination plants and solar energy. • Emissions related to on-road vehicles assumes an increase in fuel efficiency, and a higher share of public transportation
(4)	50% natural gas 50% solar	50% reduction in GHG emissions coefficient from the medium scenario developed in Chapter 4	50% reduction in GHG emissions coefficient from the medium scenario developed in Chapter 4	• Energy mix assumes the current plans for building solar power plants will contribute to 50% of the energy mix and 50% of natural gas. • Emissions related to water production assume a decrease of 50%, due to using more advanced and efficient systems at desalination plants and solar energy. • Emissions related to on-road vehicles assume an increase in fuel efficiency and a higher share of public transportation

6.3 Results

6.3.1 Energy consumption and GHG emissions by housing stock, 2050

In this section, the results of energy consumption for housing stock by the year 2050 are presented. Energy consumption is reported for three sectors (electricity, transportation, energy for water production). However, reported energy use includes direct and indirect data, based on the cradle to gate approach. In addition, the embodied GHG emissions for each sector were calculated following the ReCiPe2016 method. Figure 6-2 presents the total energy demand (direct and indirect) for Riyadh's future housing stock. It also shows GHG emissions associated with the three sectors. The justifications for limiting the scope of assessment to only these three sectors were mentioned in Chapter 5. According to an overview conducted by King Abdullah City for Atomic and Renewable Energy (KACARE), power generation and water desalination consumes more than 50% of Saudi's energy, while the transportation sector consumes about 21%[9].

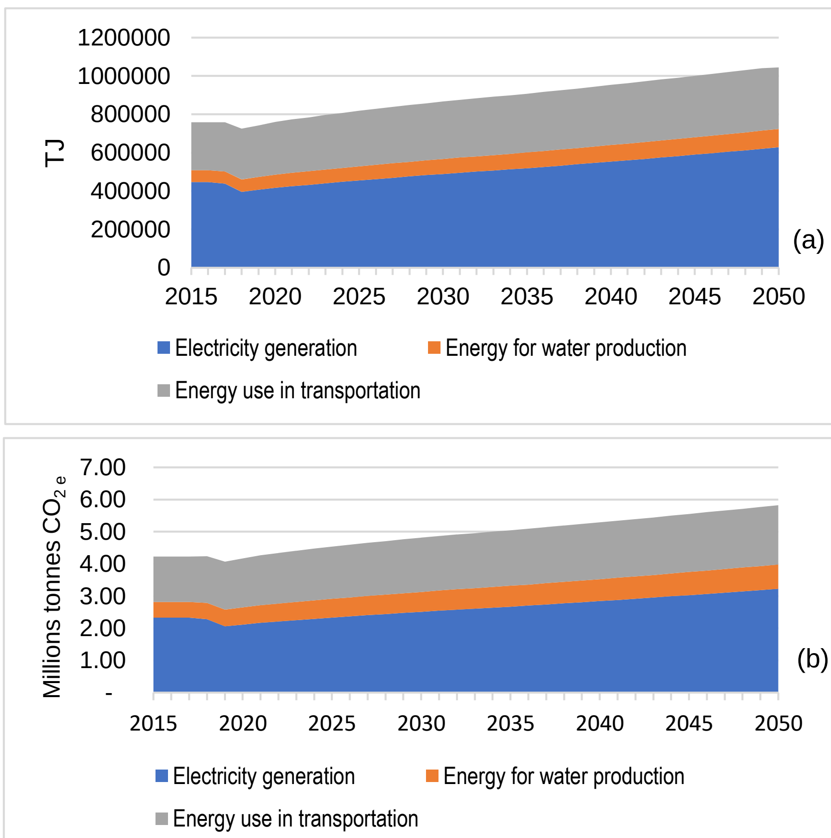


Figure 6-2 (a)Total primary energy demand, and (b) total GHG emissions (Direct and embodied).

[9] https://ksa-climate.com/wp-content/uploads/2018/11/Saudi-Arabias-sustainable-energy-program-in-a-Nutshell.pdf

In answer to question (1), Chapter 5 provided a review of the applicability of stock model, to study and analyse the built environment and its role in mitigating climate change. This chapter examines how the different scenarios associated with power generation, transportation, fuel consumption, and water production, as shown in Table 6-2 influence climate change mitigation policies.

6.3.2 GHG emissions reduction scenarios

A scenario-based approach was used to evaluate reductions in GHG emissions considering the different assumptions outlined in Table 6-2. The results of each scenario are presented in Figure 6-3.

For the base scenario, there will be an increase in GHG emissions of 40% the 2016 level. This increase is largely due to the assumption that the current electricity mix will be the same in 2050 (Oil (50.2%), Natural gas (49.8%)). The baseline scenario shows a predicted increase in GHG emissions of 40% the 2016 level. This scenario considered current practices and consumption trends across the three studied sectors. More details about this scenario were reported in Chapter 5 (medium scenario). Although, in this scenario, the housing stock would increase by 69% and the population by 71%, the emissions were estimated to increase by 40%. This is due to assumptions made in this scenario that a decline would be observed in regard to key factors. These factors include per capita data related to services demand, and related energy intensity factors. These assumptions were explained in Chapter 5, as they establish a decrease in energy intensity, due to an increase in efficiency and lower demand from the population as more tariffs are introduced.

Scenario 2 assumes that the electricity mix by 2050 will be 30% natural gas, 20% oil, 20% wind, and 30% solar. This is based on the assumption that the current plans of building solar and wind power plants will contribute to 50% of the current national energy mix. Moreover, this scenario assumes that there will be a 30% GHG emission reduction in emissions related to transportation and water production. This reduction of GHG emissions related to transportation assumes an increase in fuel efficiency and a higher proportion of public transportation, whereas missions related to water production assume a decrease of 30% due to using more advance and efficient systems at desalination plants (e.g., reverse osmosis (RO) membrane systems). Based on these assumptions, GHG emissions will decrease by 38% of the 2016 level by 2050.

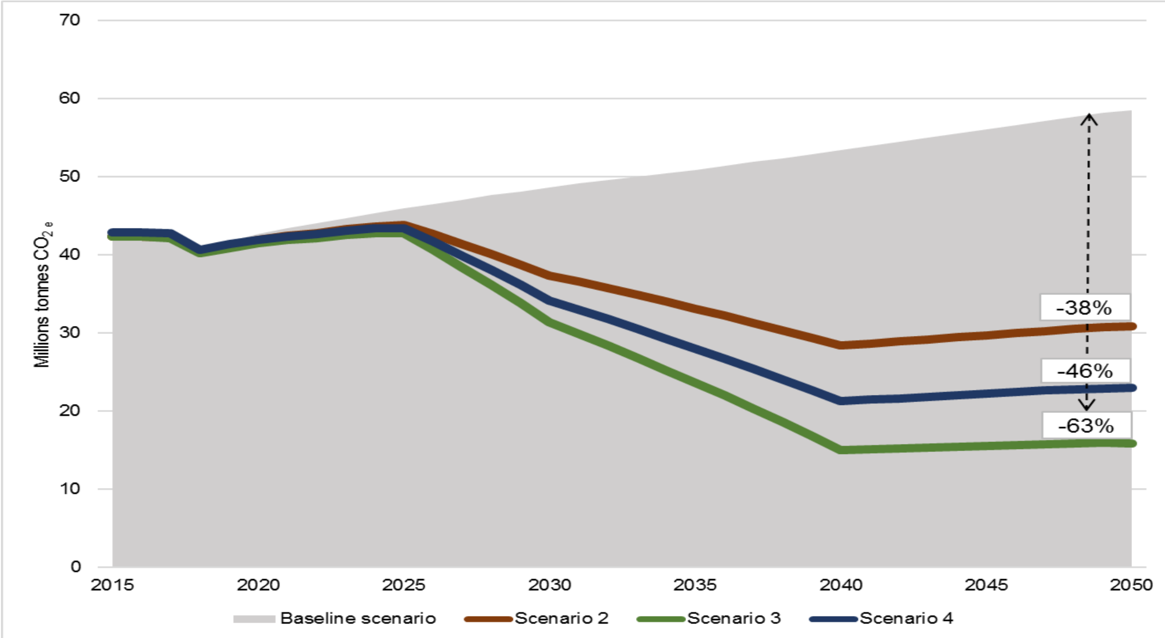


Figure 6-3 GHG emissions reduction compared to the baseline scenario.

Scenario 3 assumes that the current plans for building solar and wind power plants will contribute to 100% of the current national energy mix (50% wind and 50% solar). Also, this scenario assumes that there be a 40% GHG emission reduction in emissions related to transportation and water production. Emissions related to water production assumes a decrease of 40%, due to using more advance and efficient systems at desalination plants and solar energy and emissions related to on-road vehicles assumes an increase in fuel efficiency and a higher share of public transportation. Based on these assumptions, there will a decrease in GHG emissions by 63% of the 2016 level by 2050.

In regards to scenario 4, it assumes that the current plans for building solar power plants will contribute to 50% of the energy mix and the other 50% will be from natural gas. Also, it assumes that emissions related to water production will a decrease of 50%, due to using more advanced and efficient systems at desalination plants and solar energy. It also assumes a decrease by 50% in emissions related to on-road vehicles due to an increase in fuel efficiency and a higher share of public transportation. In this scenario, GHG emissions will witness a decrease by 46% of the 2016 level by 2050.

To summarise, scenarios 2, 3 and 4, reported a reduction in GHG emissions of 38%, 63% and 46% respectively. As further indicated in Figure 6-4, the energy generation sector has the greatest potential to reduce GHG emissions. In scenarios 2, 3 and 4, it was assumed that renewable energy would contribute a different percentage to the national energy mix.

In scenarios 2 and 4, renewable energy (solar, wind) contributes about 50%. However, in scenario 4, the only fossil fuel used in energy production was natural gas, whereas in scenario 2 both oil and natural gas were used. This signifies the importance of limiting reliance on fossil fuels when embarking on any GHG mitigation policies. Scenarios (2-4) suggested that despite a significant increase in stock size and population by 2050, a GHG emissions reduction of 38% to 63% can be attained. While some of these scenarios represent extreme alternatives, they nevertheless shed light on pathways going forward to tackle climate change.

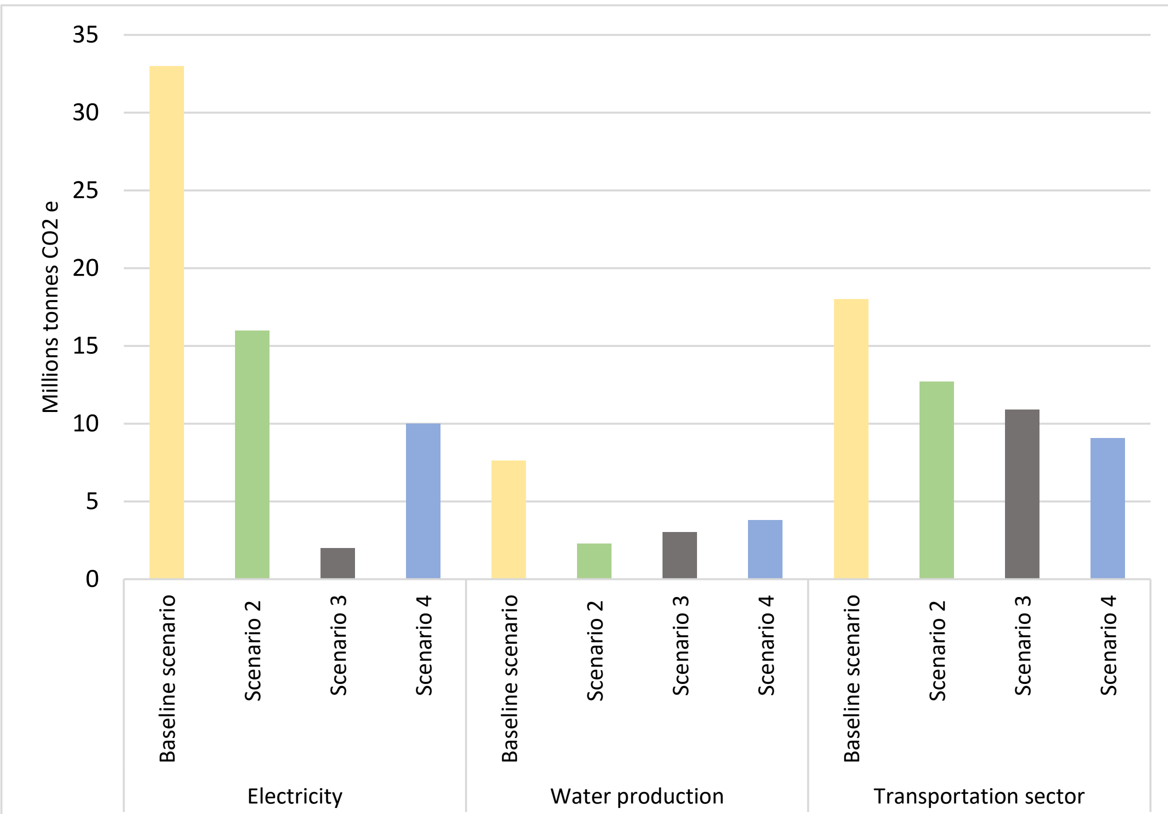


Figure 6-4 GHG emissions reduction by sector.

6.4 Model limitations

Although the model provided an estimate of GHG emissions for future stock, this estimation is based on ecoinvent v3.6 (released 2019). This estimation assumed no changes in temporal upstream and downstream systems. However, the current approach provides a reasonable estimation strategy, to provide necessary information to decision-makers regarding climate change mitigation pathways, given the fact that a number of recent reports call for immediate action on climate change policies.

Moreover, the model did not consider the full life cycle of the reviewed services. As technology advances in relation to recycling carbon dioxide, the full impact of change may differ from considering only upstream effects (Quadrelli *et al.*, 2011).

Although the model assesses GHG reduction scenarios, it does not consider the rebound effects of these policies. This could be overcome by applying a holistic assessment of the mitigation policies that address the interplay between the different sectors impacted by such policies.

Finally, the assessed mitigation polices did not address lifestyle changes, such as occupant behaviour and demand for services. A full assessment analysing the social aspects of GHG mitigation policies is therefore recommended as vital.

6.5 Discussion

The use of stock dynamic model within the context of a developing country provides a new approach to analysing the impact of housing stock. It extends the current stock model to include service in-use as a means to analyse related energy flows and the associated environmental impact. Based on stock-driven model energy, the demand associated with housing stock and the population itself is estimated. The applied model provides an understanding of the environmental impacts known to relate to the development of housing stock.

As the results showed, a stock dynamic approach is essential to understanding complicated and dynamic systems, and providing insights into the environmental impacts associated with the resources demanded by future housing stock. When applying the stock dynamic model for evaluating GHG emissions mitigation policies, the results illustrate the usefulness of the model as it describes the cause-effect relationship between stock development and the environment.

The scenario-based assessment shows further GHG emissions reduction are possible when additional measures are included. For example, frequent renovations to current housing stock can generate further energy savings and thereby lower the level of GHG emissions related to energy use.

6.6 Conclusion

This chapter showed the potential role that housing stock can play in reducing the city's energy demand and related GHG emissions. This role was analysed using a scenario-based assessment of different policies indented to reduce the impact of housing stock. Although the assessment was limited in scope, the results attained can serve as a basis upon which to conduct future holistic assessment.

The results suggested that the desired GHG emissions reduction (50%) is attainable, although the assessment was focused on changes from the supply side. A combination of different GHG reduction measures can create higher levels of reduction in the long term. This means that other aspects need to be considered, including related social and economic factors.

.

Chapter 7 **Conclusion**

This chapter concludes the study, and provides the context employed when developing the model used in this research. It also outlines the research questions, and summarizes the findings of each chapter, relating the findings to the research questions. The main contribution of this study is also summarized. This chapter concludes with recommendations for future work.

7.1 Introduction

This thesis has developed and extended a material flow analysis model using three cases: the first was to assess the sustainability of the urban system (Riyadh city), the second was to explore the long-term dynamics of Riyadh's residential housing stocks, and the third was to assess the impact of different climate change mitigation measures related to housing stock. The model used in the first stage was based on static material flow analysis, and was extended to include general biophysical, and socio-economic indicators. Then, LCA was applied to assess the environmental impacts of material and energy flows. This integrated approach was applied to Riyadh's housing stock including service in-use indicators to fisrt assess future development impacts and second to evaluate several GHG mitigation policies.

7.2 Results in relation to the research questions

The overall goal of the research was to establish a robust method to move the MFA framework beyond accounting and towards strategy development. To accomplish this goal, this research proposed integrating three methods: MFA, Stock Dynamic, and LCA, into a systematic approach. The overall objective was to use MFA and DMFA in combination with LCA to support the transition of Riyadh's current built environment to a sustainable urban environment. Other subsequent objectives were also developed. Several questions were posed at the start of this thesis to achieve the objectives of the study.

What are the environmental impacts of an urbanizing population? (Chapters 2, 4)

Considering the case of Riyadh city, as highly characterised by its rapid urban growth, a question was asked in relation to the impacts of growth. To answer this question, a review of current tools was undertaken to help assess such impacts. Tools such as MFA were identified as a useful approach to understanding the impacts of rapid population growth in terms of demand for resources. With the help of the MFA approach, resource consumption within the city was determined, and a temporal trend established. Furthermore, introducing the LCA method into the equation made it possible to assess the environmental footprint of the city's population over time, as reported on a per capita basis.

What are the most influential factors through which these impacts occur? (Chapter 4)

The study developed a set of indicators designed to identify the main driving factors that influence growth in demand for resources. The set of indicators presented included socioeconomic and biophysical. The former were designed to analyse the social aspect of urban development, while the latter captured changes in the city's ecosystem. A data collection exercise was conducted, and results reported. The findings helped clarify those factors that had an impact on temporal trends in resource consumption. For instance, the temporal increase in energy mobile consumptions was explained by automobile ownership, trips per day, average distance per trip. Other examples included the relationship between changes in population lifestyle (e.g., floor area per capita) and floor demand.

How will the demand for housing floor area and related construction materials in Riyadh develop over the next decades, in view of the ongoing urbanization? (Chapter 5)

Combining the proposed stock dynamic model with intensity factors related to construction materials, the housing floor area demand for 2050 was estimated. Although the findings suggested a reduction in housing demand from additional population by 2050, they show an increase in demand arising from buildings being retired as they reach their end of their life. The findings also showed an increase in demolition activities in the near future (2035 and onward), which signified the role of recycling as a way to minimize related environmental impacts. Moreover, the study investigated different growth scenarios, and assessed associated impacts. These scenarios represent low, medium, and high growth.

How can dynamic stock models be extended to include both direct and indirect energy consumption and carbon emissions, and what are the critical assumptions and variables? (Chapter 5)

This research question was investigated based on the stock DMFA model using Riyadh's housing stock as a case study. It used the findings reported in Chapter 3 that identified the main driving forces of stock development (e.g., floor area per capita, population growth rate per annum). The study extended the model's scope by adding two subsystems. The first related to service in-use, and the second combined LCA with the main system and the service in-use subsystem. Using this method, the direct and indirect energy consumption was estimated. The trends for inflows and outflows were observed, and the related environmental impact assessed. Furthermore, the study identified, through a sensitivity analysis, that the main critical factor related to stock demand was population lifestyle, which determined floor area per capita. The model was less sensitive to assumptions concerning the building's lifetime. Validating the model with real data showed the model is valid and useful for estimating and assessing impacts related to housing stock.

What will be the environmental impacts related to housing stock development? (Chapter 5)

This question was answered by introducing service in-use intensity factor. The scope was limited to three main services (electricity, water, transportation). Building on findings from previous Chapters (3, 4), a trendline was estimated as the three scenarios were developed to estimate future demand for services. Limiting the scope of assessment to climate change, life cycle assessment was applied, and the environmental impacts associated with demand were reported. Then, using year 2016 as the reference year, all three scenarios were compared and analysed. This was intended to help develop related climate change mitigation policies to be assessed in question 5.

How can a stock dynamic model be applied to assess climate change mitigation policies? (Chapter 6)

The reported outcome when integrating the stock dynamic with LCA served as the basis when answering this question. Current climate change mitigation policies were reviewed, and the emissions reduction required by 2050 reported. Adding service in-use indicators to the stock model made it possible to assess energy demand and related impacts based on a variety of different development scenarios. For each scenario, GHG emissions were estimated and analysed. The results showed the potential contribution of the stock dynamic model combined with life cycle assessment when providing an estimate about the level of effect each policy had in terms of achieving the GHG emissions reduction target by 2050.

7.3 Study main contribution

The merits of this research, and its contributions to the existing literature, can be summarized as follows:

1. It extends the current MFA framework to enable the assessment of the sustainability of urban systems in the context of a developing country, namely that of Riyadh, Saudi Arabia. The proposed framework integrates a set of indicators that describe the evolution of the built environment, and changes in the population's social characteristics over time using a static MFA;
2. It expands the scope of the analysis provided by the MFA approach by combining the MFA results with an LCA;

3. The results of the urban MFA-LCA framework constitute the first attempt to provide an environment-based assessment of the built environment in Saudi Arabia;
4. The stock-dynamic model proposed constitutes the first application of this approach in the region concerned;
5. This study adds new knowledge to the extant literature regarding the application of the stock dynamic model in the context of developing countries;
6. This study furthers the application of the current stock dynamic model, which is based on an MFA, to environmentally assess the interplay between housing stock and material and energy flows, using an LCA.

7.4 Study limitations

The study's limitations are as follows.

- The urban MFA study conducted in this thesis was limited in its scope, due to data availability and the several approaches applied to overcome missing data.
- The MFA applied in this thesis did not offer a full account of the city's input and output flows; and was limited in its scope regarding what are considered main flows.
- The integrative framework was focused on the environmental side of the sustainability equation. Analysis of the social and economic aspects of sustainability were beyond the scope of this thesis.
- Integrating the life cycle assessment with MFA led to an assessment of complex systems based on one static snapshot of time. This limitation is regarded as common to LCA in general.
- Intensity factors applied in the stock dynamic model in this thesis were not precise for every building, but are considered to be based on reasonable assumptions in the model when projecting possible future development scenarios.
- The DMFA model was limited in its application to the housing stock, and did not include infrastructure or other building types.
- The potential impact of climate change mitigation policies was assessed considering housing stock only, as including other factors was not relevant to the research problem investigated in the thesis.

7.5 Conclusion

The predicted increase in city populations results in greater investment in infrastructure to manage population growth. It is imperative for cities, as they continue to grow, to model the development of the built environment over years to assess associated environmental impacts and implement sustainable development goals. Methods such as MFA and LCA have proven to be well suited for this objective.

In the first part of this thesis (Chapter 4), the MFA framework was enhanced by synthesizing critical factors, including biophysical and socio-economic indicators, with the goal of moving MFA beyond an accounting framework towards a strategic planning framework. This framework was applied over different periods of time to investigate how key indicators change over time. Second, results from the MFA stage were utilized as an inventory of input and output which can then be supplied to the LCA stage to assess the environmental impacts of these flows. Sustainability in Riyadh's ecosystem was analysed and evaluated using indicators based on the integrative approach. The application of the proposed framework for urban development in Riyadh show it is unsustainable over the studied period. The environmental pressures of the main flows are reported across five impact categories. These five impact categories are selected as representing impacts that are critical to the case study. The results indicate that the energy consumption component is the main contributor to all impacts, with the exception of freshwater ecotoxicity, to which energy mobile contributes the most. Groundwater production contributes most to the water potential use impact category. On a per capita basis, the city showed an increase in most of the MFA components. Throughout the literature there were many definitions of sustainable systems. However, in this study, sustainability was defined from the perspective of efficiency in urban flows over the studied period. The results indicate that a proposed integrative approach can be used to quantify and assess these flows, while revealing information about the social and economic characteristics of the city.

The second part of the thesis (Chapter 5 onwards) applied a DMFA approach, as the chapter was motivated by the fact that the built environment is characterised by a long service lifetime, so a long-term perspective helps advance understanding of the dynamics of the system, its critical variables, and can also provide valuable information to support the implementation of sustainable strategies. The potential use of DMFA when analysing past and future trends in housing stock and associated flows was investigated. The study reported results in pathways complementing DMFA with LCA to assess the environmental impacts associated with the housing stock. The findings emphasised that a framework combining stock dynamics and LCA can support the development of policies related to urban sustainability and climate change mitigation. The study also reported on the importance of DMFA when analysing changes and the long-term effects arising from the built environment. This is because the built environment is characterised by a long service lifetime, so a long-term perspective based on DMFA was proven to be crucial for providing valuable information to support the implementation of sustainable strategies. From an urban sustainable development point of view, the stock-dynamic LCA model was useful as a means of providing a system-based understanding of the embedded impacts of housing stock development.

The final part of the thesis (Chapter 6) evaluated the potential role of the stock dynamic model in assessing climate change mitigation policies. The findings showed the potential role housing stock can play in analysing pathways to reduce the city's energy demand and related GHG emissions. This role was analysed using a scenario-based assessment of different policies aimed at reducing the impacts of housing stock. Although the assessment was limited in scope, the results can serve as a basis to conduct future holistic assessment.

7.6 Recommendations and future work

The MFA framework applied in this thesis can be improved and expanded upon. Some points to consider in this regard are as follows.

- As indicated throughout this thesis, conducting an MFA study involves collecting data according to a vast quantity of processes. Future work is needed to develop standardized data to facilitate conducting MFA at the urban scale considering factors more critically related to cities in developing countries.
- The quantification of environmental burdens associated with material and energy flows need to be addressed using more detailed data pertaining to these flows, so that results can provide a clearer understanding of these impacts and help direct policies to curb resource consumption.
- The stock dynamic model has the potential to provide valuable insights into the assessment of the built environment; however, there are several future directions indicated to improve this potential.
- The model developed in this thesis relied on aggregated data, and future work needs to consider bottom-up approaches to provide detailed information regarding building stock.

- Although this study attempted to include service in-use factors, aggregated data was also used and further analysis is recommended to disaggregate the data according to building type.
- The model was limited in its scope to residential buildings, and so there is a need to study other building types in the future. This needs to consider determining factors.
- To present and transfer the model results into action platforms for households is recommended for future research.
- Including economic models with a stock dynamic and LCA would be worth investigating and so is recommended for future work.

Appendix A

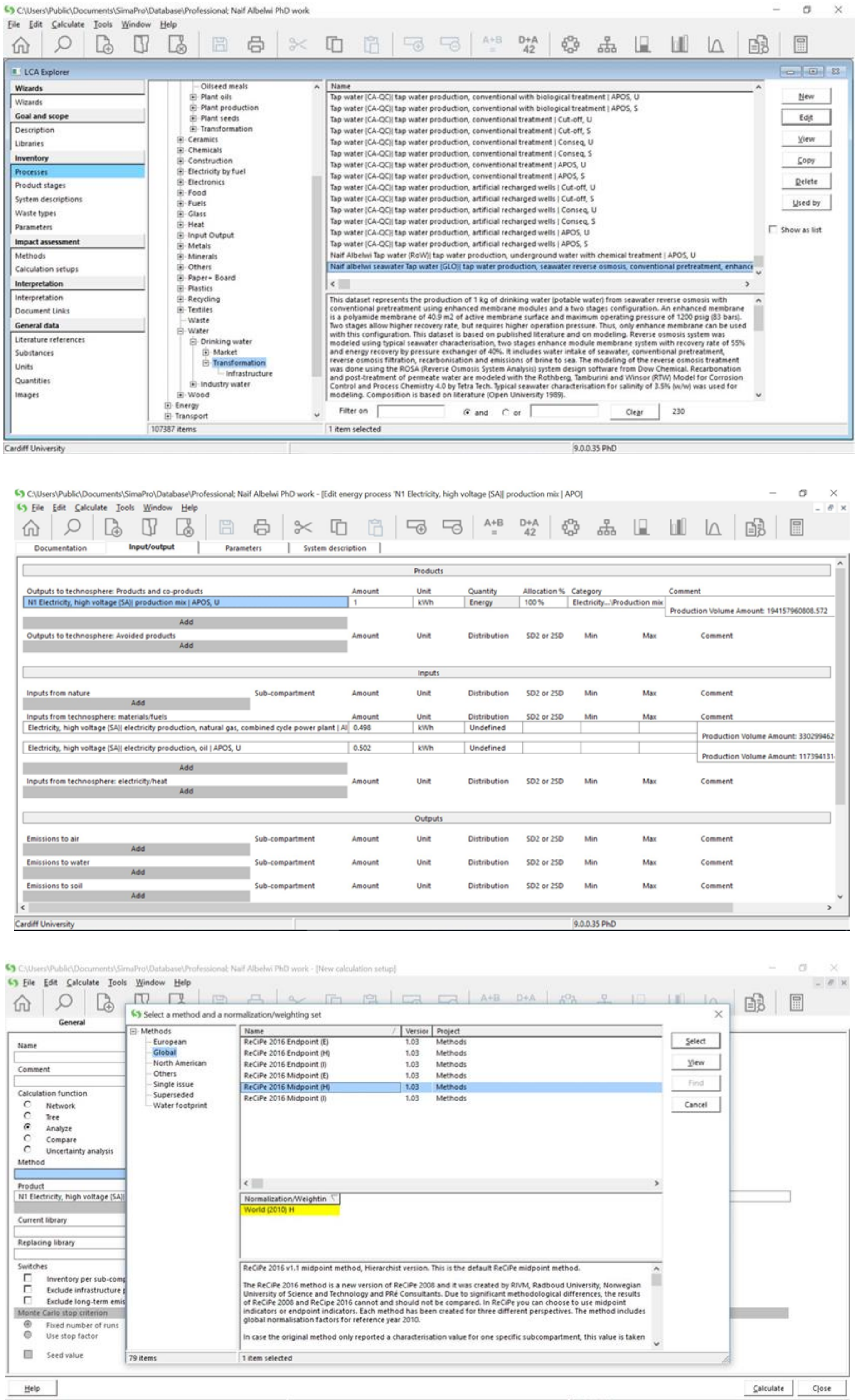


Figure 1 The process of selecting LCA elements and impact assessment method in SimaPro

Appendix B

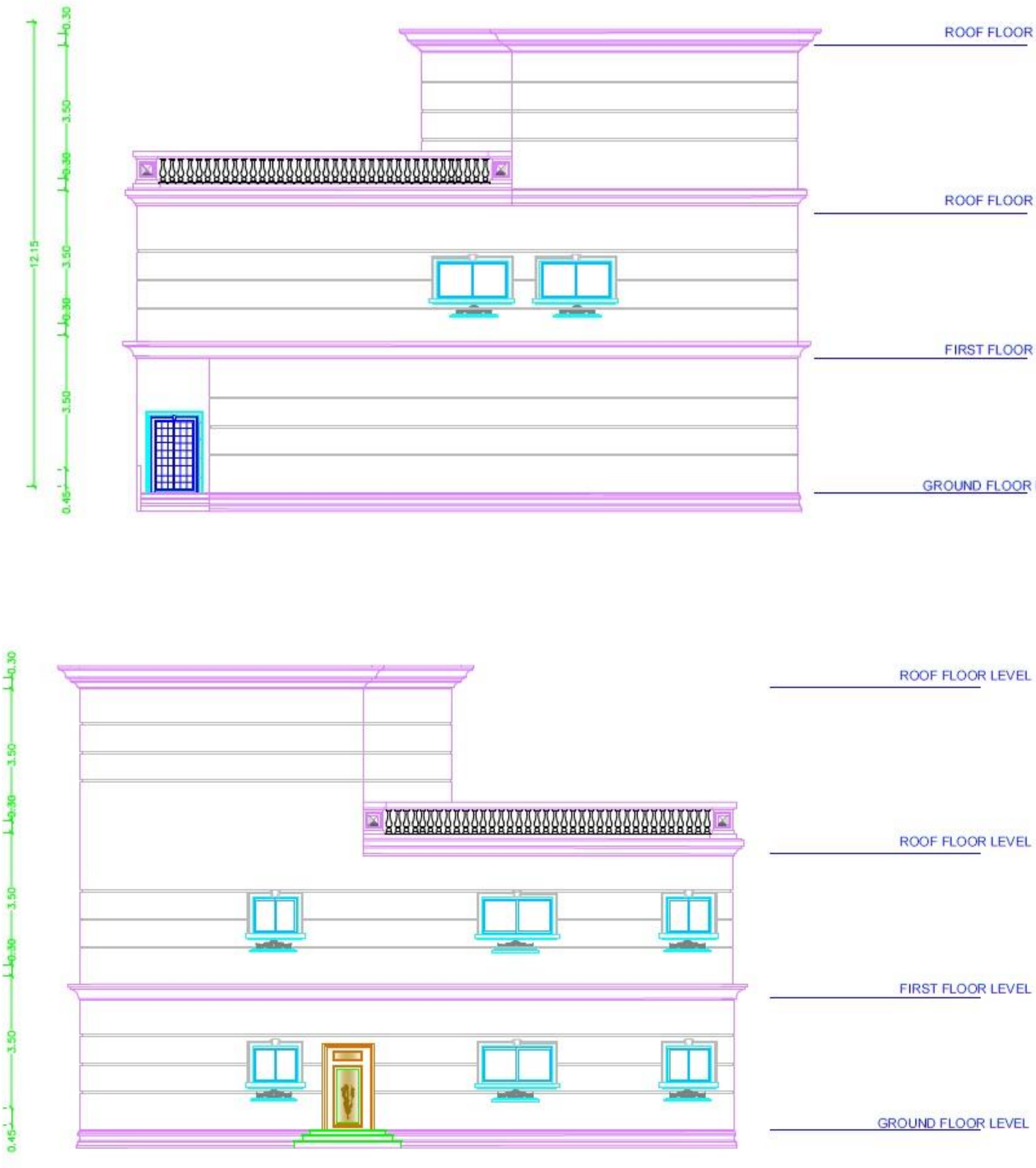


Figure 2 Architectural drawing for Villa 1

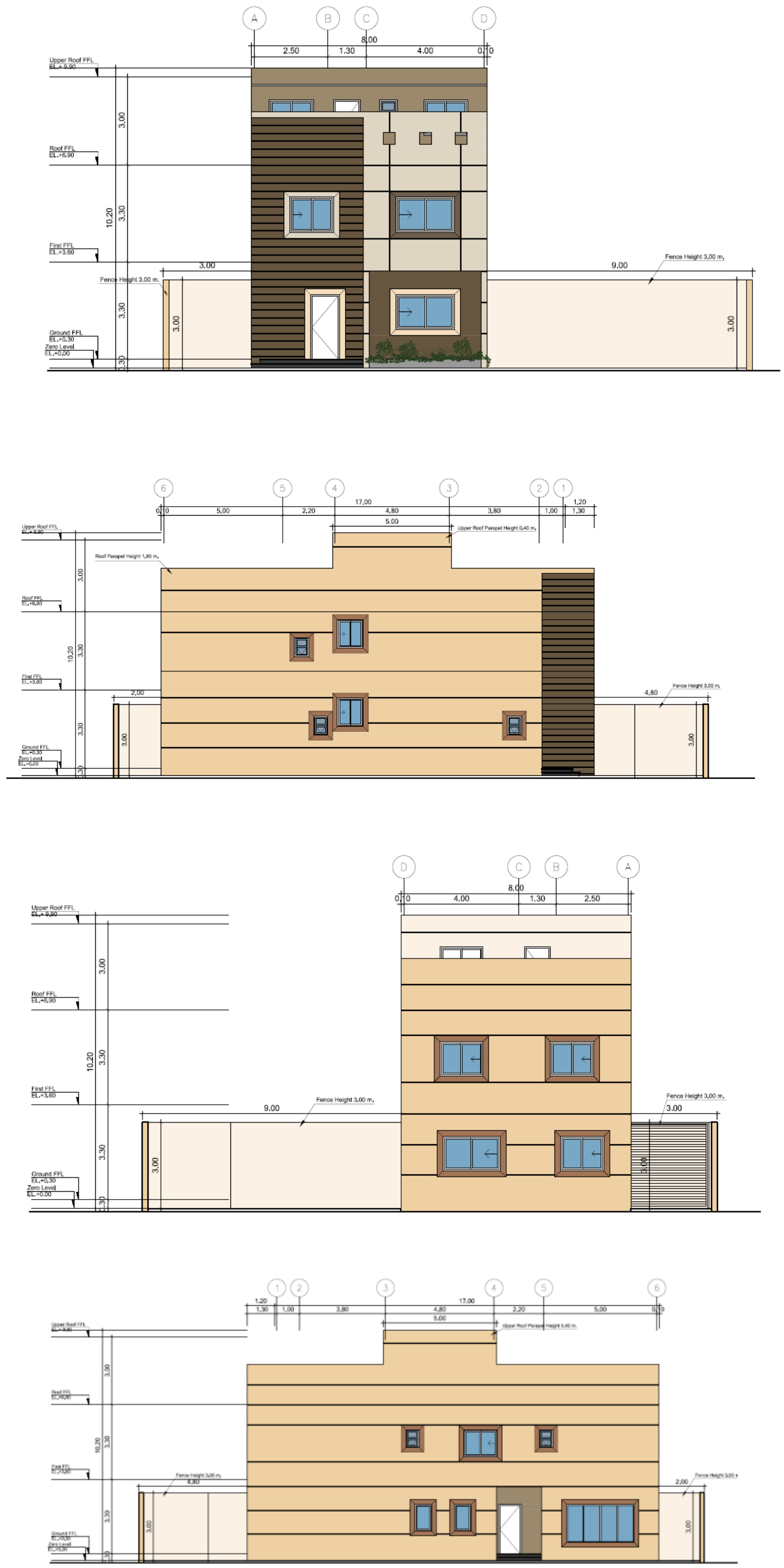
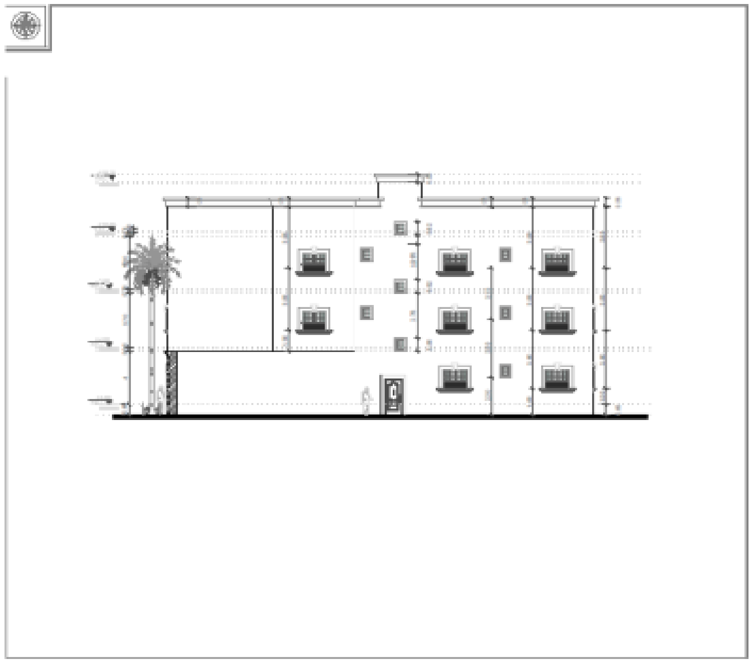


Figure 3 Architectural drawing for Villa 2 (precast)



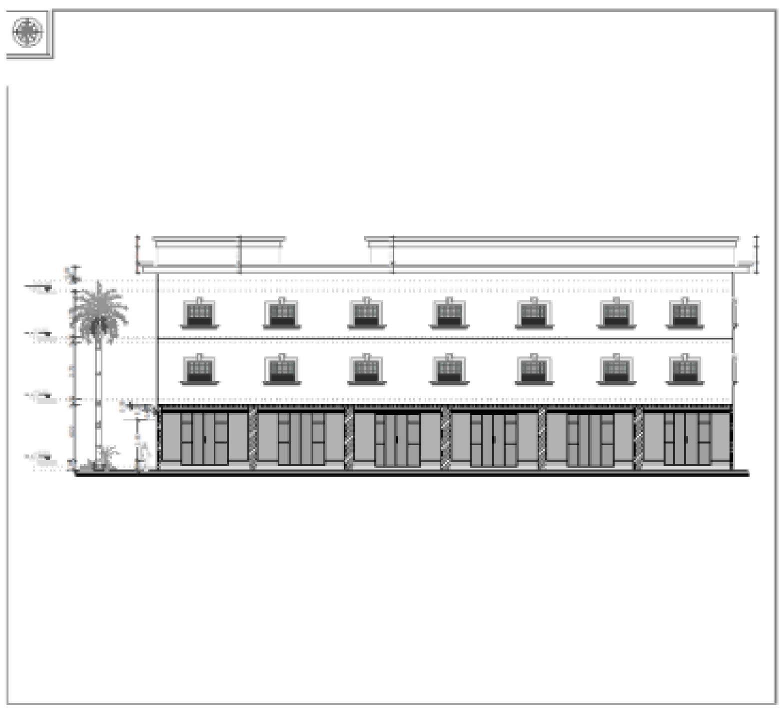


Figure 4 Architectural drawing for Apartment building

References

Al-ahmad, M. (n.d.). Life span of KSA buildings 25 years. Retrieved August 15, 2019, from https://www.arabnews.com/news/519231

Al-Karaghouli, A. and Kazmerski, L. L. (2013) ‘Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes’, *Renewable and Sustainable Energy Reviews*, 24, pp. 343–356. doi: 10.1016/j.rser.2012.12.064.

Albelwi, N., Kwan, A. and Rezgui, Y. (2017a) ‘Temporal Trends Of Energy Consumption And CO2 Emissions In Riyadh, Saudi Arabia’, *International Journal of Energy Production and Management*. WIT Press, 2(2), pp. 165–172.

Albelwi, N., Kwan, A. and Rezgui, Y. (2017b) ‘Using Material and Energy Flow Analysis to Estimate Future Energy Demand at the City Level’, *Energy Procedia*, 115, pp. 440–450. doi: https://doi.org/10.1016/j.egypro.2017.05.041.

Albertí, J. *et al.* (2017) ‘Towards life cycle sustainability assessment of cities. A review of background knowledge’, *Science of The Total Environment*, 609, pp. 1049–1063. doi: https://doi.org/10.1016/j.scitotenv.2017.07.179.

Aldagheiri, M. (2009) ‘The role of the transport road network in the economic development of Saudi Arabia’, in *WIT Transactions on The Built Environment*. WIT Press, pp. 275–285. doi: 10.2495/UT090251.

Aldalbahi, M. and Walker, G. (2015) ‘Attitudes and Policy Implications of Urban Growth Boundary and Traffic Congestion Reduction in Riyadh , Saudi Arabia’, in *International Conference Data Mining, Civil and Mechanical Engineering (ICDMCME’2015)*, pp. 56–64. doi: http://dx.doi.org/10.15242/IIE.E0215016.

Alfonso Piña, W. H. and Pardo Martínez, C. I. (2014) ‘Urban material flow analysis: An approach for Bogotá, Colombia’, *Ecological Indicators*, 42, pp. 32–42. doi: 10.1016/j.ecolind.2013.10.035.

Alkhathlan, K. and Javid, M. (2015) ‘Carbon emissions and oil consumption in Saudi Arabia’, *Renewable and Sustainable Energy Reviews*. Elsevier, 48, pp. 105–111. doi: 10.1016/j.rser.2015.03.072.

Almulhim, M. S. M., Hunt, D. V. L. and Rogers, C. D. F. (2020) ‘A Resilience and Environmentally Sustainable Assessment Framework (RESAF) for Domestic Building Materials in Saudi Arabia’, *Sustainability*. Multidisciplinary Digital Publishing Institute, 12(8), p. 3092.

Alnatheer, O. (2005) ‘The potential contribution of renewable energy to electricity supply in Saudi Arabia’, *Energy Policy*, 33(18), pp. 2298–2312. doi: 10.1016/j.enpol.2003.12.013.

Alrashed, F. and Asif, M. (2014) ‘Trends in residential energy consumption in Saudi Arabia with particular reference to the Eastern Province’, *Journal of Sustainable Development of Energy, Water and Environment Systems*, 2(4), pp. 376–387. doi: 10.13044/j.sdewes.2014.02.0030.

Alyousef, Y. and Abu-ebid, M. (2012) ‘Energy Efficiency Initiatives for Saudi Arabia on Supply and Demand Sides’, *Energy Efficiency - A Bridge to Low Carbon Economy, Dr. Zoran Morvaj (Ed.), ISBN: 978-953-51-0340- 0*, pp. 280–308. doi: 10.5772/38660.

Alyousef, Y. and Varnham, A. (2010) ‘Saudi Arabia’s National Energy Efficiency Programme: Description, achievements and way forward’, *International Journal of Low-Carbon Technologies*, 5(4), pp. 291–297. doi: 10.1093/ijlct/ctq017.

Anderson, J. E., Wulfhorst, G. and Lang, W. (2015) ‘Expanding the use of life-cycle assessment to capture induced impacts in the built environment’, *Building and Environment*. Elsevier Ltd, 94, pp. 403–416. doi: 10.1016/j.buildenv.2015.08.008.

Asif, M. *et al.* (2017) ‘Life Cycle Assessment of a Three-Bedroom House in Saudi Arabia’, *Environments*, 4(3), p. 52. doi: 10.3390/environments4030052.

Augiseau, V. and Barles, S. (2017) ‘Studying construction materials flows and stock: A review’, *Resources, Conservation and Recycling*, 123, pp. 153–164. doi: https://doi.org/10.1016/j.resconrec.2016.09.002.

Baccini, P. and Brunner, P. H. (2012) *Metabolism of the Anthroposphere Analysis, Evaluation, Design*. Second Edi. MIT Press.

Bai, J. *et al.* (2019) ‘Spatial and temporal variations of embodied carbon emissions in China’s infrastructure’, *Sustainability (Switzerland)*, 11(3). doi: 10.3390/su11030749.

Bao, Z. *et al.* (2010) ‘A Review of Material Flow Analysis’, *Management and Service Science (MASS), 2010 International Conference on*, pp. 1–8. doi: 10.1109/ICMSS.2010.5577113.

Barau, A. S. and Al Hosani, N. (2014) ‘Prospects of environmental governance in addressing sustainability challenges of seawater desalination industry in the Arabian Gulf’, in *Energy and Environment in Saudi Arabia: Concerns & Opportunities*. Elsevier Ltd, pp. 27–51. doi: 10.1016/j.envsci.2015.02.008.

Barles, S. (2009) ‘Urban metabolism of Paris and its region’, *Journal of Industrial Ecology*, 13(6), pp. 898–913. doi: 10.1111/j.1530-9290.2009.00169.x.

Barles, S. (2010) ‘Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues’, *Journal of Environmental Planning and Management*, 53(4), pp. 439–455. doi: 10.1080/09640561003703772.

Bartelmus, P. (2003) ‘Dematerialization and capital maintenance: two sides of the sustainability coin’, *Ecological Economics*, 46(1), pp. 61–81. doi: 10.1016/S0921-8009(03)00078-8.

Beloin-Saint-Pierre, D. *et al.* (2017) ‘A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation’, *Journal of Cleaner Production*, 163, pp. S223–S240. doi: 10.1016/j.jclepro.2016.09.014.

Bergsdal, H., Brattebø, H., Bohne, Rolf A., *et al.* (2007) ‘Dynamic material flow analysis for Norway’s dwelling stock’, *Building Research & Information*, 35(5), pp. 557–570. doi: 10.1080/09613210701287588.

Bergsdal, H., Brattebø, H., Bohne, Rolf A, *et al.* (2007) ‘Dynamic material flow analysis for Norway’s dwelling stock’, *Building Research & Information*, 35(5), pp. 557–570. doi: 10.1080/09613210701287588.

Bergsdal, H. (2009) ‘Dynamic modeling and analysis of stocks and flows in building systems’, *Department of Hydraulic and Environmental Engineering*. Available at: http://urn.kb.se/resolve?urn=urn:nbn:no:ntnu:diva-6639.

Bergsdal, H., Bohne, R. A. and Bratteb, H. (2007) ‘Projection of construction and demolition waste in Norway’, *Journal of Industrial Ecology*, 11(3), pp. 27–39. doi: 10.1162/jiec.2007.1149.

Binder, C. R. (2007) ‘From material flow analysis to material flow management Part I: social sciences modeling approaches coupled to MFA’, *Journal of Cleaner Production*, 15(17), pp. 1596–1604. doi: 10.1016/j.jclepro.2006.08.006.

Bleischwitz, R. *et al.* (2018) ‘Extrapolation or saturation – Revisiting growth patterns , development stages and decoupling’, *Global Environmental Change*. Elsevier Ltd, 48, pp. 86–96. doi: 10.1016/j.gloenvcha.2017.11.008.

BP Statistical Review of World Energy (2017). Available at: http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html.

Brattebø, H. *et al.* (2009) 'Exploring built environment stock metabolism and sustainability by systems analysis approaches', *Building Research & Information*, 37(5–6), pp. 569–582. doi: 10.1080/09613210903186901.

Browne, D., O'Regan, B. and Moles, R. (2005) 'A comparative analysis of the application of sustainability metric tools using Tipperary Town, Ireland, as a case study', *Management of Environmental Quality: An International Journal*, 16(1), pp. 37–56. doi: 10.1108/14777830510574335.

Brunner, P. H. and Rechberger, H. (2016) *Practical Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers*. CRC press.

Buchner, H. *et al.* (2015) 'Dynamic material flow modeling: An effort to calibrate and validate aluminum stocks and flows in austria', *Environmental Science & Technology*, 49(9), pp. 5546–5554. doi: 10.1021/acs.est.5b00408.

Butt, A. A. *et al.* (2018) *Framework for Urban Metabolism and Life Cycle Assessment of Hardscape*.

Byrne, S. and O'Regan, B. (2016) 'Material flow accounting for an Irish rural community engaged in energy efficiency and renewable energy generation', *Journal of Cleaner Production*. Elsevier Ltd, 127, pp. 363–373. doi: 10.1016/j.jclepro.2016.03.069.

Carbajo, R. and Cabeza, L. F. (2019) 'Sustainability and social justice dimension indicators for applied renewable energy research: A responsible approach proposal', *Applied Energy*. Elsevier, 252(August 2018), p. 113429. doi: 10.1016/j.apenergy.2019.113429.

Castro, M. *et al.* (2019) 'Promotion of Plant Growth in Soils Degraded by Urban Mining Through the Addition of Construction and Demolition Waste', *The Journal of Solid Waste Technology and Management*. The Journal of Solid Waste Technology and Management, 45(1), pp. 13–20.

Cellura, M., Longo, S. and Mistretta, M. (2011) 'Sensitivity analysis to quantify uncertainty in life cycle assessment: the case study of an Italian tile', *Renewable and Sustainable Energy Reviews*. Elsevier, 15(9), pp. 4697–4705.

Chen, W. Q. and Graedel, T. E. (2015) 'Improved alternatives for estimating in-use material stocks', *Environmental Science and Technology*, 49(5), pp. 3048–3055. doi: 10.1021/es504353s.

Cheng, L. *et al.* (2019) '2018 Continues Record Global Ocean Warming', *Advances in Atmospheric Sciences*, 36(3), pp. 249–252. doi: 10.1007/s00376-019-8276-x.

Chester, M., Pincetl, S. and Allenby, B. (2012) 'Avoiding unintended tradeoffs by integrating life-cycle impact assessment with urban metabolism', *Current Opinion in Environmental Sustainability*. Elsevier B.V., 4(4), pp. 451–457. doi: 10.1016/j.cosust.2012.08.004.

Codoban, N. and Kennedy, C. A. (2008) 'Metabolism of neighborhoods', *Journal of urban planning and development*. American Society of Civil Engineers, 134(1), pp. 21–31.

Cohen, B. (2006) 'Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability', *Technology in Society*, 28(1–2), pp. 63–80. doi: 10.1016/j.techsoc.2005.10.005.

Colombier, M. and Li, J. (2012) 'Shaping climate policy in the housing sector in northern Chinese cities', *Climate Policy*, 12(4), pp. 453–473. doi: 10.1080/14693062.2011.592665.

Condeixa, K., Haddad, A. and Boer, D. (2017) 'Material flow analysis of the residential building stock at the city of Rio de Janeiro', *Journal of Cleaner Production*, 149, pp. 1249–1267. doi: https://doi.org/10.1016/j.jclepro.2017.02.080.

Conke, L. S. and Ferreira, T. L. (2015) 'Urban metabolism: Measuring the city's contribution to sustainable development', *Environmental Pollution*, 202, pp. 146–152. doi: 10.1016/j.envpol.2015.03.027.

Cuéllar-Franca, R. M. and Azapagic, A. (2012) 'Environmental impacts of the UK residential sector: Life cycle assessment of houses', *Building and Environment*. Pergamon, 54, pp. 86–99. doi: 10.1016/J.BUILDENV.2012.02.005.

Dahlbo, H. *et al.* (2015) 'Construction and demolition waste management - A holistic evaluation of environmental performance', *Journal of Cleaner Production*, 107, pp. 333–341. doi: 10.1016/j.jclepro.2015.02.073.

Darwish, M., Hassabou, A. H. and Shomar, B. (2013) 'Using Seawater Reverse Osmosis (SWRO) desalting system for less environmental impacts in Qatar', *Desalination*. Elsevier B.V., 309, pp. 113–124. doi: 10.1016/j.desal.2012.09.026.

Dean, B. *et al.* (2016) *Towards zero-emission efficient and resilient buildings.: Global Status Report*. Global Alliance for Buildings and Construction (GABC).

Decker, E. H. *et al.* (2000) 'ENERGY ANDMATERIAL FLOW THROUGH THE URBAN ECOSYSTEM', *Annual Review of Environment & Resources*, pp. 685–740.

Delgado-Ramos, G. (2013) 'Climate change and metabolic dynamics in Latin American major cities', *WIT Transactions on Ecology and the Environment*, 179 VOLUME, pp. 39–53. doi: 10.2495/SC130041.

DeNicola, E. *et al.* (2015) 'Climate Change and Water Scarcity: The Case of Saudi Arabia', *Annals of Global Health*, 81(3), pp. 342–353. doi: https://doi.org/10.1016/j.aogh.2015.08.005.

Densley Tingley, D., Giesekam, J. and Cooper-Searle, S. (2018) 'Applying Circular Economic Principles to Reduce Embodied Carbon', in Pomponi, F., De Wolf, C., and Moncaster, A. (eds) *Embodied Carbon in Buildings: Measurement, Management, and Mitigation*. Cham: Springer International Publishing, pp. 265–285. doi: 10.1007/978-3-319-72796-7_12.

Dias, A. *et al.* (2018) 'Comparison of tools for quantifying the environmental performance of an urban territory', *Journal of Industrial Ecology*, 22(4), pp. 868–880. doi: 10.1111/jiec.12614.

Dias, A. C. *et al.* (2014) 'Environmentally extended input–output analysis on a city scale – application to Aveiro (Portugal)', *Journal of Cleaner Production*, 75, pp. 118–129. doi: https://doi.org/10.1016/j.jclepro.2014.04.012.

Dixit, M. K. *et al.* (2010) 'Identification of parameters for embodied energy measurement: A literature review', *Energy and Buildings*, 42(8), pp. 1238–1247. doi: https://doi.org/10.1016/j.enbuild.2010.02.016.

Dixon, T., Connaughton, J. and Green, S. (2018) *Sustainable Futures in the Built Environment to 2050*. Wiley Online Library.

Van Eck, N. J. and Waltman, L. (2007) 'VOS: A new method for visualizing similarities between objects', in *Advances in data analysis*. Springer, pp. 299–306.

Electricity and Cogeneration Regulatory Authority (2016) *Annual statistical booklet for electricity and seawater desalination industries*.

Elshkaki, A. *et al.* (2005) 'Dynamic stock modelling: A method for the identification and estimation of future waste streams and emissions based on past production and product stock characteristics', *Energy*, 30(8 SPEC. ISS.), pp. 1353–1363. doi: 10.1016/j.energy.2004.02.019.

Eurostat (2001) *Economy-wide material flow accounts and derived indicators A methodological guide*.

Facchini, A. *et al.* (2017) ‘The energy metabolism of megacities’, *Applied Energy*, 186, pp. 86–95. doi: https://doi.org/10.1016/j.apenergy.2016.09.025.

Fang, W. *et al.* (2017) ‘Accessing on the sustainability of urban ecological-economic systems by means of a coupled emergy and system dynamics model: A case study of Beijing’, *Energy Policy*. Elsevier, 100, pp. 326–337. doi: https://doi.org/10.1016/j.enpol.2016.09.044.

Finnveden, G. (2000) ‘On the limitations of life cycle assessment and environmental systems analysis tools in general’, *The International Journal of Life Cycle Assessment*, 5(4), p. 229. doi: 10.1007/BF02979365.

Finnveden, G. *et al.* (2009) ‘Recent developments in Life Cycle Assessment’, *Journal of Environmental Management*. Elsevier Ltd, 91(1), pp. 1–21. doi: 10.1016/j.jenvman.2009.06.018.

Fishman, T., Schandl, H. and Tanikawa, H. (2015) ‘The socio-economic drivers of material stock accumulation in Japan’s prefectures’, *Ecological Economics*, 113, pp. 76–84. doi: 10.1016/j.ecolecon.2015.03.001.

Frenken, K. (2009) ‘Irrigation in the Middle East region in figures AQUASTAT Survey-2008.’, *Water Reports*. Food and Agriculture Organization of the United Nations (FAO), (34).

Gallardo, C., Sandberg, N. H. and Brattebo, H. (2014a) ‘Dynamic-MFA examination of Chilean housing stock: long- term changes and earthquake damage’, *Building Research and Information*, 42(3), pp. 343–358. doi: 10.1080/09613218.2014.872547.

Gallardo, C., Sandberg, N. H. and Brattebo, H. (2014b) ‘Dynamic-MFA examination ofChilean housing stock: long- term changes and earthquake damage’, *Building Research and Information*, 42(3), pp. 343–358. doi: 10.1080/09613218.2014.872547.

García-Guaita, F. *et al.* (2018) ‘Integrating Urban Metabolism, Material Flow Analysis and Life Cycle Assessment in the environmental evaluation of Santiago de Compostela’, *Sustainable Cities and Society*, 40, pp. 569–580. doi: https://doi.org/10.1016/j.scs.2018.04.027.

General Authority for Statistics (2017) *Housing Survey*.

Giljum, S. *et al.* (2011) ‘A comprehensive set of resource use indicators from the micro to the macro level’, *Resources, Conservation and Recycling*. Elsevier B.V., 55(3), pp. 300–308. doi: 10.1016/j.resconrec.2010.09.009.

Goldstein, B. *et al.* (2013) 'Quantification of urban metabolism through coupling with the life cycle assessment framework: concept development and case study', *Environmental Research Letters*, 8, p. 035024. doi: 10.1088/1748-9326/8/3/035024.

Gonzalez-Garcia, S. *et al.* (2018) 'Assessing the sustainability of Spanish cities considering environmental and socio-economic indicators', *Journal of Cleaner Production*, 178, pp. 599–610. doi: https://doi.org/10.1016/j.jclepro.2018.01.056.

Göswein, V. *et al.* (2019) 'Dynamic Assessment of Construction Materials in Urban Building Stocks: A Critical Review', *Environmental Science & Technology*, 53(17), pp. 9992–10006. doi: 10.1021/acs.est.9b01952.

Götz, G. *et al.* (2017) 'Doing more with less (data): complexities of resource flow analysis in the Gauteng City-Region', *Environmental Research Letters*, 12(12), p. 125006. doi: 10.1088/1748-9326/aa7c21.

Grimm, N. B. *et al.* (2008) 'Global Change and the Ecology of Cities ', *Science*, 319(February), pp. 756–760.

Gude, V. G., Nirmalakhandan, N. and Deng, S. (2010) 'Renewable and sustainable approaches for desalination', *Renewable and Sustainable Energy Reviews*, 14(9), pp. 2641–2654. doi: https://doi.org/10.1016/j.rser.2010.06.008.

Hammond, G. P. and Jones, C. I. (2008) 'Embodied energy and carbon in construction materials', *Proceedings of the Institution of Civil Engineers - Energy*, 161(2), pp. 87–98. doi: https://doi.org/10.1680/ener.2008.161.2.87.

Harbi, F. Al and Csala, D. (2019) 'Saudi Arabia's Electricity: Energy Supply and Demand Future Challenges', in *2019 1st Global Power, Energy and Communication Conference (GPECOM)*, pp. 467–472. doi: 10.1109/GPECOM.2019.8778554.

Harvey, L. D. D. *et al.* (2014) 'Construction of a global disaggregated dataset of building energy use and floor area in 2010', *Energy and Buildings*. Elsevier B.V., 76, pp. 488–496. doi: 10.1016/j.enbuild.2014.03.011.

He, H. *et al.* (2017) 'Assessment on the energy flow and carbon emissions of integrated steelmaking plants', *Energy Reports*. Elsevier Ltd, 3, pp. 29–36. doi: 10.1016/j.egyr.2017.01.001.

Hendriks, Caroline; Obernosterer, Richard; Müller, Daniel; Kytzia, Susanne; Baccini, Peter; Brunner, P. H. (2000) 'Material Flow Analysis : a tool to support environmental policy decision making . Case-studies on the city of Vienna and the Swiss lowlands', *Local* *environment*, 5(3), pp. 311–328. doi: 10.1080/13549830050134257.

Hepbasli, A. and Alsuhaibani, Z. (2011) 'A key review on present status and future directions of solar energy studies and applications in Saudi Arabia', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 15(9), pp. 5021–5050. doi: 10.1016/j.rser.2011.07.052.

Hilty, L. M. *et al.* (2014) 'Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods'.

Hodson, M. *et al.* (2012) 'Reshaping Urban Infrastructure: Material Flow Analysis and Transitions Analysis in an Urban Context', *Journal of Industrial Ecology*, 16(6), pp. 789–800. doi: 10.1111/j.1530-9290.2012.00559.x.

Hong, L. *et al.* (2016) 'Building stock dynamics and its impacts on materials and energy demand in China', *Energy Policy*. Elsevier, 94(June 2015), pp. 47–55. doi: 10.1016/j.enpol.2016.03.024.

Hoornweg, D. and Pope, K. (2014) *Socioeconomic Pathways and Regional Distribution of the World's 101 Largest Cities*.

Hoque, M. R. *et al.* (2012) 'Energy Intensity of the Catalan Construction Sector: An Application of Material and Exergy Flow Analysis', *Journal of Industrial Ecology*, 16(5), pp. 699–709. doi: 10.1111/j.1530-9290.2012.00482.x.

Household Energy Survey (2017). Available at: https://www.stats.gov.sa/sites/default/files/household_energy_survey_2017en.pdf.

Household Energy Survey (2018).

Hu, D. *et al.* (2010) 'Input, stocks and output flows of urban residential building system in Beijing city, China from 1949 to 2008', *Resources, Conservation and Recycling*, 54(12), pp. 1177–1188. doi: 10.1016/j.resconrec.2010.03.011.

Hu, M. (2010) *Dynamic Material Flow Analysis to Support Sustainable Built Environment Development*. Leiden University.

Hu, M., Bergsdal, H., *et al.* (2010) 'Dynamics of urban and rural housing stocks in China', *Building Research & Information*, 38(3), pp. 301–317. doi: 10.1080/09613211003729988.

Hu, M., Pauliuk, S., *et al.* (2010) 'Iron and steel in Chinese residential buildings: A dynamic analysis', *Resources, Conservation and Recycling*, 54(9), pp. 591–600. doi: 10.1016/j.resconrec.2009.10.016.

Hu, M., van der Voet, E. and Huppes, G. (2010) 'Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing', *Journal of Industrial Ecology*, 14(3), pp. 440–456. doi: 10.1111/j.1530-9290.2010.00245.x.

Huang, B. *et al.* (2018) 'Building Material Use and Associated Environmental Impacts in China 2000-2015', *Environmental Science and Technology*. American Chemical Society, 52(23), pp. 14006–14014. doi: 10.1021/acs.est.8b04104.

Huang, C.-L. *et al.* (2012) 'Using material/substance flow analysis to support sustainable development assessment: A literature review and outlook', *Resources, Conservation and Recycling*. Elsevier B.V., 68, pp. 104–116. doi: 10.1016/j.resconrec.2012.08.012.

Huang, S. L. and Chen, C. W. (2009) 'Urbanization and socioeconomic metabolism in Taipei an emergy synthesis', *Journal of Industrial Ecology*, 13(1), pp. 75–93. doi: 10.1111/j.1530-9290.2008.00103.x.

Huang, T. *et al.* (2013a) 'Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis', *Resources, Conservation and Recycling*, 72, pp. 91–101. doi: 10.1016/j.resconrec.2012.12.013.

Huang, T. *et al.* (2013b) 'Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis', *Resources, Conservation and Recycling*, 72, pp. 91–101. doi: 10.1016/j.resconrec.2012.12.013.

Huijbregts, M. A. . *et al.* (2016) 'ReCiPe 2016 : A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization', *ReCiPe 2016 : Een geharmoniseerde levenscyclus impact assessment methode op 'midpoint' en 'endpoint' niveau Rapport 1: karakterisatie*. Rijksinstituut voor Volksgezondheid en Milieu RIVM. Available at: https://rivm.openrepository.com/bitstream/10029/620793/3/2016-0104.pdf.

Huijbregts, M. A. J. *et al.* (2017) 'ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level', *The International Journal of Life Cycle Assessment*, 22(2), pp. 138–147. doi: 10.1007/s11367-016-1246-y.

Hunt, D. V. L. *et al.* (2014) 'Material Flow Analysis (MFA) for Liveable Cities', in *The 4th World Sustainability Forum*. Available at: http://www.sciforum.net/conference/wsf-4.

Hunt, D. V. L. and Rogers, C. (2016) 'Aspirational City Futures: A Short Review of Foresight Approaches', *The University of Birmingham*.

Investment climate in Riyadh (2016). Riyadh.

IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories*.

Islam, M. T. and Huda, N. (2019) 'Material flow analysis (MFA) as a strategic tool in E-waste management: Applications, trends and future directions', *Journal of Environmental Management*, 244, pp. 344–361. doi: https://doi.org/10.1016/j.jenvman.2019.05.062.

ISO (2006) *Environmental Management: Life Cycle Assessment; Principles and Framework*. International Organization for Standardization.

Jones, P., Patterson, J. and Lannon, S. (2007) 'Modelling the built environment at an urban scale-Energy and health impacts in relation to housing', *Landscape and Urban Planning*, 83(1), pp. 39–49. doi: 10.1016/j.landurbplan.2007.05.015.

Jun, H. (2013) 'Saudi Arabia ' s Domestic Energy Situation and Policy : Focusing on Its Power Sector', *Kyoto Bulletin of Islamic Area Studies*, 6(March), pp. 107–135.

Kajenthira, A., Siddiqi, A. and Anadon, L. D. (2012) 'A new case for promoting wastewater reuse in Saudi Arabia: Bringing energy into the water equation', *Journal of Environmental Management*. Elsevier Ltd, 102, pp. 184–192. doi: 10.1016/j.jenvman.2011.09.023.

Kalmykova, Y., Rosado, L. and Patrício, J. (2015a) 'Resource consumption drivers and pathways to reduction: economy, policy and lifestyle impact on material flows at the national and urban scale', *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2015.02.027.

Kalmykova, Y., Rosado, L. and Patrício, J. (2015b) 'Resource consumption drivers and pathways to reduction: economy, policy and lifestyle impact on material flows at the national and urban scale', *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2015.02.027.

Kapur, A. *et al.* (2008) 'Dynamic modeling of in-use cement stocks in the United States', *Journal of Industrial Ecology*, 12(4), pp. 539–556. doi: 10.1111/j.1530-9290.2008.00055.x.

Kapur, A. *et al.* (2009) 'The contemporary cement cycle of the United States', *Journal of Material Cycles and Waste Management*, 11(2), pp. 155–165. doi: 10.1007/s10163-008-0229-x.

Kennedy, C. *et al.* (2011) 'Greenhouse Gas Emissions from Global Cities', *Environ. Sci. Technol.*, 43(19), pp. 7297–7302. doi: doi: 10.1021/es900213p.

Kennedy, C. *et al.* (2014) 'Developing a multi-layered indicator set for urban metabolism studies in megacities', *Ecological Indicators*. Elsevier Ltd. doi: 10.1016/j.ecolind.2014.07.039.

Kennedy, C. A. *et al.* (2015) 'Energy and material flows of megacities', *Proceedings of the National Academy of Sciences*, 112(19), pp. 5985–5990. doi: 10.1073/pnas.1504315112.

Kennedy, C., Baker, L. and Brattebø, H. (2014a) 'Analyzing a city's metabolism', *Elgar Companion to Sustainable Cities*, pp. 255–282. doi: 10.4337/9780857939999.00019.

Kennedy, C., Baker, L. and Brattebø, H. (2014b) 'Analyzing a city ' s metabolism', in Mazmanian, D. A. and Blanco, H. (eds) *Elgar companion to sustainable cities: strategies, methods, and outlook*. 1st edn. Edward Elgar, pp. 225–282.

Kennedy, C., Baker, L. and Brattebø, H. (2014c) 'Analyzing a city ' s metabolism', in Mazmanian, D. A. and Blanco, H. (eds) *Elgar companion to sustainable cities: strategies, methods, and outlook*. 1st edn. Edward Elgar, pp. 225–282.

Kennedy, C., Cuddihy, J. and Engel-Yan, J. (2007) 'The Changing Metabolism of Cities', *Journal of Industrial Ecology*, 11(2), pp. 43–59. doi: 10.1162/jie.2007.1107.

Kennedy, C. and Hoornweg, D. (2012) 'Mainstreaming Urban Metabolism', *Journal of Industrial Ecology*, 16(6), pp. 780–782. doi: 10.1111/j.1530-9290.2012.00548.x.

Kennedy, C., Pincetl, S. and Bunje, P. (2011) 'The study of urban metabolism and its applications to urban planning and design', *Environmental Pollution*. Elsevier Ltd, 159(8–9), pp. 1965–1973. doi: 10.1016/j.envpol.2010.10.022.

Khondaker, A. N. *et al.* (2014) 'Dynamics of energy sector and GHG emissions in Saudi Arabia', *Climate Policy*. Taylor & Francis, 15(4), pp. 517–541. doi: 10.1080/14693062.2014.937387.

Khondaker, A. N. *et al.* (2016) 'Dynamics of energy sector and GHG emissions in Saudi Arabia Dynamics of energy sector and GHG emissions in Saudi Arabia', *Climate Policy*, 3062(August). doi: 10.1080/14693062.2014.937387.

Khonpikul, S. *et al.* (2017) 'Resource use and improvement strategy analysis of the livestock and feed production supply chain in Thailand', *International Journal of Life Cycle Assessment*. The International Journal of Life Cycle Assessment, 22(11), pp. 1692–1704. doi: 10.1007/s11367-017-1361-4.

Kissinger, M. and Stossel, Z. (2019) 'Towards an interspatial urban metabolism analysis in an interconnected world', *Ecological Indicators*. Elsevier, 101(February), pp. 1077–

1085. doi: 10.1016/j.ecolind.2018.11.022.

Klein Goldewijk, K., Beusen, A. and Janssen, P. (2010) ‘Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1’, *The Holocene*, 20(4), pp. 565–573. doi: 10.1177/0959683609356587.

Krausmann, F. *et al.* (2018) ‘From resource extraction to out flows of wastes and emissions : The socioeconomic metabolism of the global economy , 1900 – 2015’, *Global Environmental Change journal*, 52, pp. 131–140. doi: 10.1016/j.gloenvcha.2018.07.003.

Krausmann, F., Gingrich, S. and Nourbakhch-Sabet, R. (2011) ‘The metabolic transition in Japan: A material flow account for the period from 1878 to 2005’, *Journal of Industrial Ecology*, 15(6), pp. 877–892. doi: 10.1111/j.1530-9290.2011.00376.x.

Lanau, M. *et al.* (2019) ‘Taking Stock of Built Environment Stock Studies: Progress and Prospects’, *Environmental Science & Technology*. American Chemical Society, 53(15), pp. 8499–8515. doi: 10.1021/acs.est.8b06652.

Laner, D., Rechberger, H. and Astrup, T. (2014) ‘Systematic Evaluation of Uncertainty in Material Flow Analysis’, *Journal of Industrial Ecology*, 18(6), pp. 859–870. doi: 10.1111/jiec.12143.

Lavers Westin, A. *et al.* (2019) ‘Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption’, *Journal of Cleaner Production*. Elsevier Ltd, 226, pp. 526–539. doi: 10.1016/j.jclepro.2019.04.036.

Li, H., Dong, L. and Ren, J. (2015) ‘Industrial symbiosis as a countermeasure for resource dependent city: a case study of Guiyang, China’, *Journal of Cleaner Production*, 107, pp. 252–266. doi: 10.1016/j.jclepro.2015.04.089.

Li, Y. *et al.* (2016) ‘Evaluating urban sustainability potential based on material flow analysis of inputs and outputs: A case study in Jinchang City, China’, *Resources, Conservation and Recycling*, 110, pp. 87–98. doi: 10.1016/j.resconrec.2016.03.023.

Li, Y. *et al.* (2018) ‘Understanding the mechanism of urban material metabolism with ecological network analysis: An experimental study of Wuxi, China’, *Ecological Modelling*, 367, pp. 58–67. doi: https://doi.org/10.1016/j.ecolmodel.2017.09.007.

Lima, R. S., de Azevedo Caldeira-Pires, A. and Cardoso, A. N. (2020) ‘Uncertainty Analysis in Life Cycle Assessments Applied to Biorefineries Systems: A Critical Review of the Literature’, *Process Integration and Optimization for Sustainability*. Springer, pp. 1–13.

Lin, C., Liu, G. and Müller, D. B. (2017) ‘Characterizing the role of built environment stocks in human development and emission growth’, *Resources, Conservation and Recycling*. Elsevier, 123, pp. 67–72.

Liu, J., Wang, R. and Yang, J. (2009) ‘Environment consumption patterns of Chinese urban households and their policy implications’, *International Journal of Sustainable Development & World Ecology*, 16(1), pp. 9–14. doi: 10.1080/13504500902749012.

Lombardi, D. R. *et al.* (2012) *Designing resilient cities: a guide to good practice*. IHS BRE Press.

Lopes Silva, D. A. *et al.* (2015) ‘Combined MFA and LCA approach to evaluate the metabolism of service polygons: A case study on a university campus’, *Resources, Conservation and Recycling*. Elsevier B.V., 94, pp. 157–168. doi: 10.1016/j.resconrec.2014.11.001.

López-Villarreal, F. *et al.* (2014) ‘An MFA optimization approach for pollution trading considering the sustainability of the surrounded watersheds’, *Computers and Chemical Engineering*. Elsevier Ltd, 63, pp. 140–151. doi: 10.1016/j.compchemeng.2014.01.005.

Makarichi, L., Techato, K. and Jutidamrongphan, W. (2018) ‘Material flow analysis as a support tool for multi-criteria analysis in solid waste management decision-making’, *Resources, Conservation and Recycling*, 139, pp. 351–365. doi: https://doi.org/10.1016/j.resconrec.2018.07.024.

Masson-Delmotte, V. *et al.* (2019) *IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels*.

Meng, F. *et al.* (2017) ‘Energy efficiency of urban transportation system in Xiamen , China . An integrated approach’, *Applied Energy*. Elsevier Ltd, 186, pp. 234–248. doi: 10.1016/j.apenergy.2016.02.055.

Miatto, A., Schandl, H. and Tanikawa, H. (2017) ‘How important are realistic building lifespan assumptions for material stock and demolition waste accounts ?’, *Resources, Conservation & Recycling*. Elsevier B.V., 122, pp. 143–154. doi: 10.1016/j.resconrec.2017.01.015.

Middleton, D. A. (2012) *Growth and Expansion in Post-War Urban Design Strategies: C. A. Doxiadis and the First Strategic Plan for Riyadh Saudi Arabia (1968--1972).* BiblioBazaar. Available at: https://books.google.co.uk/books?id=EBp5MAEACAAJ.

Milford, R. L. *et al.* (2013) 'The Roles of Energy and Material Efficiency in Meeting Steel Industry CO 2 Targets', *Environmental Science & Technology*, 47(7), pp. 3455–3462. doi: 10.1021/es3031424.

Ministry of Energy Industry and Mineral Resources (2016) 'Third National Communication of the Kingdom of Saudi Arabia', (December), pp. 173–174. Available at: https://unfccc.int/files/national_reports/non-annex_i_natcom/application/pdf/saudi_arabia_nc3_22_dec_2016.pdf.

Moncaster, A. M. and Symons, K. E. (2013) 'A method and tool for "cradle to grave" embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards', *Energy and Buildings*, 66, pp. 514–523. doi: https://doi.org/10.1016/j.enbuild.2013.07.046.

Montangero, A., Le, C. N., *et al.* (2007) 'Optimising water and phosphorus management in the urban environmental sanitation system of Hanoi, Vietnam.', *The Science of the total environment*, 384(1–3), pp. 55–66. doi: 10.1016/j.scitotenv.2007.05.032.

Montangero, A., Cau, L. N., *et al.* (2007) 'Optimising water and phosphorus management in the urban environmental sanitation system of Hanoi, Vietnam', *Science of the Total Environment*, 384(1–3), pp. 55–66. doi: 10.1016/j.scitotenv.2007.05.032.

Moore, J., Kissinger, M. and Rees, W. E. (2013) 'An urban metabolism and ecological footprint assessment of Metro Vancouver.', *Journal of environmental management*, 124, pp. 51–61. doi: 10.1016/j.jenvman.2013.03.009.

Mostafavi, N., Farzinmoghadam, M. and Hoque, S. (2014) 'A framework for integrated urban metabolism analysis tool (IUMAT)', *Building and Environment*. Elsevier Ltd, 82, pp. 702–712. doi: 10.1016/j.buildenv.2014.10.020.

Mpakati-Gama, E. C., Brown, A. and Sloan, B. (2016) 'Embodied energy and carbon analysis of urban residential buildings in Malawi', *International Journal of Construction Management*. Taylor & Francis, 16(1), pp. 1–12. doi: 10.1080/15623599.2015.1110274.

Müller, D. B. (2005) 'Stock dynamics for forecasting material flows—Case study for housing in The Netherlands', *Ecological Economics*, 59, pp. 142–156. doi: 10.1016/j.eco.

Müller, D. B. (2006) 'Stock dynamics for forecasting material flows—Case study for housing in The Netherlands', *Ecological Economics*, 59, pp. 142–156. doi: :10.1016/j.eco lecon.2005.09.025.

Müller, D. B., Bader, H.-P. and Baccini, P. (2004) 'Long-term Coordination of Timber

Production and Consumption Using a Dynamic Material and Energy Flow Analysis', *Journal of Industrial Ecology*, 8(3), pp. 65–88. doi: 10.1162/1088198042442342.

Müller, E. *et al.* (2014) 'Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods', *Environmental Science & Technology*. American Chemical Society, 48(4), pp. 2102–2113. doi: 10.1021/es403506a.

Myers, D. R. *et al.* (2002) *Final Report for Annex II — Assessment of Solar Radiation Resources in Saudi Arabia Final Report for Annex II — Assessment of Solar Radiation Resources in Saudi Arabia- 1998–2000*. Available at: http://www.osti.gov/bridge.

Nachet, S. and Aoun, M.-C. (2015) *The Saudi electricity sector: pressing issues and challenges*. Institut français des relations internationales.

Nahiduzzaman, K. M., Aldosary, A. S. and Rahman, M. T. (2015) 'Flood induced vulnerability in strategic plan making process of Riyadh city', *Habitat International*, 49, pp. 375–385. doi: https://doi.org/10.1016/j.habitatint.2015.05.034.

National Academies of Sciences and Medicine, E. (2016) *Pathways to urban sustainability: challenges and opportunities for the United States*. National Academies Press.

Nejat, P. *et al.* (2015) 'A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries)', *Renewable and Sustainable Energy Reviews*. Elsevier, 43, pp. 843–862. doi: 10.1016/j.rser.2014.11.066.

Ngo, N. S. and Pataki, D. E. (2008) 'The energy and mass balance of Los Angeles County', *Urban Ecosyst*, (February), pp. 121–139. doi: 10.1007/s11252-008-0051-1.

Nichols, B. G. and Kockelman, K. (2015) 'Urban form and life-cycle energy consumption: Case studies at the city scale', *Journal of Transport and Land Use*, 8(3), pp. 115–128. doi: 10.5198/jtlu.2015.598.

Niza, S. *et al.* (2015) 'Australia is "free to choose" economic growth and falling environmental pressures', *Journal of Industrial Ecology*. Springer Japan, 16(1), pp. 263–274. doi: 10.1111/j.1530-9290.2011.00368.x.

Niza, S., Rosado, L. and Ferrdo, P. (2009) 'Urban metabolism methodological advances in urban material flow accounting based on the lisbon case study', *Journal of Industrial Ecology*, 13(3), pp. 384–405. doi: 10.1111/j.1530-9290.2009.00130.x.

OECD (2008) *Measuring material flows and resource productivity: synthesis report*.

Available at: http://www.oecd.org/dataoecd/55/12/40464014.pdf.

Ohnishi, S. *et al.* (2017) ‘A comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan’, *Ecological Indicators*, 73, pp. 513–524. doi: https://doi.org/10.1016/j.ecolind.2016.10.016.

Päivinen, R. *et al.* (2012) ‘A concept for assessing sustainability impacts of forestry-wood chains’, *European Journal of Forest Research*, 131(1), pp. 7–19. doi: 10.1007/s10342-010-0446-4.

Pardo Martínez, C. I. (2015) ‘Energy and sustainable development in cities: A case study of Bogotá’, *Energy*, 92, pp. 612–621. doi: 10.1016/j.energy.2015.02.003.

Pauliuk, S. and Müller, Daniel B (2014) ‘The role of in-use stocks in the social metabolism and in climate change mitigation’, *Global Environmental Change*, 24, pp. 132–142. doi: 10.1016/j.gloenvcha.2013.11.006.

Pauliuk, S. and Müller, Daniel B. (2014a) ‘The role of in-use stocks in the social metabolism and in climate change mitigation’, *Global Environmental Change*, 24, pp. 132–142. doi: 10.1016/j.gloenvcha.2013.11.006.

Pauliuk, S. and Müller, Daniel B. (2014b) ‘The role of in-use stocks in the social metabolism and in climate change mitigation’, *Global Environmental Change*, 24(1), pp. 132–142. doi: 10.1016/j.gloenvcha.2013.11.006.

Pauliuk, S., Sjöstrand, K. and Müller, Daniel B. (2013a) ‘Transforming the Norwegian dwelling stock to reach the 2 degrees celsius climate target: Combining material flow analysis and life cycle assessment techniques’, *Journal of Industrial Ecology*, 17(4), pp. 542–554. doi: 10.1111/j.1530-9290.2012.00571.x.

Pauliuk, S., Sjöstrand, K. and Müller, Daniel B. (2013b) ‘Transforming the Norwegian dwelling stock to reach the 2 degrees celsius climate target: Combining material flow analysis and life cycle assessment techniques’, *Journal of Industrial Ecology*, 17(4), pp. 542–554. doi: 10.1111/j.1530-9290.2012.00571.x.

Pauliuk, S., Sjöstrand, K. and Müller, Daniel B (2013) ‘Transforming the Norwegian dwelling stock to reach the 2 degrees celsius climate target: Combining material flow analysis and life cycle assessment techniques’, *Journal of Industrial Ecology*, 17(4), pp. 542–554. doi: 10.1111/j.1530-9290.2012.00571.x.

Pauliuk, S., Wang, T. and Müller, Daniel B (2012) ‘Moving toward the circular economy: The role of stocks in the Chinese steel cycle’, *Environmental Science & Technology*, 46(1), pp. 148–154. doi: 10.1021/es201904c.

Pauliuk, S., Wang, T. and Müller, Daniel B. (2012) ‘Moving toward the circular economy: The role of stocks in the Chinese steel cycle’, *Environmental Science & Technology*, 46(1), pp. 148–154. doi: 10.1021/es201904c.

Pauliuk, S., Wang, T. and Müller, D. B. (2013) ‘Steel all over the world: Estimating in-use stocks of iron for 200 countries’, *Resources, Conservation and Recycling*, 71, pp. 22–30. doi: 10.1016/j.resconrec.2012.11.008.

Pickett, S. T. A. *et al.* (2001) ‘Urban ecological systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas’, *Annual review of ecology and systematics*. Annual Reviews 4139 El Camino Way, PO Box 10139, Palo Alto, CA 94303-0139, USA, 32(1), pp. 127–157.

Pickett, S. T. A. *et al.* (2014) ‘Ecological resilience and resilient cities’, *Building Research & Information*. Routledge, 42(2), pp. 143–157. doi: 10.1080/09613218.2014.850600.

Pincetl, S. *et al.* (2014a) ‘Enabling Future Sustainability Transitions’, *Journal of Industrial Ecology*, 18(6), pp. 871–882. doi: 10.1111/jiec.12144.

Pincetl, S. *et al.* (2014b) ‘Enabling Future Sustainability Transitions An Urban Metabolism Approach to Los Angeles’, *Journal of Industrial Ecology*, 18(6), pp. 871–882. doi: 10.1111/jiec.12144.

Pincetl, S., Bunje, P. and Holmes, T. (2012) ‘An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes’, *Landscape and Urban Planning*. Elsevier B.V., 107(3), pp. 193–202. doi: 10.1016/j.landurbplan.2012.06.006.

Pingmuanglek, P., Jakrawatana, N. and Gheewala, S. H. (2017) ‘Freshwater use analysis of cassava for food feed fuel in the Mun River basin, Thailand’, *International Journal of Life Cycle Assessment*. The International Journal of Life Cycle Assessment, 22(11), pp. 1705–1717. doi: 10.1007/s11367-017-1286-y.

Population Study of Riyadh City (2016). Riyadh. Available at: http://www.ada.gov.sa/idc/groups/public/documents/AR_ADA_Researches/007523.pdf.

Pothen, F. and Tovar Reaños, M. A. (2018) ‘The Distribution of Material Footprints in Germany’, *Ecological Economics*. Elsevier, 153(February), pp. 237–251. doi: 10.1016/j.ecolecon.2018.06.001.

Poveda, C. A. and Lipsett, M. G. (2014) ‘An integrated approach for sustainability assessment: The Wa-Pa-Su project sustainability rating system', *International Journal of Sustainable Development and World Ecology*. Taylor & Francis, 21(1), pp. 85–98. doi: 10.1080/13504509.2013.876677.

Quadrelli, E. A. *et al.* (2011) 'Carbon dioxide recycling: emerging large-scale technologies with industrial potential', *ChemSusChem*. Wiley Online Library, 4(9), pp. 1194–1215.

Raluy, G., Serra, L. and Uche, J. (2006) 'Life cycle assessment of MSF, MED and RO desalination technologies', *Energy*, 31(13), pp. 2361–2372. doi: 10.1016/j.energy.2006.02.005.

Ramaswami, A., Chavez, A. and Chertow, M. (2012) 'Carbon Footprinting of Cities and Implications for Analysis of Urban Material and Energy Flows', *Journal of Industrial Ecology*, 16(6), pp. 783–785. doi: 10.1111/j.1530-9290.2012.00569.x.

Ramesh, T., Prakash, R. and Shukla, K. K. (2010) 'Life cycle energy analysis of buildings: An overview', *Energy and Buildings*, 42(10), pp. 1592–1600. doi: 10.1016/j.enbuild.2010.05.007.

Reusswig, F., Lotze-Campen, H. and Gerlinger, K. (2003) 'Changing global lifestyle and consumption patterns: The case of energy and food', in *PERN workshop on population, consumption and the environment*.

Reyna, Janet L. and Chester, M. V. (2015) 'The Growth of Urban Building Stock: Unintended Lock-in and Embedded Environmental Effects', *Journal of Industrial Ecology*, 19(4), pp. 524–537. doi: 10.1111/jiec.12211.

Reyna, Janet L and Chester, M. V (2015) 'The Growth of Urban Building Stock: Unintended Lock-in and Embedded Environmental Effects', *Journal of Industrial Ecology*, 19(4), pp. 524–537. doi: 10.1111/jiec.12211.

Rincón, L. *et al.* (2013) 'Evaluation of the environmental impact of experimental buildings with different constructive systems using Material Flow Analysis and Life Cycle Assessment', *Applied Energy*, 109, pp. 544–552. doi: 10.1016/j.apenergy.2013.02.038.

Riyadh Chamber (2016) *Riyadh in Figures*.

Riyadh Development Authority (2016) *Tatweer*. doi: 10.1192/bjp.112.483.211-a.

Riyadh Local Urban Observatory (2018) *Riyadh CPI profile*. doi: 10.1192/bjp.111.479.1009-a.

Riyadh Urban Indicators (2017).

Rochat, D. *et al.* (2013) ‘Combining material flow analysis, life cycle assessment, and multiattribute utility theory: Assessment of end-of-life scenarios for polyethylene terephthalate in Tunja, Colombia Rochat et al. Combining MFA, LCA, and MAUT’, *Journal of Industrial Ecology*, 17(5), pp. 642–655. doi: 10.1111/jiec.12025.

Röhrlich, M. *et al.* (2000) ‘A method to calculate the cumulative energy demand (CED) of lignite extraction’, *The International Journal of Life Cycle Assessment*, 5(6), pp. 369–373. doi: 10.1007/BF02978675.

Roibás, L., Loiseau, E. and Hospido, A. (2017) ‘Determination of the carbon footprint of all Galician production and consumption activities: Lessons learnt and guidelines for policymakers’, *Journal of Environmental Management*, 198, pp. 289–299. doi: https://doi.org/10.1016/j.jenvman.2017.04.071.

Sahely, H. R., Dudding, S. and Kennedy, C. A. (2003) ‘Estimating the urban metabolism of Canadian cities : Greater Toronto Area case study’, *Canadian Journal of Civil Engineering*, 483, pp. 468–483. doi: 10.1139/L02-105.

Saline Water Conversion Corporation (2016) *SWCC Annual Report*.

Sandberg, N. H., Sartori, I., Heidrich, O., *et al.* (2016) ‘Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU’, *Energy and Buildings*, 132, pp. 26–38. doi: https://doi.org/10.1016/j.enbuild.2016.05.100.

Sandberg, N. H., Sartori, I., Vestrum, Magnus I, *et al.* (2016) ‘Explaining the historical energy use in dwelling stocks with a segmented dynamic model: Case study of Norway 1960–2015’, *Energy and Buildings*. Elsevier B.V., 132, pp. 141–153. doi: 10.1016/j.enbuild.2016.05.099.

Sandberg, N. H., Sartori, I., Vestrum, Magnus I., *et al.* (2016) ‘Explaining the historical energy use in dwelling stocks with a segmented dynamic model: Case study of Norway 1960–2015’, *Energy and Buildings*. Elsevier B.V., 132, pp. 141–153. doi: 10.1016/j.enbuild.2016.05.099.

Sandberg, N. H., Sartori, I., Vestrum, Magnus I., *et al.* (2017) ‘Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016–2050’, *Energy and Buildings*. Elsevier B.V., 146, pp. 220–232. doi: 10.1016/j.enbuild.2017.04.016.

Sandberg, N. H., Sartori, I., Vestrum, Magnus I, *et al.* (2017) ‘Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016–2050', *Energy and Buildings*. Elsevier B.V., 146, pp. 220–232. doi: 10.1016/j.enbuild.2017.04.016.

Sandberg, N. H., Bergsdal, H. and Brattebø, H. (2011) 'Historical energy analysis of the Norwegian dwelling stock', *Building Research & Information*, 39(1), pp. 1–15. doi: 10.1080/09613218.2010.528186.

Sandberg, N. H. and Bratteb, H. (2012) 'Analysis of energy and carbon flows in the future Norwegian dwelling stock', *Building Research and Information*, 40(2), pp. 123–139. doi: 10.1080/09613218.2012.655071.

Sandberg, N. H. and Brattebø, H. (2012a) 'Analysis of energy and carbon flows in the future Norwegian dwelling stock', *Building Research & Information*, 40(2), pp. 123–139. doi: 10.1080/09613218.2012.655071.

Sandberg, N. H. and Brattebø, H. (2012b) 'Analysis of energy and carbon flows in the future Norwegian dwelling stock', *Building Research & Information*, 40(2), pp. 123–139. doi: 10.1080/09613218.2012.655071.

Sandberg, N. H., Nord, N. and Lausselet, C. (2018) *STOCK MODEL FOR LONG-TERM DYNAMIC ANALYSES OF ENERGY General model description and case studies*. doi: 10.13140/RG.2.2.13718.24640.

Sandberg, N. H., Sartori, I. and Brattebø, H. (2014a) 'Sensitivity analysis in long-term dynamic building stock modeling—Exploring the importance of uncertainty of input parameters in Norwegian segmented dwelling stock model', *Energy and Buildings*, 85, pp. 136–144. doi: 10.1016/j.enbuild.2014.09.028.

Sandberg, N. H., Sartori, I. and Brattebø, H. (2014b) 'Sensitivity analysis in long-term dynamic building stock modeling—Exploring the importance of uncertainty of input parameters in Norwegian segmented dwelling stock model', *Energy and Buildings*, 85, pp. 136–144. doi: 10.1016/j.enbuild.2014.09.028.

Sandberg, N. H., Sartori, I. and Brattebø, H. (2014c) 'Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock', *Energy and Buildings*, 82, pp. 287–295. doi: 10.1016/j.enbuild.2014.07.005.

Sartori, I., Bergsdal, H., Müller, Daniel B., *et al.* (2008) 'Towards modelling of construction, renovation and demolition activities: Norway's dwelling stock, 1900–2100', *Building Research & Information*, 36(5), pp. 412–425. doi: 10.1080/09613210802184312.

Sartori, I., Bergsdal, H., Müller, Daniel B, *et al.* (2008) 'Towards modelling of construction, renovation and demolition activities: Norway's dwelling stock, 1900–2100', *Building Research & Information*, 36(5), pp. 412–425. doi: 10.1080/09613210802184312.

Sato, F. E. K., Furubayashi, T. and Nakata, T. (2019) 'Application of energy and CO 2 reduction assessments for end-of-life vehicles recycling in Japan', *Applied Energy*. Elsevier, 237(December 2018), pp. 779–794. doi: 10.1016/j.apenergy.2019.01.002.

Shen, L. Y. *et al.* (2011) 'The application of urban sustainability indicators - A comparison between various practices', *Habitat International*. Elsevier Ltd, 35(1), pp. 17–29. doi: 10.1016/j.habitatint.2010.03.006.

Shi, F. *et al.* (2012a) 'Toward a low carbon-dematerialization society: Measuring the materials demand and co 2 emissions of building and transport infrastructure construction in China', *Journal of Industrial Ecology*, 16(4), pp. 493–505. doi: 10.1111/j.1530-9290.2012.00523.x.

Shi, F. *et al.* (2012b) 'Toward a low carbon-dematerialization society: Measuring the materials demand and co 2 emissions of building and transport infrastructure construction in China', *Journal of Industrial Ecology*, 16(4), pp. 493–505. doi: 10.1111/j.1530-9290.2012.00523.x.

Shi, L. *et al.* (2014) 'Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies', *Proceedings of the National Academy of Sciences*, 112(20), pp. 6277–6282. doi: 10.1073/pnas.1312753111.

Sinclair, P. *et al.* (2005) 'Towards an integrated regional materials flow accounting model', *Journal of Industrial Ecology*, 9(1–2), pp. 69–84. doi: 10.1162/1088198054084716.

Skofronick-Jackson, G. *et al.* (2018) 'The Global Precipitation Measurement (GPM) mission's scientific achievements and societal contributions: reviewing four years of advanced rain and snow observations', *Quarterly Journal of the Royal Meteorological Society*. John Wiley & Sons, Ltd, 144(S1), pp. 27–48. doi: 10.1002/qj.3313.

Södersten, C. J., Wood, R. and Hertwich, E. G. (2018) 'Environmental Impacts of Capital Formation', *Journal of Industrial Ecology*, 22(1), pp. 55–67. doi: 10.1111/jiec.12532.

Song, K. *et al.* (2019) 'Scale, distribution and variations of global greenhouse gas emissions driven by U.S. households', *Environment International*, 133, p. 105137. doi: https://doi.org/10.1016/j.envint.2019.105137.

Stephan, A. and Athanassiadis, A. (2017) 'Quantifying and mapping embodied environmental requirements of urban building stocks', *Building and Environment*, 114, pp. 187–202. doi: 10.1016/j.buildenv.2016.11.043.

Stephan, A. and Athanassiadis, A. (2018) 'Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks', *Resources, Conservation and Recycling*. Elsevier, 129(April 2017), pp. 248–262. doi: 10.1016/j.resconrec.2017.09.022.

Stephan, A. and Crawford, R. H. (2014) 'A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings', *Architectural Science Review*, 57(1), pp. 39–48. doi: 10.1080/00038628.2013.837814.

Study of Riyadh land use (2013).

Su, X. and Zhang, X. (2016) 'A detailed analysis of the embodied energy and carbon emissions of steel-construction residential buildings in China', *Energy and Buildings*. Elsevier B.V., 119, pp. 323–330. doi: 10.1016/j.enbuild.2016.03.070.

Surahman, U., Kubota, T. and Higashi, O. (2015) 'Life Cycle Assessment of Energy and CO2 Emissions for Residential Buildings in Jakarta and Bandung, Indonesia', *Buildings*, 5(4), pp. 1131–1155. doi: 10.3390/buildings5041131.

Swan, L. G. and Ugursal, V. I. (2009) 'Modeling of end-use energy consumption in the residential sector: A review of modeling techniques', *Renewable and Sustainable Energy Reviews*, 13(8), pp. 1819–1835. doi: 10.1016/j.rser.2008.09.033.

Symmes, R. *et al.* (2019) 'The weight of islands: Leveraging Grenada's material stocks to adapt to climate change', *Journal of Industrial Ecology*, pp. 1–14. doi: 10.1111/jiec.12853.

Taher, N. and Hajjar, B. (2013) *Energy and environment in Saudi Arabia: Concerns & opportunities*. Springer Science & Business Media.

Taher, N. and Hajjar, B. (2014) *Energy and environment in Saudi Arabia: Concerns and opportunities*, *Energy and Environment in Saudi Arabia: Concerns and Opportunities*. doi: 10.1007/978-3-319-02982-5.

Tanikawa, H. *et al.* (2015) 'The weight of society over time and space: A comprehensive account of the construction material stock of Japan, 1945-2010', *Journal of Industrial Ecology*, 19(5), pp. 778–791. doi: 10.1111/jiec.12284.

Testa, F. *et al.* (2016) 'Perceptions on LCA implementation: evidence from a survey on adopters and nonadopters in Italy', *The International Journal of Life Cycle Assessment*. Berlin/Heidelberg, 21(10), pp. 1501–1513. doi: 10.1007/s11367-016-1106-9.

Thomson, G. and Newman, P. (2018) ‘Urban fabrics and urban metabolism – from sustainable to regenerative cities’, *Resources , Conservation and Recycling*. Elsevier B.V., 132, pp. 218–229. doi: 10.1016/j.resconrec.2017.01.010.

Thyholt, M. *et al.* (2009) ‘Energy analysis of the Norwegian dwelling stock’, *IEA Task*, 37.

Towards Saudi Arabia’s sutainable tomorrow (2018).

Uihlein, A., Poganietz, W. R. and Schebek, L. (2006) ‘Carbon flows and carbon use in the German anthroposphere: An inventory’, *Resources, Conservation and Recycling*, 46(4), pp. 410–429. doi: 10.1016/j.resconrec.2005.09.001.

UNDP (2015) ‘Human Development Report 2015 Technical notes’. New York.

United Nations (2014) *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352)*. doi: 10.4054/DemRes.2005.12.9.

United Nations (2016) *Transforming our world: The 2030 agenda for sustainable development*.

United Nations (2018) *The World ’s Cities in 2018*, *United Nations, Department of Economic and Social Affairs, Population*.

United Nations Population Division, D. of E. and S. A. (2014) ‘World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER. A/352)’. UN.

Urban indicators of Riyadh (2012). Riyadh.

Vásquez, F., Løvik, Amund N., *et al.* (2016a) ‘Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock’, *Energy and Buildings*, 111, pp. 37–55. doi: 10.1016/j.enbuild.2015.11.018.

Vásquez, F., Løvik, Amund N, *et al.* (2016) ‘Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock’, *Energy and Buildings*. Elsevier B.V., 111, pp. 37–55. doi: 10.1016/j.enbuild.2015.11.018.

Vásquez, F., Løvik, Amund N., *et al.* (2016b) ‘Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock’, *Energy and Buildings*. Elsevier B.V., 111, pp. 37–55. doi: 10.1016/j.enbuild.2015.11.018.

Vilaysouk, X., Schandl, H. and Murakami, S. (2017) ‘Improving the knowledge base on material flow analysis for Asian developing countries: A case study of Lao PDR’, *Resources, Conservation and Recycling*, 127, pp. 179–189. doi: https://doi.org/10.1016/j.resconrec.2017.09.006.

Voskamp, I. M. *et al.* (2016) 'Enhanced Performance of the Eurostat Method for Comprehensive Assessment of Urban Metabolism A Material Flow Analysis of Amsterdam', *Journal of Industrial Ecology*, 21(4), pp. 887–902. doi: 10.1111/jiec.12461.

Wada, I. (2017) 'Energy production and economic growth in Saudi Arabia: Dynamic causality', *Energy Sources, Part B: Economics, Planning, and Policy*. Taylor & Francis, 12(6), pp. 584–590. doi: 10.1080/15567249.2016.1248872.

Waltman, L., Van Eck, N. J. and Noyons, E. C. M. (2010) 'A unified approach to mapping and clustering of bibliometric networks', *Journal of Informetrics*. Elsevier, 4(4), pp. 629–635.

Wang, T. *et al.* (2015a) 'Concrete transformation of buildings in China and implications for the steel cycle', *Resources, Conservation and Recycling*, 103, pp. 205–215. doi: 10.1016/j.resconrec.2015.07.021.

Wang, T. *et al.* (2015b) 'Concrete transformation of buildings in China and implications for the steel cycle', *Resources, Conservation and Recycling*, 103, pp. 205–215. doi: 10.1016/j.resconrec.2015.07.021.

Weinzettel, J. and Kovanda, J. (2011) 'Structural decomposition analysis of raw material consumption: The case of the Czech Republic', *Journal of Industrial Ecology*, 15(6), pp. 893–907. doi: 10.1111/j.1530-9290.2011.00378.x.

Weisz, H. and Steinberger, J. K. (2010) 'Reducing energy and material flows in cities', *Current Opinion in Environmental Sustainability*. Elsevier B.V., 2(3), pp. 185–192. doi: 10.1016/j.cosust.2010.05.010.

Weisz, H., Suh, S. and Graedel, T. E. (2015) 'Industrial Ecology: The role of manufactured capital in sustainability', *Proceedings of the National Academy of Sciences*, 112(20), pp. 6260 LP – 6264. doi: 10.1073/pnas.1506532112.

Wiedenhofer, D. *et al.* (2015) 'Maintenance and Expansion: Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25', *Journal of Industrial Ecology*, 19(4), pp. 538–551. doi: 10.1111/jiec.12216.

Wilson, J., Tyedmers, P. and Grant, J. (2013) 'Measuring environmental impact at the neighbourhood level', *Journal of Environmental Planning and Management*, 56(1), pp. 42–60. doi: 10.1080/09640568.2011.649557.

Windsperger, B. *et al.* (2019) 'Greenhouse gas emissions due to national product consumption: from demand and research gaps to addressing key challenges', *International Journal of Environmental Science and Technology*. Springer Berlin Heidelberg, 16(2), pp. 1025–1038. doi: 10.1007/s13762-018-1743-6.

Wittmer, D. and Lichtensteiger, T. (2007) ‘Exploration of urban deposits: long-term prospects for resource and waste management’, *Waste Management & Research*, 25(3), pp. 220–226. doi: 10.1177/0734242X07079183.

Wogan, D., Carey, E. and Cooke, D. (2019) *Policy Pathways to Meet Saudi Arabia’s Contribution to the Paris Agreement*.

Wolff, F. and Schönherr, N. (2011) ‘The Impact Evaluation of Sustainable Consumption Policy Instruments’, *Journal of Consumer Policy*, 34(1), pp. 43–66. doi: 10.1007/s10603-010-9152-3.

Xiang, N., Xu, F. and Sha, J. (2013) ‘Simulation analysis of China’s energy and industrial structure adjustment potential to achieve a low-carbon economy by 2020’, *Sustainability*, 5(12), pp. 5081–5099. doi: 10.3390/su5125081.

Xu, W. *et al.* (2016) ‘CO2 emissions from China’s iron and steel industry’, *Journal of Cleaner Production*. Elsevier Ltd, 139, pp. 1504–1511. doi: 10.1016/j.jclepro.2016.08.107.

Yang, W. and Kohler, N. (2008) ‘Simulation of the evolution of the Chinese building and infrastructure stock’, *Building Research & Information*, 36(March 2015), pp. 1–19. doi: 10.1080/09613210701702883.

Yin, G., Liu, L. and Yuan, C. (2015) ‘Assessing environmental risks for high intensity agriculture using the material flow analysis method--a case study of the Dongting Lake basin in South Central China.’, *Environmental monitoring and assessment*, 187(7), p. 472. doi: 10.1007/s10661-015-4696-y.

Zellner, M. L. *et al.* (2008) ‘A new framework for urban sustainability assessments: Linking complexity, information and policy’, *Computers, Environment and Urban Systems*, 32(6), pp. 474–488. doi: 10.1016/j.compenvurbsys.2008.08.003.

Zhang, Y., Yang, Z. and Yu, X. (2009) ‘Evaluation of urban metabolism based on emergy synthesis: A case study for Beijing (China)’, *Ecological Modelling*, 220(13–14), pp. 1690–1696. doi: 10.1016/j.ecolmodel.2009.04.002.

Zhang, Y., Yang, Z. and Yu, X. (2015) ‘Urban Metabolism: A Review of Current Knowledge and Directions for Future Study’, *Environmental Science & Technology*, 49(19), pp. 11247–11263. doi: 10.1021/acs.est.5b03060.

Zhao, W. (2012) ‘Analysis on the Characteristic of Energy Flow in Urban Ecological Economic System—A Case of Xiamen City’, *Procedia Environmental Sciences*, 13, pp. 2274–2279. doi: 10.1016/j.proenv.2012.01.216.

Zhou, G. *et al.* (2015) ‘Evaluating low-carbon city initiatives from the DPSIR framework perspective’, *Habitat International*, 50, pp. 289–299. doi: 10.1016/j.habitatint.2015.09.001.

Zucaro, A. *et al.* (2014) ‘Urban resource use and environmental performance indicators. An application of decomposition analysis’, *Ecological Indicators*, 47, pp. 16–25. doi: 10.1016/j.ecolind.2014.04.022.

Zurbrügg, C., Caniato, M. and Vaccari, M. (2014) ‘How Assessment Methods Can Support Solid Waste Management in Developing Countries—A Critical Review’, *Sustainability*, 6, pp. 545–570. doi: 10.3390/su6020545.